VI MEETING SUL TITANIO

Organizzato dalla GTT

23 Novembre 1990

GTT

GINATTA TORINO TITANIUM

INDICE

- Marco V. Ginatta — Pag. 1
  GTT S.p.A.
  CELEBRAZIONE DEL BICENTENARIO DELLA SCOPERTA DEL TITANIO

- Tom Farthing — Pag. 2
  Consultant (Gran Bretagna)
  ACKNOWLEDGEMENT

- David K. Peacock — Pag. 3.1
  Timet Corporation (Gran Bretagna)
  EFFECTIVE DESIGN USING TITANIUM

- Friedrich Gieg — Pag. 4.0
  Titanium Development Association (U.S.A.)
  RMI Company (U.S.A)
  GROWTH POTENTIAL OF TITANIUM

- Peter Morcom — Pag. 5.0
  Deeside (Gran Bretagna)
  THE DEVELOPMENT OF COMPUTER CONTROL IN TITANIUM SPONGE GRANULE MANUFACTURE

- Francesco Botrè — Pag. 6.1
  Aeronautica Militare Italiana (Italia)
  OPERATING BEHAVIOUR OF AERONAUTIC TITANIUM COMPONENTS

- Michael J. Trzcinski — Pag. 7.1
  Advanced Materials Management (U.S.A.)
  POWDER TITANIUM FABRICATION PROCESSES, ECONOMICS AND MARKET APPLICATIONS

- Carlo Pession — Pag. 8.0
  Studio Pession (Italia)
  TITANIO E ARCHITETTURA

- Eric Schoeps — Pag. 9.0
  Sierracin Corporation Europe (Francia)
  TITANIUM TUBE ASSEMBLES FOR EROSPACE APPLICATIONS

- Gian Maria Gros Pietro - Monica Cariola — Pag. 10.1
  Ceris (Italia)
  IDEE NUOVE NELLA CRESCITA ECONOMICO-INDUSTRIALE DEL TITANIO

- Thomas H. Harrington — Pag. 11.0
  Consarc (U.K.)
  NEW ADVANCES IN ELECTRON-BEAM REFINING

- Gianmichele Orsello - Ezio Debernardi Pag. 12.1
  GTT S.p.A.
  AGGIORNAMENTO SULLE ATTIVITA' INDUSTRIALI DELLA GTT NEL TITANIO

- William R. Chinnis Pag. 13.1
  Teledyne Allvac (U.S.A.)
  PLASMA COLD HEART MELTING OF TITANIUM IN A PRODUCTION FURNACE

- Ferdinando Felli Pag. 14.1
  Università "La Sapienza" (Italia)
  Paolo Maria Lingua
  GTT S.p.A.
  COMPORTAMENTO MECCANICO DI UNA LEGA BETA-C COMMERCIALE

- Kazuyasu Kitaoka Pag. 15.0
  Kobe Steel (Giappone)
  MARKETING OF TITANIUM FOR ARCHITECTURE APPLICATION IN JAPAN

- Luca Colombo Pag. 16.1
  Titania S.r.l. (Italia)
  COLORAZIONE ANODICA DEL TITANIO E APPLICAZIONI

- Miroslav Nigkolov Pag. 17.1
  Scientific Research Institute of Automatic Means of Production and Control (U.R.S.S.)
  DIFFUSION WELDING OF TITANIUM ALLOYS OF DIFFERENT TYPES

- Massimo Zucchetti Pag. 18.1
  Politecnico di Torino (Italia)
  CHARACTERIZATION OF A TITANIUM ALLOY FOR NUCLEAR FUSION APPLICATIONS

CELEBRAZIONE DEL BICENTENARIO DELLA SCOPERTA DEL TITANIO

Marco V. Ginatta - GTT S.p.A.

Buongiorno Signore e Signori, Amici e Collaboratori.

Io sono Marco Ginatta e ho il piacere di dare il benvenuto, a nome della GTT, a tutti gli intervenuti che vedo con soddisfazione sempre più numerosi ad ogni anno: possiamo dire di pari passo con la crescita del titanio.

Apriamo quindi questo VI Meeting Internazionale di Torino sul titanio, che è anche l'occasione per celebrare il bicentenario della scoperta del titanio.
Infatti la targa di quest'anno è dedicata alla memoria del Reverendo William Gregor studioso di minerali che nel 1790 scoprì l'elemento titanio analizzando le sabbie contenenti ilmenite trovate nel distretto minerario della sua parrocchia, nella cittadina di Menaccan in Cornovaglia.

Gregor pubblicò nel 1791 una discussione dettagliata del suo lavoro, nel quale aveva isolato l'ossido di un metallo sconosciuto: Gregor propose di chiamare questo metallo Menaccanite (dal nome della sua città).

Perché è stato chiamato titanio?

Perché pochi anni dopo, nel 1795, il chimico Prof. Klaproth, dell'Accademia delle Scienze di Berlino, dopo una estesa e sistematica analisi di molti composti di minerali fra cui il rutilo, usando laboratori chimici molto meglio attrezzati di Gregor, arrivò alla medesima conclusione che si trattasse dell'ossido di un metallo nuovo, e lo chiamò titanio dai Titani della mitologia, anche perché riteneva che il metallo fondesse a temperatura molto più elevata degli altri.

Ritornando al Reverendo Gregor, siamo onorati di conferirgli una targa commemorativa in titanio, che verrà ritirata dal massimo esperto inglese, come Gregor, di titanio: il Dr. Tom Farthing, perché a nome nostro la porti alla Parrocchia di Menaccan per l'affissione all'interno della chiesa, in ricordo della data di nascita del titanio ed in omaggio al suo scopritore.

ACKNOWLEDGEMENT

Tom Farthing - Consultant

It is a great privilege and an honour to accept this assignment from Marco Ginatta. I will be delighted to take this beautiful inscribed Titanium memorial plaque to the church at Manaccan, in Cornwall, England, and present it to the Church on behalf of the Ginatta family. It is a very timely gesture, and one that will be much appreciated not just by the inhabitants of Manaccan, but also by all those associated with the Titanium Industry.

It seems to me to be very appropriate, in view of both of their contributions to the Titanium Industry, that this plaque should honour not only the memory of William Gregor and the 200th anniversary of the discovery of Titanium, but also the great contribution of Marco and Ugo Ginatta to Titanium. This is the VIth GTT Meeting and from the number of people attending, and the extremely interesting and wide range of papers, I am sure that the meeting will be even more successful that those in the past. The Ginatta family deserves all our congratulations far all that they have done for the Industry.

As many of you will know, Titanium was first discovered as a new element some 200 years ago, in 1791, by a clergyman named William Gregor who was born in Cornwall, the most westerly county in England. He was in fact born on Christmas Day, which obviously augured well for the future success of Titanium. In my brief research on the matter, I found that Mr. Gregor went to Cambridge University, which is where I subsequently attended. His College was St. Johns and mine Jesus. In view of bis birthday, it might perhaps have been more appropriate if he had gone to my college instead.

The name Titanium was in fact given to this unknown element by the famous chemist Klaproth, a few years after its discovery by William Gregor, in recognition of its great strength and stability. William Gregor wanted to name it Manaccanite or even Georgium, after the then King of England. Klaproth clearly had the most accurate appreciation of the true character and properties of the new element and Titanium became the accepted name.

However not even Klaproth could have realized how appropriate and indicative his choice of name would be in describing the properties of the metal and its alloys. The GTT Conference has an honoured and recognized place in the International work which is carried out to widen our knowledge of the properties and applications of Titanium. I wish this VI'th Conference all success. Thank you very much.

EFFECTIVE DESIGN USING TITANIUM

by David K. Peacock, CEng., M.I.Corr., F.I.M.*

Summary

The effective and successful use of titanium requires the recognition, understanding and correct application of the unique combination of useful physical, mechanical and corrosion resistant properties which titanium possesses. These properties are considered in turn, and guidance is given to design for end use and fabrication, using available products and cost effective methods.

Introduction

This paper identifies and details the principal factors to be considered in successful and effective design using titanium. These are, mechanical and thermal performance, corrosion resistance, practical aspects of fabrication and installation, product availability and price.

Titanium is light and strong and has a family of alloys offering forms and properties appropriate to a wide variety of applications and working environments. Choice of the correct alloy, product form and manufacturing route provide the means of achieving the lowest cost design. Successful use of the metal in heat exchangers and condensers has confirmed the parameters for effective heat transfer.

Titanium and its alloys are resistant to corrosion in a wide range of aggressive conditions. Outstanding resistance to seawater, brines, brackish waters and chlorides is of particular importance. Product availability is good in all of the industrially familiar semi-finished products and components. Fabrication techniques for machining, forming , welding and other processes are well understood, and whilst different in some respects to those used for other metals, are not to any significant extent more costly, nor more difficult to apply successfully.

The final section of this paper gives some background information on availability and price, and the correct approach to costing titanium in its role as an industrial metal of ever increasing importance.

---

* David Peacock is Director European Manufacturing and Technology, Titanium Metals Corporation, London.

The Mechanical Properties of Titanium and its Alloys

The range of grades and alloys of titanium available to the designer makes possible the selection of a combination of properties appropriate both to fabrication and end use. A convenient and widely used system for identification of the various grades of commercially pure titanium and titanium alloys used for engineering and corrosion resisting applications is provided by ASTM:-

Grades 1,2,3,4 are commercially pure titanium, used primarily for corrosion resistance. Strength and hardness increase, and ductility reduces with grade number. Grade 2 is the most widely used specification in all product forms. Grade 1 is specified when superior formability is required. Grades 3 and 4 are used where higher levels of strength are necessary.

Grades 7, 11 and 12 are alloys possessing superior corrosion resistance in particular to reducing acid chlorides. The mechanical properties of grades 7 and 11 are identical to those of Grades 2 and 1 respectively. Grade 12 is stronger and retains useful levels of strength up to 300°C.

Grades 5 and 9 are alloys with good corrosion resistance and medium levels of strength. They are frequently limited in use to specific products.

Beta-C is included as an important high strength corrosion resistant alloy for sea water application, which has not yet received an ASTM grading.

The range of ASTM specifications cover all the forms supplied in titanium and its alloys:-

ASTM B 265 - Strip Sheet and Plate

ASTM B 337 - Seamless and Welded Pipe

ASTM B 338 - Seamless and Welded Tube

ASTM B 348 - Bars and Billets

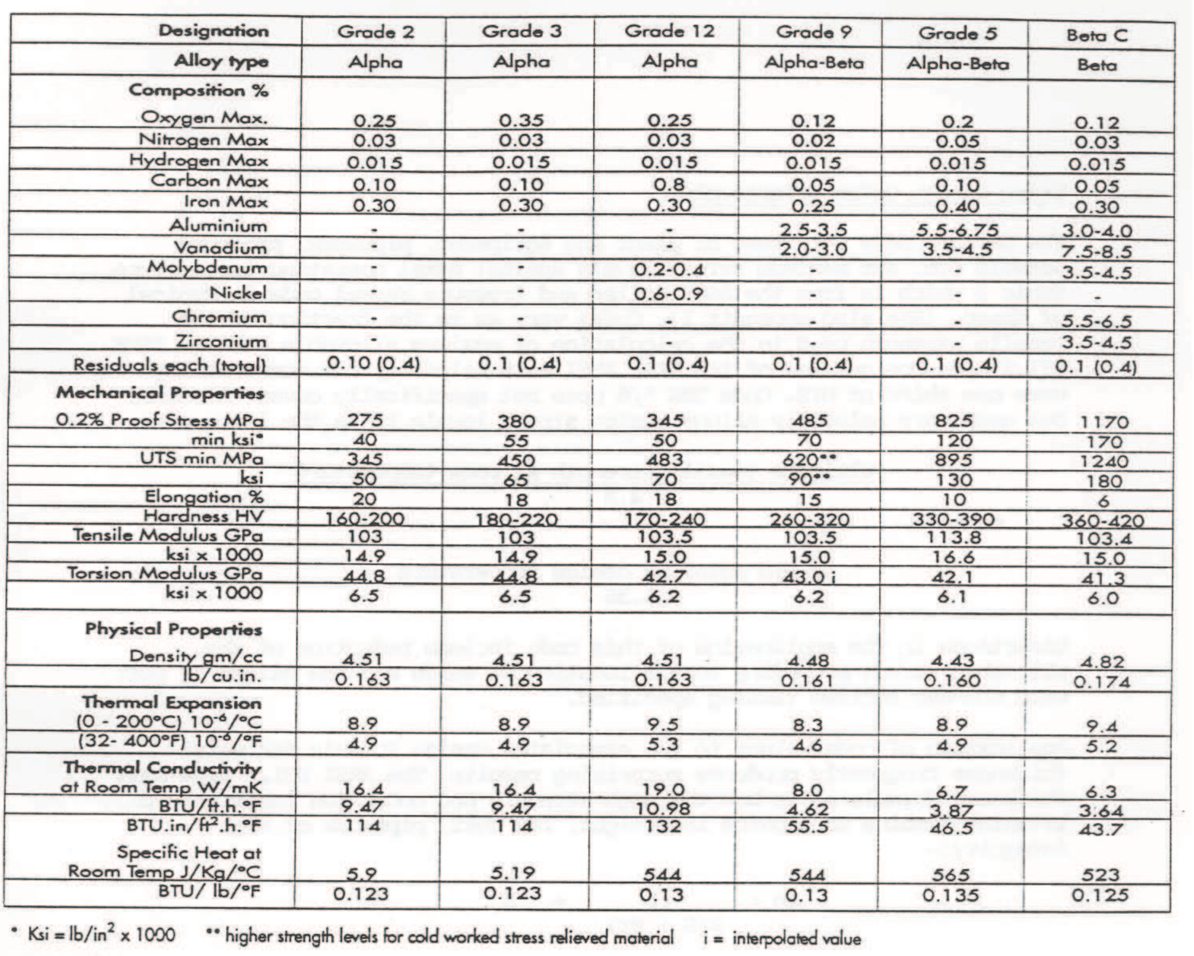
ASTM B 363 - Seamless and Welded Fittings

ASTM B 367 – Castings

ASTM B 381 - Forgings

Welding consumables are covered by AWS Specification A5.16.
A summary of key properties appears in Table 1, over. (1)

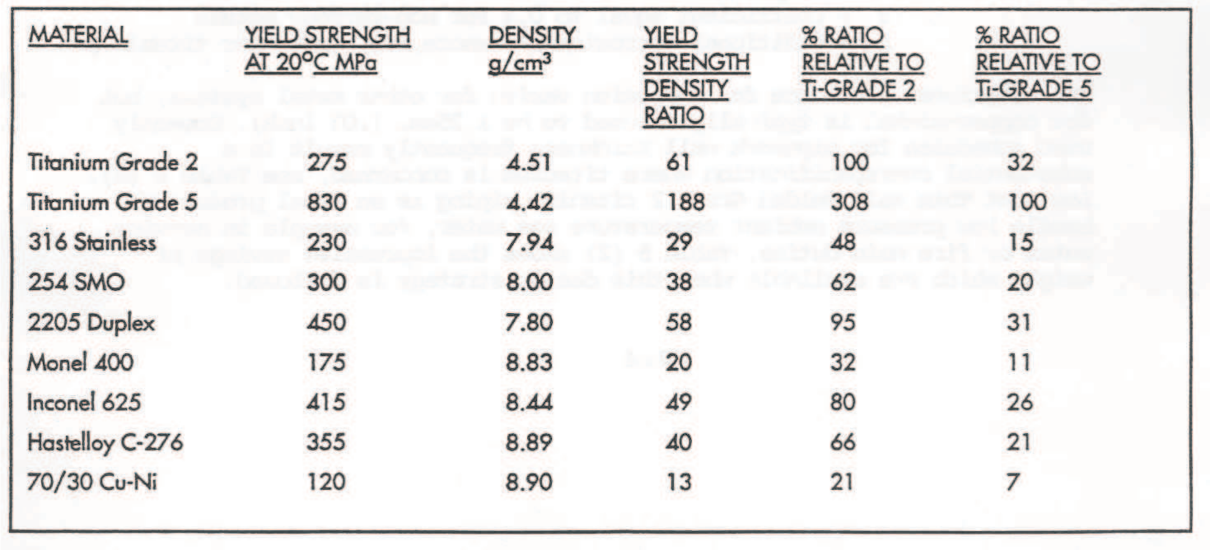
The comparative strength to weight ratios with other corrosion resistant alloys are given in Table 2.(1)



Designation	Grade 2	Grade 3	Grade 12	Grade 9	Grade 5	Beta C
Alloy type	Alpha	Alpha	Alpha	Alpha-Beta	Alpha-Beta	Beta
Composition %						
Oxygen Max.	0.25	0.35	0.25	0.12	0.2	0.12
Nitrogen Max	0.03	0.03	0.03	0.02	0.05	0.03
Hydrogen Max	0.015	0.015	0.015	0.015	0.015	0.015
Carbon Max	0.10	0.10	0.8	0.05	0.10	0.05
Iron Max	0.30	0.30	0.30	0.25	0.40	0.30
Aluminium	-	-	-	2.5-3.5	5.5-6.75	3.0-4.0
Vanadium	-	-	-	2.0-3.0	3.5-4.5	7.5-8.5
Molybdenum	-	-	0.2-0.4	-	-	3.5-4.5
Nickel	-	-	0.6-0.9	-	-	-
Chromium	-	-	-	-	-	5.5-6.5
Zirconium	-	-	-	-	-	3.5-4.5
Residuals each (total)	0.10 (0.4)	0.1 (0.4)	0.1 (0.4)	0.1 (0.4)	0.1 (0.4)	0.1 (0.4)
Mechanical Properties						
0.2% Proof Stress MPa	275	380	345	485	825	1170
min ksi*	40	55	50	70	120	170
UTS min MPa	345	450	483	620**	895	1240
ksi	50	65	70	90**	130	180
Elongation %	20	18	18	15	10	6
Hardness HV	160-200	180-220	170-240	260-320	330-390	360-420
Tensile Modulus GPa	103	103	103.5	103.5	113.8	103.4
ksi x 1000	14.9	14.9	15.0	15.0	16.6	15.0
Torsion Modulus GPa	44.8	44.8	42.7	43.0 i	42.1	41.3
ksi x 1000	6.5	6.5	6.2	6.2	6.1	6.0
Physical Properties						
Density gm/cc	4.51	4.51	4.51	4.48	4.43	4.82
lb/cu.in.	0.163	0.163	0.163	0.161	0.160	0.174
Thermal Expansion (0 - 200°C) 10^{-6}/°C	8.9	8.9	9.5	8.3	8.9	9.4
(32- 400°F) 10^{-6}/°F	4.9	4.9	5.3	4.6	4.9	5.2
Thermal Conductivity at Room Temp W/mK	16.4	16.4	19.0	8.0	6.7	6.3
BTU/ft.h.°F	9.47	9.47	10.98	4.62	3.87	3.64
BTU.in/ft^2.h.°F	114	114	132	55.5	46.5	43.7
Specific Heat at Room Temp J/Kg/°C	5.9	5.19	544	544	565	523
BTU/ lb/°F	0.123	0.123	0.13	0.13	0.135	0.125

* Ksi = lb/in^2 x 1000   ** higher strength levels for cold worked stress relieved material   i = interpolated value

TABLE 1



MATERIAL	YIELD STRENGTH AT 20°C MPa	DENSITY g/cm^3	YIELD STRENGTH DENSITY RATIO	% RATIO RELATIVE TO Ti-GRADE 2	% RATIO RELATIVE TO Ti-GRADE 5
Titanium Grade 2	275	4.51	61	100	32
Titanium Grade 5	830	4.42	188	308	100
316 Stainless	230	7.94	29	48	15
254 SMO	300	8.00	38	62	20
2205 Duplex	450	7.80	58	95	31
Monel 400	175	8.83	20	32	11
Inconel 625	415	8.44	49	80	26
Hastelloy C-276	355	8.89	40	66	21
70/30 Cu-Ni	120	8.90	13	21	7

TABLE 2

Using Design Codes Effectively

The design codes for items of plant and equipment, pipework, pressure vessels etc. set maximum stress levels against metal operating temperature, Table 3 which is from the ASME Boiler and Pressure Vessel code is typical of these, (See also appendix 1). Codes vary as to the fraction of the tensile strength used in the calculation of maximum allowable stress. ASME B31.1 uses one quarter of the UTS, ANSI more helpfully and economically uses one third af UTS. Code TBK 5/6 does not specifically cover titanium, but even more helpfully allows design stress levels to be the lower of:-

$$\frac{\text{Ultimate tensile strength at room temperature}}{2.4}$$

or:-

$$\frac{\text{Yield point at design temperature}}{1.35}$$

Directions in the application of this code include reduction of the allowable stress according to the location of welds and the extent of post weld non-destructive testing specified.

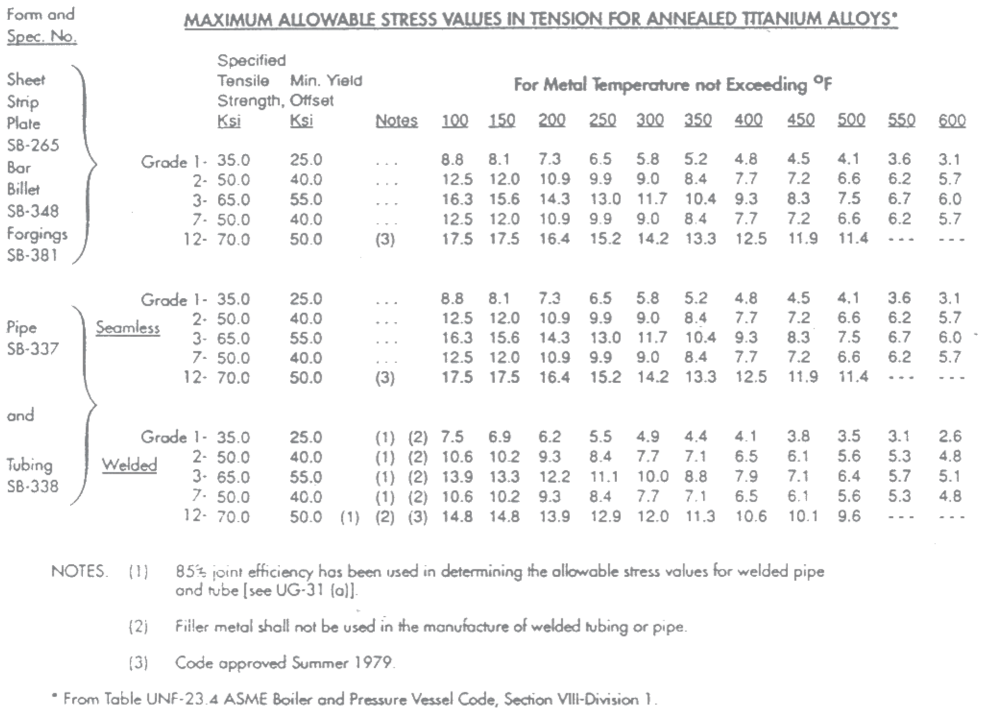
Application of code values to the associated design formula for metal thickness frequently produces surprising results. The ANSI B31.1 pipe wall thickness formula shows how the high strength and corrosion resistance of titanium combine to provide low weight, low cost, pipework of high integrity:-

$$Tm=\frac{PD}{2(S+PY)}+A$$

Tm = Minimum required wall thickness, mm
P = System Pressure, MPa
D = Pipe outside diameter, mm
S = Maximum allowable stress for material at design temperature, MPa
Y = Coefficient equal to 0.4 for non-ferrous metals
A = Additional corrosion allowance, mm (zero for titanium)

The additional allowance for corrosion varies for other metal systems, but for copper-nickel is typically assumed to be 1.25mm, (.05 inch). Commonly used schedules for pipework wall thickness frequently result in a substantial overspecification where titanium is concerned, see Table 4 (2). Low cost thin wall welded Grade 2 titanium piping is an ideal product to handle low pressure ambient temperature sea water, for example in service water or fire main duties. Table 5 (2) shows the impressive savings of weight which are available when this design strategy is followed.

Table 3:-



MAXIMUM ALLOWABLE STRESS VALUES IN TENSION FOR ANNEALED TITANIUM ALLOYS*

Form and Spec. No.		Grade	Specified Tensile Strength, Ksi	Min. Yield Offset Ksi	Notes	100	150	200	250	300	350	400	450	500	550	600
Sheet Strip Plate SB-265 Bar Billet SB-348 Forgings SB-381		Grade 1-	35.0	25.0	. . .	8.8	8.1	7.3	6.5	5.8	5.2	4.8	4.5	4.1	3.6	3.1
		2-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		3-	65.0	55.0	. . .	16.3	15.6	14.3	13.0	11.7	10.4	9.3	8.3	7.5	6.7	6.0
		7-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		12-	70.0	50.0	(3)	17.5	17.5	16.4	15.2	14.2	13.3	12.5	11.9	11.4	---	---
Pipe SB-337 and Tubing SB-338	Seamless	Grade 1-	35.0	25.0	. . .	8.8	8.1	7.3	6.5	5.8	5.2	4.8	4.5	4.1	3.6	3.1
		2-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		3-	65.0	55.0	. . .	16.3	15.6	14.3	13.0	11.7	10.4	9.3	8.3	7.5	6.7	6.0
		7-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		12-	70.0	50.0	(3)	17.5	17.5	16.4	15.2	14.2	13.3	12.5	11.9	11.4	---	---
	Welded	Grade 1-	35.0	25.0	(1) (2)	7.5	6.9	6.2	5.5	4.9	4.4	4.1	3.8	3.5	3.1	2.6
		2-	50.0	40.0	(1) (2)	10.6	10.2	9.3	8.4	7.7	7.1	6.5	6.1	5.6	5.3	4.8
		3-	65.0	55.0	(1) (2)	13.9	13.3	12.2	11.1	10.0	8.8	7.9	7.1	6.4	5.7	5.1
		7-	50.0	40.0	(1) (2)	10.6	10.2	9.3	8.4	7.7	7.1	6.5	6.1	5.6	5.3	4.8
		12-	70.0	50.0	(1) (2) (3)	14.8	14.8	13.9	12.9	12.0	11.3	10.6	10.1	9.6	---	---

For Metal Temperature not Exceeding °F

NOTES. (1) 85% joint efficiency has been used in determining the allowable stress values for welded pipe and tube [see UG-31 (a)].

(2) Filler metal shall not be used in the manufacture of welded tubing or pipe.

(3) Code approved Summer 1979.

* From Table UNF-23.4 ASME Boiler and Pressure Vessel Code, Section VIII-Division 1.

Table 4:- Pipe Wall Thicknesses for Grade 2 Titanium

	Pipe wall thickness mm				
Pipe N.B.ins	Class 200 90/10 Cu-Ni	Gr 2 Ti Calculated*	Gr 2 Ti Sched 5s	Gr 2 Ti Sched 10s	Gr 2 Ti Sub Sched 5
2	2.1	.5	1.6	2.8	1.2
3	2.4	.7	2.1	3.1	1.6
6	3.4	1.3	2.8	3.4	2.0
12	6.4	2.6	4.0	4.6	3.0

* Calculated per ASME Code for service at 200 p.s.i. at 38°C
Schedule 5 and 10 wall thicknesses per ASME B337
Sub Schedule 5 suggested for seawater service at 200 p.s.i at 38°C max.

Table 5:- Weight Savings Achieved When Thin-Wall Titanium Piping Replaces Class 200 90/10 Copper Nickel Piping

Pipe N.B. ins	Weight of Class 200 Pipe kg/m	% Weight Savings Sched 5 Ti	Sub Sched 5 Ti
2	345	60	70
3	586	56	72
6	1577	59	71
12	5825	69	78

Physical Properties of Titanium and its Alloys

The physical properties of primary importance in mechanical design are the metal density, 4.51 gm/cc, (.163 lb/cu.in.) which is almost half that of other corrosion resistant alloys, and the modulus of elasticity.

In applications which are weight critical, the weight savings achievable with a properly designed titanium system will be appreciable. Where titanium is used to replace a heavier metal, e.g. retubing of heat exchangers and condensers, it may be necessary to modify the arrangements by which the unit is supported or suspended. (3)

Attention to the modulus is essential for the correct design and application of struts and supports, e.g. heat exchanger baffle spacing, (4) and unsupported pipe spans. The relatively low modulus is however a factor in the substantial resistance to shock which titanium and its alloys possess. Shock resistance is calculated from the maximum allowable stress divided by the square root of the product of the density and the elastic modulus. These two properties are both low for titanium and its alloys, and strengths are relatively high. The shock resistance of titanium is greater than that of most competing copper and nickel based corrosion resistant alloys. (2)

Fatigue, Fracture Toughness and Creep

Fatigue strength of smooth test specimens of titanium and its alloys is typically 50% - 60% of the tensile strength values. Notched specimen tests give lower values. Care is required in design and manufacture to avoid stress concentrating factors where cyclic stress is applied to high levels, or with great frequency. Poor surface finish, sharp sectional transitions, unblended radii and corners are typical conditions to avoid.

Commercially pure titanium and titanium alloys possess a low ductile to brittle transition temperature and have useful levels of impact and fracture toughness even at sub zero temperatures. The ASME Boiler and Pressure Vessel Code allows the rom temperature stress levels of Grades 1, 2, 3, 7 and 11 to be used in design for operational service down to -60°C, (-75°F).

Metallurgical and surface stability of titanium and its alloys is excellent within the working temperature range set by the value of useful strength. Creep values for commercially pure titanium to .1% plastic strain in 100,000 hours are approximately 50% those of the tensile strength at appropriate temperatures up to 300°C. Creep values for welds in commercially pure titanium lie in the same range as for base metal.

Thermal Performance of Titanium and Titanium Alloys

The thermal conductivity of titanium is low, and of the same order as that of stainless steel. Titanium heat exchangers can however be safely designed with low cost thin wall welded tubing, to the point where the tube resistance r^m is less than 2.5% of the total resistance, (Fig.1). The corrosion and general fouling resistance of titanium, and its ability to withstand higher fluid velocities permits design for equal and frequently superior overall heat transfer rates than can be achieved with full metals of higher thermal conductivity. The published (HEI) metal correction factors for titanium reflect lower values than achieved in many applications and may act as an artificial restraint to fully cost effective design, (Table 6), (4). Test results from titanium tubes installed in England showed titanium tubes to be operating at a heat transfer rate 9% higher than the clean calculated HEI rate. After 14 months service without cleaning the tubes were still performing with a cleanliness factor of 0.96. These levels of performance have also been confirmed by the Swedish State Power Board.

Figure 1: Total Resistance of Heat Exchanger Tubes

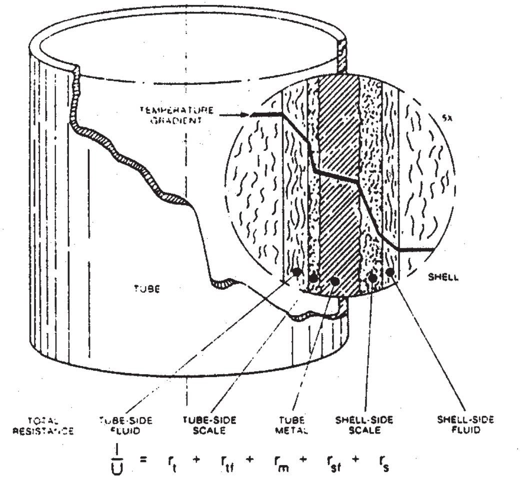


Table 6: Comparison of Heat Transfer Rates – HEI vs Resistance

Material	BWG	HEI Clean* BTU/hr ft² °F	Resistance Method BTU/hr ft² °F	Cleanliness Factor	DesignRate BTU/hr ft² °F
Al. Brass	18	675		.85	574
90/10 CuNi	18	626		.85	532
90/10 CuNi	19	640		.85	544
Titanium Ti-50A	22	564	617	.90	555
Titanium Ti-50A	25	598	646	.90	581

*Includes metal correction factor
The above method indicates improved performances over HEI design with thin wall titanium tubes.

Designing a Corrosion Resistant System

A stable, substantially inert, tenacious and permanent oxide film provides titanium with outstanding resistance to corrosion in a wide range cf aggressive media (5). The oxide film forms equally on welds as on parent metal, and on the industrial alloys as on commercially pure titanium. In situations where the oxide film is maintained or its formation supported - essentially in neutral to oxidising conditions over a wide range of pH and temperature, (Fig 2).- titanium will survive erosion, cavitation, pittings and crevice corrosion. Enhanced resistance is obtained from alloys containing nickel and molybdenum, - ASTM Grade 12, (Fig 3); or palladium, - ASTM Grades 7, 11 (Fig. 4) (6).

Long established application of titanium for vessels, pipework, heat exchangers and other process equipment in chemical, petrochemical and other plant has confirmed the following:-

1. Titanium requires no corrosion allowance.

The breakdown potential of titanium is very high in most environments, and pitting, which occurs when the potential of the metal exceeds the breakdown potential of its protective oxide film, is rarely encountered. The breakdown potential of titanium in phosphate and sulphate media is about 100 volts, in chlorides it is about 8 - 10 volts. Oxidising species, e.g. ferric ions, in the environment will enhance passivation. No corrosion allowance is required for titanium, and equipment should be designed to the minimum thickness of material to satisfy mechanical requirements.

2. Titanium resists erosion and cavitation

Seawater flowing at velocities up to 30 m/sec can be safely handled by titanium, (Fig 5). This permits safe increase of system flow rates, permitting design with smaller diameter pipework, and tighter pipework bend radii. The presence of sand or other abrasive particles has a small but significantly less effect on the erosion of titanium than on other metals, (Table 7). Titanium alloy castings used in hydrojet vehicles travelling at speeds around 50 mph, (80 km/hr) continue to demonstrate the outstanding resistance of the metal to erosion and cavitation damage.

3. Titanium is essentially immune to stress corrosion cracking

Commercially pure titanium grades 1 and 2 are essentially immune to stress corrosion cracking, (SCC), in sea water and chlorides. The few and specialised environments and media which may cause SCC in titanium, or in single titanium alloys have been well documented. Of these the one which gives rise to the most frequent concern is methanol. SCC failures of titanium have occurred in dry methanol, and in methanol/halide and methanol/acid mixtures. The presence of water above 1.5% maintains the passivity of commercially pure titanium. Titanium alloys vary in their susceptibility to SCC. Notched precracked specimens have had to be used in the laboratory to identify environments and rank alloys for susceptibility, with actual field failures being few or none. Ti-6Al-4V ELI, a low oxygen variant of the workhorse of titanium alloy range is ranked close in its performance to commercially pure titanium (5).

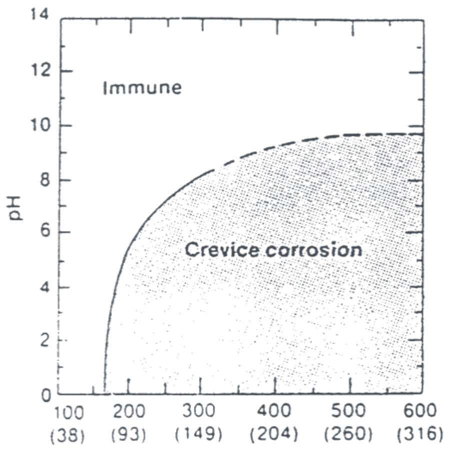


Figure 2 – Effect of Temperature and pH on Crevice Corrosion of Unalloyed Titanium (Ti-50A) in Saturated NaCl Brine

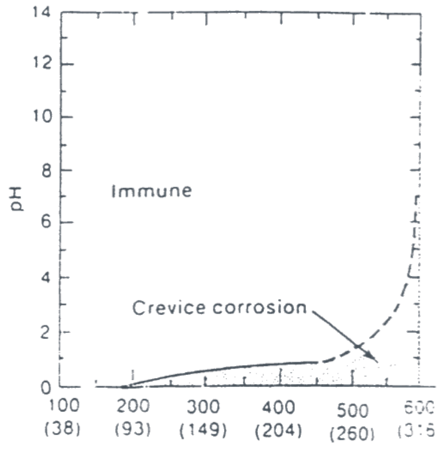


Figure 4 – Effect of Temperature and pH on Crevice Corrosion of Ti-Pd in Saturated NaCl Brine

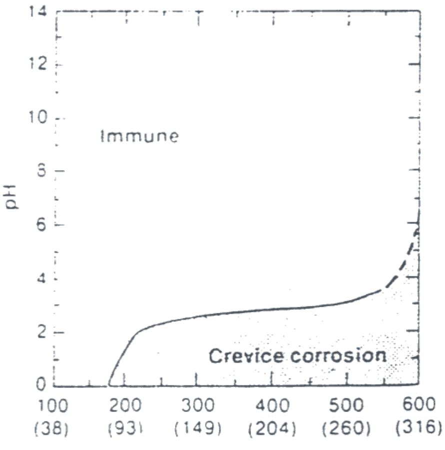


Figure 3 – Effect of Temperature and pH on Crevice Corrosion of TiCode-12 in Saturated NaCl Brine

Table 7:

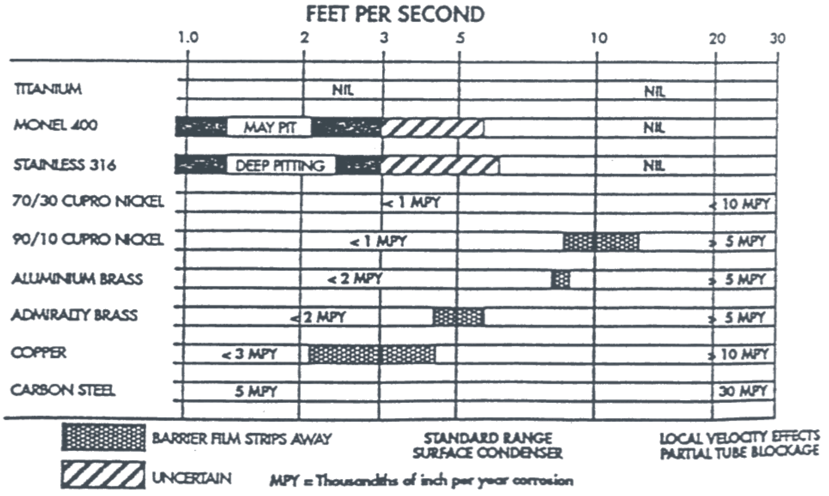
Erosion of Unalloyed Titanium in Seawater Containing Suspended Solids

Flow Rate ft/sec (m/sec)	Suspended Matter	Duration Hrs.	Corrosion / Erosion - mpy Gr. 2 Ti	70/30 Cu-Ni*	Al. Brass
23.6 (7.2)	None	10,000	Nil	Pitted	Pitted
6.6 (2)	40 g/l 60 Mesh Sand	2,000	0.1	3.9	2.0
6.6 (2)	40 g/l 10 Mesh Emery	2,000	0.5	Severe Erosion	Severe Erosion

* High iron, high manganese 70-30 cupro nickel.

Figure 5:

EFFECTS OF SEAWATER VELOCITY ON MATERIALS



4.Titanium is essentially resistant to corrosion fatigue
Commercially pure titanium suffers no significant loss af fatigue strength in sea water and other aqueous chloride media. (Table 8). Welds and parent metal, which are equally protected by the oxide film, typically exhibit smooth fatigue run out stress to tensile strength ratios of 50 - 60%.

5. Titanium will stay cleaner longer in fouling environments
Fouling factors between .90 and .99 are regularly used for titanium in heat exchangers. Marine biofouling will occur on titanium in static or slow moving sea water, but the integrity of the oxide film is maintained under the deposits which can be removed safely by mechanical methods or by regular or shock chlorination, or prevented by maintaining water velocity above 2 m/sec. It is popular belief that copper based alloys sucessfully resist biofouling. Fig. 6 shows that after a period of exposure, the fouling of cupronickel tubes used without chlorination approaches that of untreated titanium tubes.

In many other fouling situations, the oxide film will resist deposit adhesion, and facilitate cleaning. Recommended inhibited cleaning solutions should be specified for use when hard scale removal is necessary. In situations where there is persistent heavy system fouling intervals betwen cleaning may be extended by using low fin tube.

6. Titanium systems are self supporting
Titanium requires no inlet or outlet or bend erosion protection, and there is normally no requirement for system protection for corrosion by dosing, coatings, sacrificial anodes or impressed current cathodic protection, unless there is the possibility of galvanic corrosion of adjacent structures.

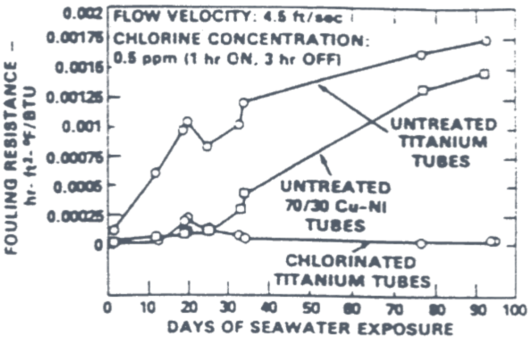
Table 8 Effect of Seawater on Fatigue Properties of Titanium

	Stress to cause Failure In 10^7 Cycles, *Ksi (MPa)	
Alloy	Air	Seawater
Ti-Gr.2	52 (359)	54 (372)
Ti-Gr.5	70 (480)	60 (410)

* Rotating beam fatigue tests on smooth, round bar specimens.

3.10

Fig. 6 Detrimental effect of seawater fouling with time on the heat transfer of titanium and cupro-nickel



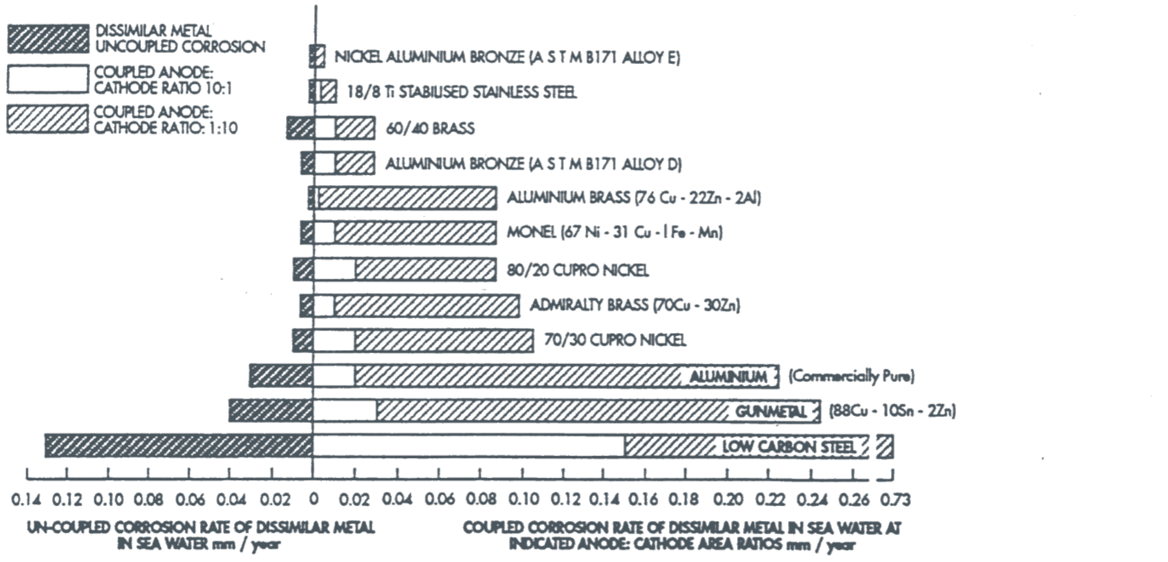
Practical Hazards of Working Systems

1. Galvanic Corrosion

It is rarely practicable to fabricate process systems entirely from one metal. Where titanium is incorporated into mixed metal plant or equipment, it will usually be the cathode if a galvanic couple exists, or is created. Alloys which are galvanically near compatible with titanium e.g. Inconel 625, Hastelloy C, 254SMO, Zeron 100, or composite materials may be selected to be in direct contact with titanium at joints. In their passive state several of the highly alloyed steels and nickel alloys are only marginally less noble than titanium, but if activated, for example by pitting, the rate of localised attack can be dramatic. Among commonly used structural corrosion resistant metals and alloys titanium will almost always be the cathode, (Fig 7).

Figure 7:-

A GUIDE ON GALVANIC CORROSION OF TITANIUM - DISSIMILAR METAL COUPLES IN STATIC SEA WATER AT ROOM TEMPERATUR



NOTES (1) RATES ARE HIGHER IN FLOWING SEA WATER AND ABOVE ROOM TEMPERATURE.
(2) CORROSION RATE DERIVED FROM WEIGHT LOSS MEASUREMENTS.
(3) 60/40 BRASS SUFFERS DEZINCIFICATION.
(4) ALUMINIUM BRONZE AND NICKEL ALUMINIUM BRONZE RATES MAY BE INCREASED IN CERTAIN METALLURGICAL CONDITIONS AND IN PRESENCE OF CREVICES OR SCALE/SILT DEPOSITS.

Design strategies to protect adjoining less noble parts of the system include, coating the titanium in the neighbourhood of the joint to reduce the effective cathode/anode ratio; application of cathodic protection to the base metal, but at no more than -1.0v SCE; electrical isolation of the titanium through the use of non conducting gaskets and sleeved bolts; installation of short easily replaced heavy wall sections of the less noble metal; chemical dosing. Conditions for rapid attack and failure of a less corrosion resistant material coupled to titanium may exist if only that metal is coated. Any coatings defects, damage or breakdown in localised areas will immediately cause problems unless cathodic or chemical protection is available or unless the adjoining titanium structure is also coated.

2. Hydrogen Absorption, (Hydriding)

Titanium oxide is an effective barrier to penetration of the metal by hydrogen. Titanium can absorb hydrogen from environments containing the gas. In practice hydrogen take-up is minimal or zero where more than 2% water vapour is present. Diffusion of hydrogen into titanium is very slow at temperatures below 80°C except where high residual or applied tensile stresses exist.

The most common cause of hydrogen absorption in reported cases comes from the generation of nascent hydrogen directly ont the surface of titanium by impressed current cathodic protection, (overzealously applied or uncontrolled), or galvanic corrosion of adjacent structures. Such absorption, occurring in the range of pH less than 3 and greater than 12 and with potentials more negative than -0.7 volts s.c.e. nay be aggravated by mechanical disruption of the oxide film or by the presence of smeared iron on the surface of titanium.

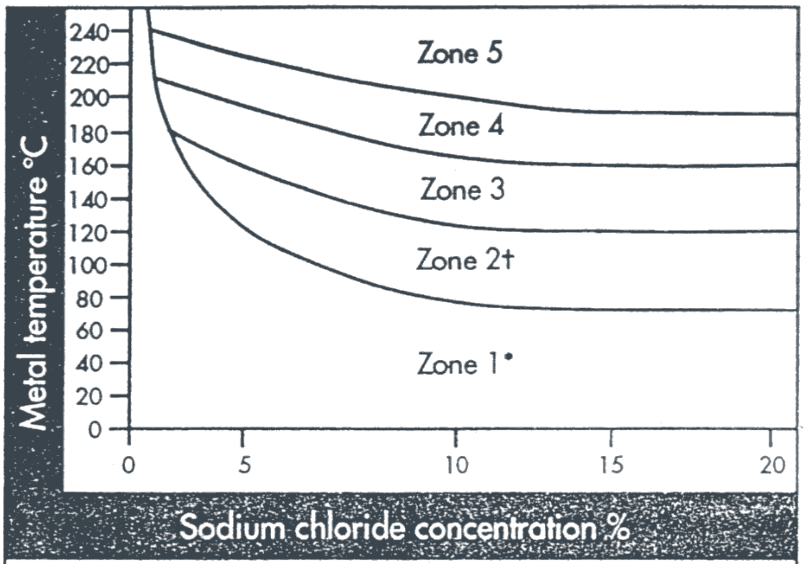
Where hydrogen absorption may occur, specification of a suitable oxidised finish is recommended. Films formed by thermal oxidation are the most resistant, oxide films produced by anodising are less effective in this respect, but the anodising process does have the benefit of removely selectively any impacted iron which might act as a point for hydrogen ingress (7). Disruption or dissolution of the oxide film allows hydrogen to diffuse into the base metal. Once the solubility limit of hydrogen in titanium is exceeded, (100 – 150 ppm for commercially pure titanium grade 2), titanium hydride will begin to precipitate. At temperatures not exceeding 80°C, (176°F), hydride will normally be restricted to the surface layers of the metal and experience in such cases indicates that this has little or no serious effect on the performance or properties of the metal. Cases of through section hydride formation, leading to embrittlement and cracking or failure under stress are very rare. Hydriding can be avoided by the proper design of equipment and control of operating conditions.

3. Crevice Corrosion

Localised pitting or corrosion, occuring in tight crevices and under scale or other deposits is a controlling factor in the application of unalloyed titanium. Attack will normally not occur on commercially pure titanium or industrial alloys below 70°C regardless of solution pH. Seawater and neutral brines above the boiling point will develop localised reducing acidic conditions, and pitting may occur. Enhanced resistance to reducing acid chlorides and crevice corrosion is available from alloy Grades 7, 11 and 12. (Fig 8). Most recent experience in testing alloys for FGD prescrubber application suggest that Fig 8 is perhaps too conservative in respect of the performance of Grade 7 in which it has been impossible to induce crevice corrosion even at very high chloride concentrations and low pH. Attention to design of flanged joints using heavy flanges and high clamping pressure, and the specification of gaskets, choosing elastic rather than plastic or hard materials may serve to prevent crevices developing. An alternative strategy is to incorporate a source of nickel, copper, molybdenum, or palladium into the gasket, as wire, foil, or as oxides impregnated into the gasket material.

Figure 8:

Immunity limits for crevice and pitting attack of titanium in sea-water and sodium chloride brines



	Commercially pure titanium	Grade 7 (Ti-0.2%Pd)
Zone 1*	Complete immunity	Complete immunity
Zone 2†	Crevice corrosion possible at titanium/titanium crevices.	Complete immunity
Zone 3	Crevice and pitting attack possible at acid pH levels	Crevice corrosion possible with titanium/tianium crevices at acid pH levels
Zone 4	Crevice and pitting attack probable	Crevice corrosion probable. Pitting attack possible at acid pH levels
Zone 5	Crevice and pitting attack probable	Crevice and pitting attack probable

* Power station condensers; refinery, offshore oil, and other sea water coolers; brine coolers; desalination heat rejection and recovery stages.

† Salt evaporation plant and deslination brine heater/recovery stages.

Design for Fabrication and Installation

In broad terms, anything that can be made in metal can be made in titanium. In practical terms, although construction in the solid metal may be possible, restraints on fabrication capacity and total cost may point to alternative solutions. Thin wall vessels and pipes will almost certainly be cost effective if made from solid titanium. Very heavy walled items will cost less if a stronger backing base metal is titanium clad. Heavy flange will prove to be expensive unless steel is used as a backer to a titanium taft or stub eend, (Fig 9). Long shafts may require extra bearing points if made from solid titanium, cladding of a stiffer base metal may provide a more effective answer, mechanically as well as economically. In each case consideration of all of the options should provide the optimum solution to combine requirements for mechanical performance, corrosion resistance and fabrication.

Design for Welding

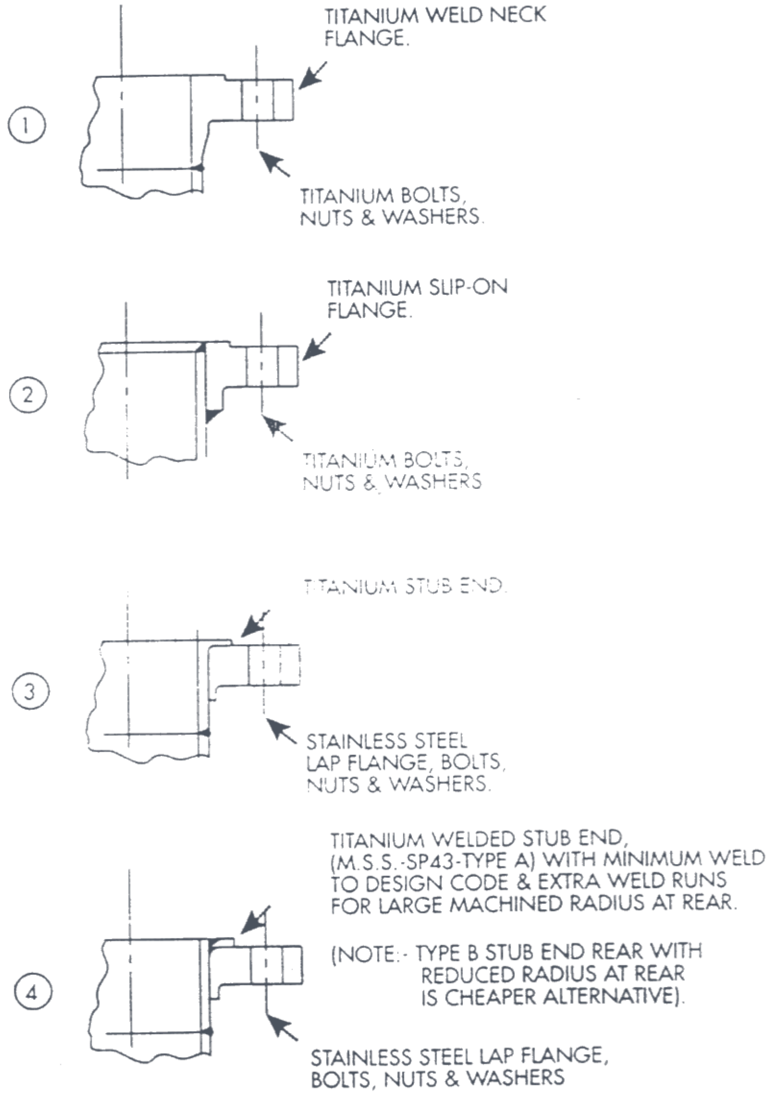
Weld joint designs for titanium are similar to those for other metals, and many excellent welding guides are now available to assist designers. Consultation with experienced fabricators is always worthwhile.

When titanium was first welded, very elaborate precautions were applied in order to minimise both distortion and weld oxidation. Practical experience and necessity has enabled these first and extreme precautions progressively to be relaxed, and open shop and field welding of large and small fabrications have been routine for many years. The provision of fully effective shielding may however be seen to be difficult if not impossible for field welds made in exposed locations such as on offshore platforms. A detailed evaluation of the effect of oxygen pick up which might occur in such circumstances has shown commercially pure titanium to be tolerant of up to 0.6% air contamination of the shielding gas, the properties of such welds and parent metal in the heat affected zone remaining within the allowable specification range.(8)

Whilst a good standard of primary and secondary inert gas shielding is normal practice, there may be fabrication design requirements where back shielding of welds is impossible. The fillet welding in situ of fitted linings is an example. The application of titanium liners in flue gas desulphurisation plant using Titaniun Resista-Clad Plate has generated considerable experience of satisfactory post weld performance where back shielding was impracticable. The development of this procedure was supported up by an evaluation programme in which horizontal vertical and overhead welds were made on 1.6mm thick overlapping sheets, without inert gas back shielding. The results indicated that although some measurable oxygen pickup occured in the absence of backshielding, that accetable engineering welds were produced, with strengths more than adequate for the FGD liner service application, (Table 8). Comparable considerations would apply to the lining or external cladding of large diameter steel pipes for offshore service.

Figure 9:

FLANGE ARRANGEMENTS IN DESCENDING ORDER OF COST.



⑤ AS ③ BUT WITH MILD STEEL EPOXY COATED FLANGE, BOLTS, NUTS & WASHERS.

⑥ AS ④ BUT WITH MILD STEEL EPOXY COATED FLANGE, BOLTS, NUTS & WASHERS.

Table 8:

EVALUATION OF TITANIUM FILLET WELDS MADE WITHOUT BACKSHIELDING

Material:-

Commercially pure titanium Grade 2 .063", (1.6mm) thick

Weld type:-

Fillet on overlapping sheets with weld joint gaps 0 to .063"

Weld runs:-

Horizontal, vertical, overhead

Weld wire:-

Titanium Grade 2, but Grade 1 proposed for field use

Weld gas:-

Argon, but helium proposed for overhead welding

Oxygen pick-up:-

Parent metal	.12%
ASTM Spec max for Grade 2	.25%
Av weld oxygen in worst case	.15%
Av weld oxygen in trials	.13%

Worst case = .063" gap near end of seam

Weld strength tests:-

Tensile tests were conducted on .25" wide,(6.5mm) samples

Load to break strongest weld	1234lbs	559kg
Load to break weakest weld	704lbs	319kg
Av load all tests	1002lbs	454kg
(Load to break unwelded parent	787lbs	357kg)

Stress Relieving

Vessels and other fabrications in commercially pure titanium will normally not require stress relief. Machined parts with very tight tolerances may be stress relieved immediately prior to finishing to size. Stress relieving should also be considered where fatigue may be a factor in service. Generally, low temperatures, 500°C - 525°C for one hour per 25mm of section are adequate. Higher temperatures up to 600°C are sometimes recommended, but generate a greater level of oxidation, without necessarily giving any improved result over the lower temperature treatment.

The Cost Element of Design

The first cost of equipment properly designed in titanium is never as high as the price, (by weight) of the metal suggests. Most designs are based on use of metal by surface area rather than by weight, and the strength, lower density and corrosion resistance of titanium are all factors which contribute positively towards cost reduction. In the following examples titanium is compared with nominally lower cost, "heavy-weight" competitors in sheet and pipe applications:-

Sheet cost by weight

....Titanium £15 per kilo	Competitor £10 per kilo

Cost per standard sheet 2 1/2 m x 1m x 1.5m

....Titanium £255	Competitor £340

The corrosion resistance of titanium especially resistance to pitting may enable the designer to specify a thinner gauge of metal. Titanium of 1mm thickness may be adequate and at £170 per standard sheet, costs half the price of the apparently cheaper competitive material!

Pipe and tube are normally quoted and sold per metre, but there is a danger on projects where substantial tonnages of pipe are required that price by weight may be used to budget total first cost. There is a serious danger that titanium would be excluded on this basis. A most studied approach would almost certainly show not only lower first cost for titanium but also substantial life cost savings and downstream technical benefits.

Kilo for kilo a titanium pipe of the same diameter and scheduled will be almost twice as long as pipe made from any one its most dense competitors. Reduction of the schedule as shown in Table 5 can cut pipe by weight by over 70%, with a substantial reduction in the total purchase price.

First cost is however only one part of the whole cost equation. Maintenance and downtime costs, wich may be a very significant element in plant designed for a long service life, are another. Titanium inherently saves cost through reliable performance. Welded titanium tube supplied by Timet for power plant surface condenser use has for some time been sold with a 40 year performance guarantee. More recently a similar guarantee has been extended to Grade 2 and Grade 3 tubeplates for the same application. Many of the earlier installations of welded tube have now outlived their original guarantee periods several times over.

Availability of Titanium

As more titanium is used in an increasing variety of applications, questions of supply and price inevitably arise. There is however no cause for any concern. Titanium dioxide, (rutile), ore as a mineral resource is available at relatively low and stable price worldwide. Titanium is the fourth most abundant structural metal in the earths crust. The extraction of titanium is a multi-strage process, the first recognisably metallic product being "sponge". This product has no value as an engineering material, and needs to be consolidated and melted to produce ingots from material semi-finished and finished products may be manufactured.

Titanium sponge

Sponge is frequently in the news and its availability and price are sometimes but not always Correctly used as a yardstick of the capacity of the industry and for product price trends. Sponge is offered from time to time on metal markets at a price depending upon the quality of the product, th situation of the seller and the state of the market. Not all sponge is suitable for conversion to specific grades and alloys of titanium.

Titanium extraction and sponge production are specialised operations, sponge melting and the subsequent conversion of ingot to semi-finished products may be carried out wherever suitable facilities exist. Total productive capacity for titanium worldwide substantially exceeds the long term forecasts of demand. In these circumstances long term price stability may be excepted. Titanium, primarily sourced in friendly countries with democratic regimes, has never been subject to crisis or politically motivated pricing factors.

Production and Range of Semi-finished Products

Titanium ingots are the proper starting point of metal manufacture and are handled as the other industrial metals and alloys by forging or rolling to produce intermediate billet or slab. Billet provides the material for manufacture of forgings, bar, wire, and extruded ar rolled/drawn seamless tube and pipe. Slab provides the starting material for plate, sheet, welded tube and welded pipe. Castings are produced directly from ingot. Cast weldments enable large components exceeding the limits of individual casting weight, (typically 750Kg), to be supplied. A combination of forging, machining and fabrication provides the route to all requirements for engineering products.

Some Practical Guidelines to Design Cost Control

Do:-

- Check available standard products and specifications to obtain best availability and lowest cost
- Use design strategies based on using minimum material thickness
- Exploit corrosion resistant characteristics to the full
- Consider the use of liners and cladders in preference to solid design where heavy sections are unavoidable
- Use welded fabrication where practicable in preference to forging and machining
- Consult suppliers and fabricators at the earliest stage of design

Do not:-

- Simply substitute titanium into existing designs
- Budget for titanium project costs by weight, especially not by the weight of steel or copper alloys
- Specify little used alloys or forms

Conclusion

Titanium has many existing and potential applications across a wide range of industries. The metal should be considered wherever corrosion is a problem of weight a factor. Titanium offers designers a unique combination of useful mechanical, physical and corrosion resistant properties which can be exploited to improve product and process quality and service life of equipment working in the most demanding environments. Effective design can be achieved by attention to the practical differences, the most relevant of which have been discussed, and which distinguish titanium from the traditional engineering metals.

Acknowledgements

My grateful thanks to the members of TIG, the U.K. Titanium Information Group for their support and encouragement, and for the use of tables and figures from the TIG publication "Titanium Pipework Systems", which were originally supplied by the member companies of TIG. My thanks also to Jim Grauman of Timet for many helpful suggestions on the presentation of this paper.

Bibliography

1. Titanium Pipework Systems, Titanium Information Group 1989.

2. Titanium: An Improved Material for Shipboard and Offshore Platform Seawater Systems, R.W. Schutz and M.R. Scaturro, U.K.Corrosion '88

3. Development of and Experience with Titanium Tubed Condensers in the United States, J.G. Barkman and D.M. McCue, HTFS Symposium, Bath 1990.

4. Code Weld Titanium Tubing, TIMET Handbook SC 5 1988

5. Corrosion of Titanium and Titanium Alloys, R.W. Schutz and D.E. Thomas Metals Handbook 9th Edition (1987) Vol 13 pp669-706

6. Corrosion Resistance of Titanium, R.W. Schutz and L.C. Covington, TIMET Handbook M2 1986

7. Effect of Oxide Films on the Corrosion Resistance of Titanium, R.W. Schutz and L.C. Covington, Corrosion Vol 37 No 10 October 1981

8. The Effects of Air Contamination on the Mechanical and Fatigue Properties of Titanium Weldments, I. Aho-Mantila et al, Paper F04, Sixth World Conference on Titanium Cannes 1986

Recommended for further Reading

Titanium for Energy and Industrial Applications, D.Eylon Ed. Published by the Metallurgical Society of AIME 1981.

APPENDIX 1

SAFE INTERNAL WORKING PRESSURES lbs/in² FOR ANNEALED ASTM Gr. 2 AND Ti-Pd ASTM Gr. 7 WELDED TUBING AT 100°F.*

OUTSIDE DIAMETER OF TUBE

WALL (INCH)	1/2"	5/8"	3/4"	7/8"	1"	1-1/4"	1-1/2"	1-3/4"	2"	2-1/4"	2-1/2
0.020	805	650	545	470	410	330	275				
0.025	1000	805	675	585	510	410	345	295			
0.028	1110	900	755	650	570	460	385	330	290		
0.032	1260	1020	860	740	650	525	440	375	330	295	
0.035	1365	1110	935	805	710	570	480	410	360	320	290
0.042	1615	1315	1110	960	845	680	570	490	430	385	345
0.049	1855	1515	1280	1110	980	790	665	570	500	445	405
0.065			1660	1445	1275	1035	870	750	660	590	530
0.072			1825	1585	1405	1140	960	830	730	650	590
0.083					1600	1300	1100	950	835	745	675

* Calculated from $P = \frac{St}{R+0.6t}$ where S is the design stress for Gr. 2 welded tubing, R is 1/2 the tube outside diameter, and t is the tube wall thickness.

MULTIPLYING FACTORS TO DETERMINE SAFE INTERNAL WORKING PRESSURES OF ANNEALED, WELDED TITANIUM TUBING AT ELEVATED TEMPERATURES *

FOR METAL TEMPERATURES NOT EXCEEDING, DEG. F

	100	150	200	250	300	350	400	450	500	550	600
(ASTM Gr. 2) (ASTM Gr. 7)	1.000	.960	.872	.792	.726	.672	.616	.576	.528	.496	.456
(ASTM Gr. 3)	1.304	1.248	1.144	1.040	.936	.832	.744	.664	.600	.536	.480
(ASTM Gr. 12)	1.400	1.400	1.312	1.216	1.136	1.065	1.000	.952	.912		

* Select safe working pressure (SWP) for Grade 2 tubing of desired diameter and wall thickness. Then use multiplying factor from this table to determine SWP for desired alloy and temperature.

EXAMPLE: Determine SWP for Grade -12 1" x .065" welded tubing at 350°F. From Table above SWP for 1" x .065" Grade 2 welded tubing at 350°F. is 1275 PSI.
The multiplying factor for Grade -12 at 350°F. is 1.065.
The SWP for Grade -12 at 350°F. is calculated as 1.065 x 1275 = 1357 PSI

VI INTERNATIONAL MEETING ON TITANIUM

GROWTH POTENTIAL OF TITANIUM(*)

Frederich Gieg
President, Titanium Development Association (USA) President,
RMI Company (USA)

(*) Paper presented by Ugo Ginatta, CEO, GTT

CALL US LUCKY

L. FREDERICK GIEG, JR.
PRESIDENT AND CHIEF EXECUTIVE OFFICER, RMI TITANIUM COMPANY
PRESIDENT, TITANIUM DEVELOPMENT ASSOCIATION

JOINT MEETING – TDA/JTS
OCTOBER 4, 1990
10:30 A.M.

GOOD MORNING LADIES AND GENTLEMEN. WELCOME TO THE FIRST JOINT MEETING OF THE TITANIUM DEVELOPMENT ASSOCIATION AND THE JAPAN TITANIUM SOCIETY. THIS MEETING IS A LANDMARK. FOR THE FIRST TIME, THE WORLDWIDE TITANIUM INDUSTRY IS FOCUSING ITS ATTENTION COLLECTIVELY ON THE DIRECTION FOR THE FUTURE. NO SINGLE COMPANY OR NO SINGLE COUNTRY CAN MAKE THE FUTURE GROWTH POTENTIAL OF TITANIUM BE REALIZED ON ITS OWN. THIS IS A TEAM EFFORT, SO LET'S BEGIN NOW.

WE TITANIUM PRODUCERS IN THE UNITED STATES ARE VERY AWARE OF THE EVER CHANGING CYCLES OF OUR BUSINESS. WE REMEMBER THE DIFFICULT TIMES PRIOR TO LATE 70'S AND EARLY 80'S WHEN THE INDUSTRY, AS A WHOLE, WAS ONE STEP AHEAD OF FORECLOSURE. SUDDENLY IN THE EARLY 80'S WE WERE AWASH IN CASH, AND OUR PLANTS WERE RUNNING AT PEAK LEVELS. THEN JUST AS SUDDENLY, WE SUNK BACK INTO RED INK AND

WAITED WITH CROSSED FINGERS FOR THE NEXT UPTURN.

AFTER SUCH WONDERFUL YEARS AS 1989 AND 1990 - ARE WE AGAIN GOING TO SIT BACK AND WAIT FOR THE NEXT CYCLE? WHAT ARE THE CURRENT DYNAMICS OF THE MARKETPLACE? OF COURSE, WE SEE SOME SIGNALS OF A PLATEAU OR DOWNTURN. AN INVENTORY ADJUSTMENT HAS BEEN UNDERWAY SINCE THE FIRST OF THE YEAR, AND DEFENSE DEMAND CONTINUES TO DECLINE. DEVELOPMENTS IN THE MIDDLE EAST HAVE CAUSED SOME ADDITIONAL UNCERTAINTY. TITANIUM DEMAND IN DEFENSE PROGRAMS COULD, IN FACT, REMAIN STRONGER THAN MOST ANALYSTS WERE PREDICTING, BUT COMMERCIAL PROGRAMS COULD BE STRETCHED DUE TO HIGHER FUEL PRICES. WE ARE ALL AWARE OF THIS, BUT LET'S LOOK OUT A LITTLE FURTHER -- SAY TO 1995. WILL THERE BE A HEAVY DEMAND IN MILITARY AEROSPACE? I DON'T THINK SO. WILL THE COMMERCIAL AEROSPACE DEMAND STILL BE CARRYING US FOR YEARS AND YEARS? I DON'T THINK SO. WHERE DOES THAT LEAVE US?

WE HAVE JUST FINISHED A CONFERENCE THAT HIGHLIGHTED THE PROGRESS TITANIUM IS MAKING IN A VARIETY OF APPLICATIONS, NEW PRODUCTS, ALLOYS AND IMPROVEMENTS IN PROCESSING THROUGH TECHNOLOGY. OBVIOUSLY, AS WE ALL KNOW, THERE IS UNLIMITED POTENTIAL FOR OUR METAL.

NOW WHAT? DO WE SIT BY, ACCEPT THE NEXT DOWNTURN AS INEVITABLE, BEMOAN OUR FATE, RETRENCH, AND WAIT FOR THE NEXT BOOM? I SAY NO -- THERE IS AN ALTERNATIVE. THAT ALTERNATIVE IS TO STOP TALKING AND WISHING, AND MOVE THESE OPPORTUNITIES TO REALITY. THE 90'S CAN BE

THE “DECADE OF OPPORTUNITY” FOR TITANIUM, THE TITANIUM DEVELOPMENT ASSOCIATION AND FOR COMPANIES WHO AGGRESSIVELY PURSUE AND SUPPORT THE DEVELOPMENT OF NEW MARKETS. WE HAVE A UNIQUE OPPORTUNITY TO FORGE THE FOUNDATION FOR THE INDUSTRY'S PROGRESS DURING THE NEXT 10 YEARS, THAT'S WHY I “CALL US LUCKY”, WE ARE THE ONES WHO ARE FORTUNATE ENOUGH TO BE A PART OF MAKING THIS ALL HAPPEN.

BEFORE GOING FURTHER, LET'S STEP BACK A MOMENT AND ANALYZE WHAT'S ALREADY BEEN PUT INTO PLACE BY OUR INDUSTRY TO HELP OUR FUTURE PROGRESS, THERE ARE SIGNS THAT OUR INDUSTRY IS MATURING. LET'S LOOK AT WHAT HAS HAPPENED OVER THE PAST 10 YEARS:[*]

1. FULL-LINE SERVICE TO AEROSPACE INDUSTRY.

2. ACCEPTANCE OF THE RESPONSIBILITY TO SUPPORT THE NONAEROSPACE MARKETS.

3. ESTABLISHMENT OF THE TITANIUM DEVELOPMENT ASSOCIATION.

4. PROFIT SHARING PLANS --IMPROVED UTILIZATION OF LABOR.

5. EXPANDED GLOBAL PARTICIPATION.

6. INCREASED CAPITAL INVESTMENT.

---

[*] Fig. 1-2

7. GREATER INDEPENDENCE OF UNITED STATES TITANIUM COMPANIES.
8. EMPHASIS ON LOWERING COST OF METALLICS.
9. INTRODUCTION OF NEW PRODUCTS AND PROCESSING TECHNOLOGY.
10. IMPROVED PRODUCTIVITY THROUGH LABOR AND MANAGEMENT ACCEPTING ADDITIONAL RESPONSIBILITIES.
11. INDUSTRY-WIDE DISTRIBUTION SYSTEMS.

AS I WAS PREPARING THIS SPEECH AND REFLECTING ON THE EVENTS OF THE PAST, I WAS QUITE AMAZED AT HOW MUCH HAS BEEN ACCOMPLISHED. MAYBE WE HAVEN'T BEEN AS PASSIVE AS ORIGINALLY THOUGHT. I THINK THE 1986-1987 TIME PERIOD BROUGHT US ALL BACK TO SOME VERY BASIC THINKING. IN THE AREAS JUST COVERED, OUR FRIENDS FROM JAPAN AND EUROPE HAVE HELPED IMMEASURABLY IN OUR PROGRESS. WE HOPE, IN THE FUTURE, THAT EVEN GREATER AVENUES WILL BE OPENED, AND THAT INCREASED ACTIVITY WILL OCCUR WITH OUR FRIENDS IN THE USSR AND EASTERN EUROPE.

NOW THAT WE UNDERSTAND WHAT IS IN PLACE -- WHAT MODUS OPERANDI DO WE SET FOR THE FUTURE? FIRST OF ALL, WE CAN NO LONGER AFFORD A REACTIVE OR DEFENSIVE APPROACH TO THE MARKETPLACE. IT'S TIME FOR OUR INDUSTRY TO APPROACH NEW MARKETS DYNAMICALLY, PROACTIVELY AND CREATIVELY. IN THE 1990'S, THE REWARDS FOR THIS APPROACH WILL BE BOUNDLESS.[*]

SALES AND MARKETING ORGANIZATIONS MUST BE TAILORED TO THE PARTICULAR NEEDS OF THE MARKETS WE PLAN TO SERVE. LET'S LOOK AT THE MARKETS CURRENTLY BEING SERVED.[**]

AEROSPACE ACCOUNTS FOR APPROXIMATELY 75 TO 80 PERCENT OF THE ANNUAL SHIPMENTS IN OUR INDUSTRY. WHILE IT CAN BE SAID THAT TITANIUM IS MATURING IN AEROSPACE, THERE ARE NEW APPLICATIONS BEING DEVELOPED THAT CONCENTRATE ON TITANIUM'S EXCELLENT STRENGTH-TO-WEIGHT PERFORMANCE IN ENGINE AND AIRFRAME APPLICATIONS. ON THE HORIZON WE SEE TITANIUM METAL MATRIX COMPOSITES AND TITANIUM ALUMINIDES AS THE NEWEST OPPORTUNITIES.[***] HERE THE CHALLENGE FOR TITANIUM IS TO BREAK THROUGH THE CURRENT TEMPERATURE BARRIERS IN ENGINE AND AIRFRAME APPLICATIONS. AIRCRAFT AND ASSOCIATED ENGINES THAT COULD USE THESE MATERIALS INCLUDE MILITARY PLANES WITH NEW HIGH PERFORMANCE ENGINES SUCH AS THE ATF AND ATB, THE EXPERIMENTAL NASP AND PARTICULAR COMMERCIAL PLANES SUCH AS THE HIGH SPEED CIVIL TRANSPORT OR A VERY LARGE COMMERCIAL AIRPLANE.

---

[*] Fig. 3

[**] Fig. 4

[***] Fig. 5

IN THIS MARKETPLACE OUR SALES/MARKETING APPROACH HAS STOOD THE TEST OF TIME. RELATIONSHIPS ARE DEVELOPED, AND OUR CUSTOMERS ARE EXTREMELY KNOWLEDGEABLE OF THE METAL TITANIUM. WE HAVE THE CORRECT CONTACTS AND, IN SOME CASES, OUR CUSTOMERS KNOW AS MUCH OR MORE THAN WE DO ABOUT OUR PRODUCT. WHILE WE NEED TO ALWAYS CREATE NEW IDEAS, EQUALLY IMPORTANT IS THE NEED TO RESPOND TO THE NEEDS AND WISHES OF OUR CUSTOMERS. REMEMBER, THEY RECOGNIZE TITANIUM'S VALUE -- THEY WANT TITANIUM TO EXPAND --OF COURSE, WE NEED TO INCREASE OUR RESEARCH DOLLARS -- WE NEED TO ENTER JOINT PROGRAMS -- ALL IN THE INTEREST OF MAINTAINING AND EXPANDING OUR MOST IMPORTANT MARKET.

YES, I THINK WE CAN AND WILL SERVICE THE AEROSPACE MARKET WELL IN THE 1990'S. BUT WHAT ABOUT OTHER MARKETS -- DO WE HAVE THE CORRECT MARKETING ORGANIZATIONS AND INFRASTRUCTURES TO REALLY PENETRATE THE NONAEROSPACE POTENTIAL?

IT IS IN THIS NONAEROSPACE ARENA WHERE NEW APPLICATIONS ABOUND, AND TITANIUM REMAINS IN THE GROWTH STAGE OF ITS LIFE CYCLE. THE NONAEROSPACE MARKETS BECOME, THEREFORE, NOT ONLY OUR BEST OPPORTUNITY FOR EXPANSION BUT AN ABSOLUTE NECESSITY FOR THE HEALTH AND GROWTH OF OUR INDUSTRY. THE ORGANIZATIONAL INFRASTRUCTURE REQUIRED HERE IS COMPLETELY DIFFERENT FROM AEROSPACE, AND I WILL EXPLORE THAT TOPIC IN MORE DETAIL IN JUST A FEW MOMENTS.

FIRST, HOWEVER, LET'S ANALYZE THESE MARKETS. THE UNIQUE AND OUTSTANDING PERFORMANCE OF TITANIUM IN ENVIRONMENTS SUCH AS SEAWATER, CHEMICAL BRINES, BRACKISH, POLLUTED AND NATURAL WATERS HAS CONTRIBUTED TO ITS EXPANSION SINCE THE EARLY 80'S FOR MANY APPLICATIONS WHICH ARE JUST NOW COMING INTO USE.[*] THE MOST SIGNIFICANT OF THESE APPLICATIONS ARE MARINE/NAVAL, ENVIRONMENTAL/POLLUTION CONTROL, ENERGY EXTRACTION, AUTOMOTIVE, INFRASTRUCTURE REHABILITATION, AND MEDICAL IMPLANTS. LET'S LOOK AT SOME OF THESE.

DEVELOPING APPLICATIONS FOR TITANIUM IN THE MARINE MARKET CAN BE DIVIDED INTO THREE GENERAL CATEGORIES -- PRESSURE VESSEL, HEAT TRANSFER AND STRUCTURAL APPLICATIONS. THE SHIP SYSTEMS OF THE WORLD NEED TITANIUM TO IMPROVE PERFORMANCE AND RELIABLE SERVICE THROUGH THEIR LIFE CYCLE. WE HAVE BEEN “OUTMARKETED” IN THESE AREAS BY THE STAINLESS AND NICKEL INDUSTRY. TITANIUM SHOULD BE THE MATERIAL OF CHOICE.[*]*

IN POWER GENERATION, GEOPOLITICS AND LONG-TERM ECONOMIC FACTORS FAVOR THE INCREASED USE OF COAL. ALL COALS CONTAIN VARIOUS CONCENTRATIONS OF SULFUR, WHICH CREATE POTENTIALLY HAZARDOUS POLLUTANTS DURING COMBUSTION. FEDERAL REGULATIONS IN THE UNITED STATES AND AROUND THE WORLD INCREASINGLY LIMIT THE AMOUNT OF THESE POLLUTANTS THAT CAN BE RELEASED INTO THE ENVIRONMENT. IN ORDER TO MEET THE CURRENT AND FUTURE

---

[*] Fig. 6-7

[**] Fig. 8

REGULATIONS, OVER 90 PERCENT OF THE POWER GENERATING FACILITIES IN THE UNITED STATES WILL BE FORCED TO UTILIZE SCRUBBER SYSTEMS -- SYSTEMS THAT SHOULD USE TITANIUM.*

THE DRILLING INDUSTRY HAS BEGUN TO TAP DEEP DEPOSITS OF OIL AND NATURAL GAS. THE KEY TO TITANIUM USAGE IN THIS INDUSTRY IS TO HAVE DESIGN ENGINEERS OPTIMIZE AROUND THE STRENGTH - DENSITY AND CORROSION RESISTANCE OF TITANIUM RATHER THAN CLONE TITANIUM WITH EXISTING DESIGNS USED FOR OTHER MATERIALS. AS MORE DEEP WELLS ARE DRILLED FOR HYDROCARBON PRODUCTION, THE POTENTIAL FOR USE OF TITANIUM ALLOYS WILL INCREASE TREMENDOUSLY. TITANIUM HAS DEMONSTRATED ITS EFFICIENCY AND COST EFFECTIVENESS IN THIS AREA ONLY TO A LIMITED EXTENT, MUCH MORE WORK NEEDS TO BE DONE.**

AUTOMOTIVE APPLICATIONS TO DATE HAVE CONSISTED OF HIGH PERFORMANCE SPECIALTY VEHICLES AND COMPRISE RELATIVELY SMALL VOLUMES. HOWEVER, THERE ARE SIGNS, SUCH AS HONDA'S NEW ACCURA NSX WHICH USES TITANIUM CONNECTING RODS, THAT THE TIME IS NEAR FOR EXPANDED AUTOMOTIVE USE. WHEN THE PRICE/VOLUME ECONOMIES OF SCALE CAN BE REALIZED, TITANIUM WILL BE SPECIFIED.***

THE REPAIR OF EXISTING INFRASTRUCTURE AGING IN OUR NATION'S HIGHWAYS, BRIDGES, AND PARKING DECKS, PERHAPS EVEN BUILDINGS, SUGGESTS ENORMOUS POTENTIAL FOR TITANIUM. THE JAPANESE INDUSTRY HAS LEAD THE WAY IN DESIGNING USE IN BUILDINGS, AND THIS SHOULD BE SPREAD THROUGHOUT THE WORLD.****

---

* Fig. 9
* * Fig. 10
* ** Fig. 11
* *** Fig. 12

TITANIUM IN THE HUMAN BODY FOR IMPLANTS HAS IMPORTANT GROWTH POTENTIAL, BUT MORE RESEARCH MUST BE CONDUCTED ON WEAR RESISTANCE, ESPECIALLY ON ARTICULATING SURFACES, AND ALLOY DEVELOPMENTS IN ORDER FOR ACCELERATED GROWTH TO OCCUR.[*]

I COULD GO ON, BUT MUCH OF THIS DATA YOU HAVE HEARD BEFORE. LET ME OFFER AN OBSERVATION OR TWO. THERE IS MORE POTENTIAL FOR TITANIUM USE IN THE MARKETS I'VE JUST HIGHLIGHTED THAN THE ENTIRE EXISTING AEROSPACE CONSUMPTION OF TITANIUM ANNUALLY! HOWEVER, THIS POTENTIAL WILL NOT COME TO THE TITANIUM INDUSTRY LIKE IT DID IN AEROSPACE. INSTEAD, WE MUST GO TO THE MARKETS! WE MUST BE THE AGGRESSOR, AND WE CANNOT AFFORD TO GO IT ALONE. HOW DO WE DO THIS?[**]

I WILL USE MY OWN COMPANY AS AN EXAMPLE OF HOW WE ARE APPROACHING NONAEROSPACE MARKETS. FIRST OF ALL, WE HAVE A TECHNICAL MARKETING GROUP WHICH IS TOTALLY DEDICATED TO DEVELOPING NEW MARKETS. IN MANY CASES, THESE PEOPLE ARE INTERFACING WITH DESIGN ENGINEERS AND COMPANIES WITH WHOM WE HAVE HAD NO PREVIOUS CONTACT, THE SALES FORCE, IN TURN, IS NOW ON AN EXISTING MARKET SEGMENT BASIS WITH PRODUCT TEAMS TO ENSURE ACCURATE AND FAST RESPONSE TO OUR DEVELOPING CUSTOMERS. THE IDEA HERE, OF COURSE, IS TO DEVELOP EXPERTISE IN THESE PRODUCTS AND MARKETS TO A LEVEL WE HAVE NEVER HAD BEFORE. WHAT HAS MADE US SUCCESSFUL IN AEROSPACE IS KNOWING EVERY FACET OF OUR MARKET. WE CANNOT EXPECT CUSTOMERS IN THESE NUMEROUS NEW

---

[*] Fig. 13

[**] Fig. 14

MARKETS TO DEVELOP APPLICATIONS AS WAS DONE IN AEROSPACE. THROUGH RESEARCH AND TECHNICAL MARKETING, WE NEED TO DIVE IN AND MAKE THINGS HAPPEN. WE MUST BE AGGRESSIVE. WE CAN'T WAIT -- WE HAVEN'T GOT TIME TO WAIT. THE POTENTIAL CUSTOMER'S PROBLEMS AND QUESTIONS MUST BE ANSWERED, AND NEW OPPORTUNITIES ADDRESSED. FOR INSTANCE, WE MUST DEMONSTRATE HOW TITANIUM CAN BE USED AS AN ALTERNATIVE TO OTHER MATERIALS THROUGH NEW DESIGNS AND CREATIVE APPROACHES. WE MUST CONDUCT EDUCATION AND TRAINING SEMINARS -- INITIATE EDUCATION IN FIELD INSTALLATION AND MAINTENANCE -- DESIGN COST COMPETITIVE SYSTEMS WITH OTHER MATERIALS -- BE WILLING TO SUBSIDIZE NECESSARY TESTING TO PROVE OUR PRODUCTS' CAPABILITIES -- DEVELOP JOINT PROJECTS WITH CUSTOMERS. IN ADDITION, WE MUST MAKE TECHNICAL MARKETING AND RESEARCH EMPLOYEES ACCOUNTABLE. CHARGE THEM WITH THE RESPONSIBILITY TO BRING PROFIT AND VOLUME TO THE BOTTOM LINE. AT THE SAME TIME, EXECUTIVE MANAGEMENT CANNOT PANIC AT THE LEAST BLIP IN THE MARKETPLACE AND REDUCE THESE IMPORTANT SEGMENTS OF MIDDLE MANAGEMENT. THERE ARE NO MORE IMPORTANT EMPLOYEES IN OUR COMPANIES TODAY THAN THOSE IN RESEARCH AND TECHNICAL MARKETING. THEY ARE OUR FUTURE -- THEY WILL MAKE US OR BREAK US, BELIEVE ME!

WHAT IS THE NEXT STEP? THE TITANIUM DEVELOPMENT ASSOCIATION, OF COURSE.[*] HOW DOES THE TITANIUM DEVELOPMENT ASSOCIATION FIT INTO ALL THIS? JUST BEAUTIFULLY, BUT HERE AGAIN WE MUST HELP MAKE IT HAPPEN. OUR TITANIUM DEVELOPMENT ASSOCIATION HAS REACHED THE

---

[*] Fig. 15

FIRST PHASE OF MATURITY. THROUGH OUTSTANDING CONTRIBUTIONS OF ORIGINAL MEMBERS, THE ASSOCIATION HAS GAINED A FOOTHOLD, AND IS RECOGNIZED AS THE REPRESENTATIVE OF OUR INDUSTRY. THE ADMINISTRATIVE MECHANISMS ARE NOW IN PLACE TO HANDLE OUR GROWTH IN THE FUTURE. HOWEVER, WE MUST MOVE TO THE NEXT STEP -- THE NEED FOR INCREASED TECHNICAL INPUT AND OUTPUT. WE MUST APPOINT A NEW TECHNICAL DIRECTOR WHO WILL EXPAND OUR PARTICIPATION AT TECHNICAL SEMINARS AND MEETINGS THROUGH EDUCATING POTENTIAL USERS ON THE PROPERTIES AND APPLICATIONS FOR TITANIUM. ADDITIONAL APPLICATION-ORIENTED COMMITTEES MUST BE ESTABLISHED FOR BOTH THE DEVELOPMENT OF NEW MARKETS AND SOLVING ANY PROBLEMS THAT WE ENCOUNTER AS WE DEVELOP NEW APPLICATIONS. THE TDA, THROUGH OUR TECHNICAL DIRECTOR, SHOULD DIRECT JOINT TESTING UNDER AN R&D PROGRAM TO SPEED UP INTRODUCTION OF NEW ALLOYS.

I ALSO FORESEE THE TDA ACTING AS A CATALYST FOR MEETING THE CHALLENGES PRESENTED BY NEW GROWTH OPPORTUNITIES FOR THE TITANIUM INDUSTRY. LIKE THE ENGINE AND AIRFRAME MANUFACTURERS, OUR INDUSTRY MUST FORM STRATEGIC ALLIANCES, POSSIBLY THROUGH THE TDA, TO DEVELOP THE NECESSARY NEW PRODUCTS AND PROCESSES. OUR FEDERAL GOVERNMENT IS RECEPTIVE MORE AND MORE TO THESE TYPES OF ARRANGEMENTS.

FURTHERMORE, TDA AND JTS TOGETHER CAN PIONEER EFFORTS OF COOPERATION IN AREAS WHERE THE WORLDWIDE INDUSTRY WOULD BENEFIT. IT IS IMPORTANT THAT TITANIUM SOCIETIES, THROUGHOUT THE

WORLD, WELCOME MEMBERS FROM OTHER COUNTRIES AS OUR TDA HAS DONE IN THE UNITED STATES.[*]

SEVERAL SUGGESTIONS FOR COOPERATIVE EFFORTS COME TO MIND -- A DIRECTION TO SOLVE INDUSTRY ENVIRONMENTAL PROBLEMS AS LEGISLATION BECOMES MORE STRINGENT, NOT ONLY FOR THE CUSTOMERS WE SERVE, BUT FOR OUR OWN INDUSTRY AS WELL. THREE MARKETING AREAS ARE RIPE FOR COMBINED DEVELOPMENT EFFORTS; FOOD PROCESSING, PHARMACEUTICALS AND WASTE DISPOSAL.

BETWEEN THE RESPONSIBILITIES WE HAVE AS THE TITANIUM INDUSTRY, AS WELL AS OUR TRADE ASSOCIATIONS, YOU SAY WE HAVE AN AWESOME TASK, YES I AGREE, BUT AT THE SAME TIME, DON'T YOU FEEL THAT WE HAVE NOW GRASPED THE METHODOLOGY TO REACH OUR FINAL DESTINATION:[*]*

1. CONTINUE OUR CURRENT AGGRESSIVE APPROACH TO REDUCING RAW MATERIAL COSTS.

2. TOTALLY CHANGE OUR SALES/MARKETING DIRECTION TO ONE OF MARKET, RATHER THAN TOTAL EMPHASIS ON PRODUCT AND SHORT-TERM SALES.

3. EXPAND IMMEDIATELY OUR TECHNICAL MARKETING BASE TO GIVE US EXPERTISE IN MANY MARKETS SIMILAR TO WHAT WE HAVE IN

---

* Fig. 16

* * Fig. 17

AEROSPACE. WE MUST EDUCATE THE USERS.

4. CONTINUE TO INCREASE RESEARCH BUDGETS, NOT ONLY FOR PRODUCT, BUT ALSO FOR PROCESSING. REMEMBER, WE STILL BASICALLY PRODUCE TITANIUM WITH METHODS THAT WERE DEVELOPED IN THE 1950'S.

5. <u>CAPITAL INVESTMENT</u> - WE'VE MADE GOOD STRIDES THE LAST FEW YEARS. HOWEVER, CONTINUED INVESTMENT IS VITAL TO GROW PRODUCTION VOLUME, REDUCE COST, IMPROVE THE PROCESS AND UPGRADE THE EQUIPMENT.

6. EXPAND OUR DISTRIBUTION NETWORK. DISTRIBUTION NOT ONLY SUPPORTS EXISTING AEROSPACE CUSTOMERS, BUT ALSO MAKES MATERIAL AVAILABLE IN SMALL QUANTITIES TO A HOST OF NEW MARKETS AND NEW CUSTOMERS.

7. WE NEED TO EXPAND OUR THINKING TO GLOBAL MARKETS. THE U.S. MARKET WILL ONLY EXPAND TO A CERTAIN DEGREE -- THE UNTAPPED MARKETS ARE IN THE FAR EAST, THE DEVELOPING NATIONS AND THE EASTERN BLOC.

8. ENTREPRENEURIAL SPIRIT -- THE FASCINATION OF OUR MARKET IS THAT THE FUTURE IS SO UNBELIEVABLY UNPREDICTABLE. THE OPPORTUNITIES WILL BE THERE. THOSE WITH CREATIVE IDEAS -- THOSE WHO ARE WILLING TO FACE THE FUTURE WITH CONFIDENCE AND COURAGE -- THOSE WHO ARE WILLING TO IMPLEMENT RATHER

THAN PROCRASTINATE. IN OTHER WORDS, THOSE WITH OLD FASHIONED ENTREPRENUERIAL SPIRIT WILL BE THE WINNERS.

I AM EXCITED ABOUT WHAT'S HAPPENING TO OUR BUSINESS. I LIKE WHAT I AM SEEING -- OUR INDUSTRY IS MATURING -- WE ARE MAKING THE RIGHT MOVES. OUR WORLD IS BECOMING SMALLER -- THERE IS A GREATER INTERFACE INTERNATIONALLY WITHIN OUR INDUSTRY TODAY THAN EVER BEFORE. THIS WILL CONTINUE TO GROW AND EXPAND. YOU KNOW, EVERY MORNING WHEN I WAKE UP, I CAN HARDLY WAIT TO GET TO WORK. THE CONSTANT CHALLENGES, THE NEW OPPORTUNITIES. AS I SAID BEFORE, JUST CALL US LUCKY. WHY? BECAUSE WE HAVE A CHANCE TO CREATE SOMETHING FEW INDIVIDUALS EVER HAVE HAD DURING THEIR BUSINESS CAREERS. WE HAVE CALLED THE 1990 TO THE YEAR 2000 TIME PERIOD THE DECADE OF OPPORTUNITY. IN THE YEAR 2000 WE'LL LOOK BACK AND WHAT WILL HAVE HAPPENED? I BELIEVE TITANIUM WILL HAVE EXPANDED INTO EVERY FACET OF OUR EVERYDAY LIVING. FROM THE ENVIRONMENT TO THE MEDICAL FIELD -- FROM AEROSPACE TO THE OIL PATCH -- FROM HIGHWAY AND BUILDING CONTRUCTION TO THE AUTOMOTIVE MARKETS. IT'S THERE BECKONING -- IT'S SAYING, “YOU HAVE FORMED AN EXCELLENT FOUNDATION -- WILL YOU TAKE THE NEXT STEP? YOU BET YOUR LIFE WE WILL. IT'S OUR DESTINY.

THANK YOU.

INDUSTRY PROGRESS
1980'S

Full line customer service

Support of nonaerospace markets

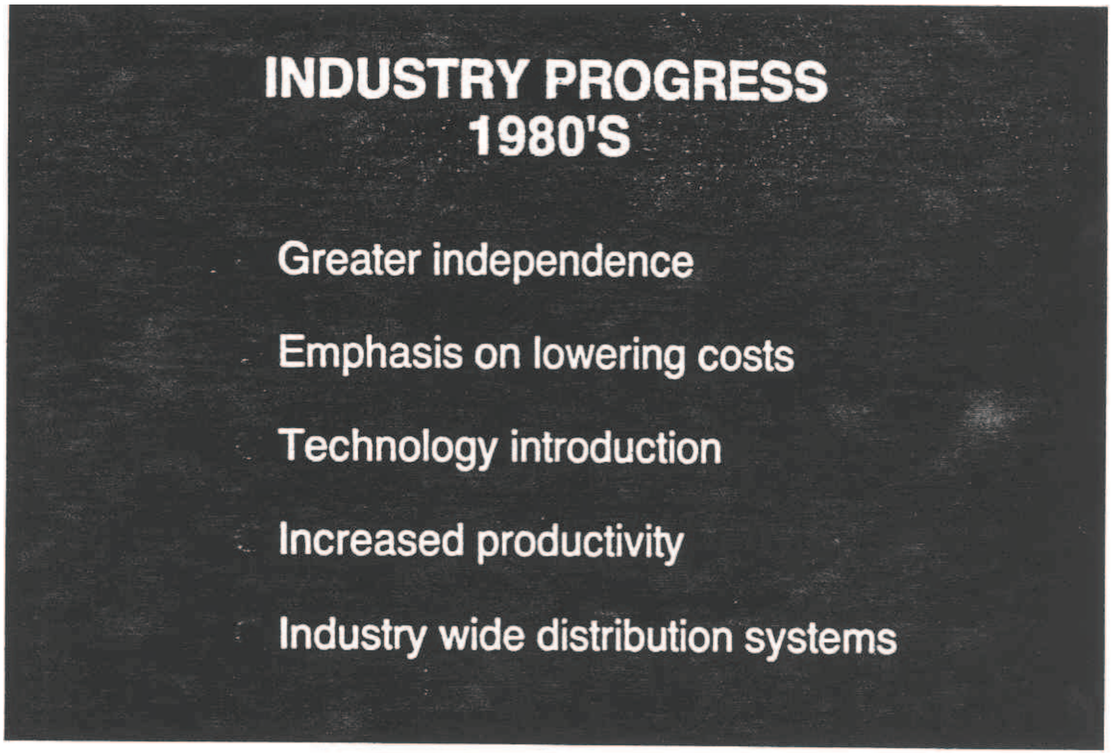
Establishment of
Titanium Development Association

Improved labor utilization

Expanded global participation

Increased capital investment

Fig. 1



INDUSTRY PROGRESS
1980'S

Greater independence

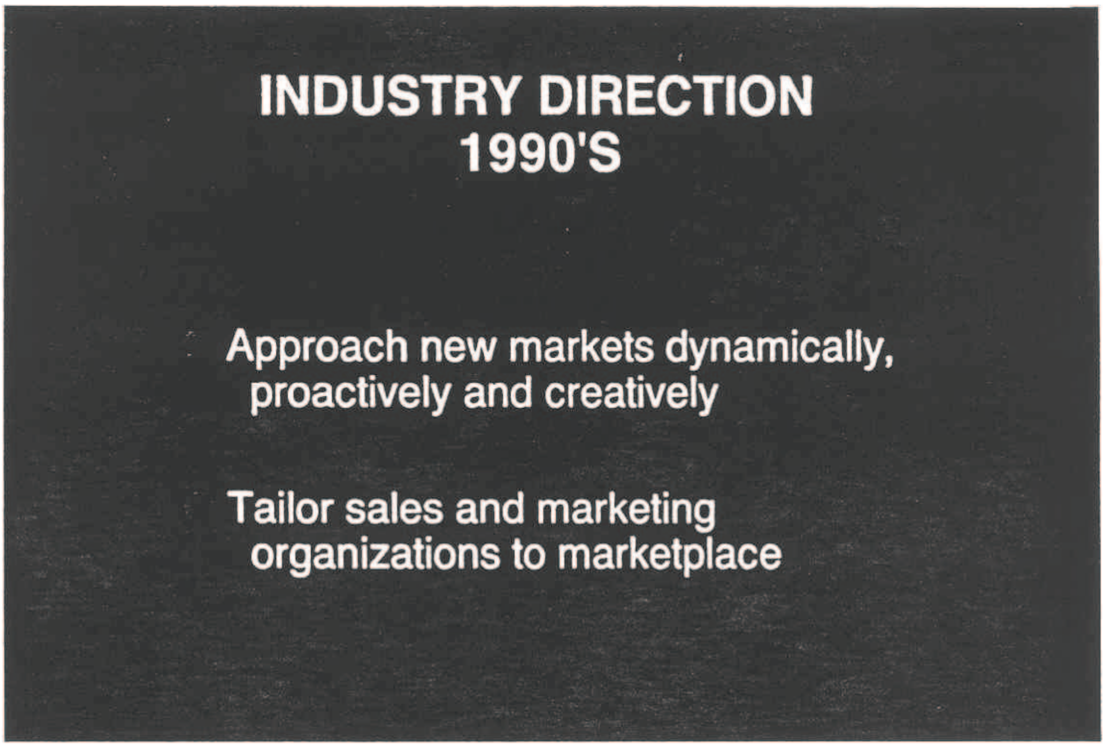
Emphasis on lowering costs

Technology introduction

Increased productivity

Industry wide distribution systems

Fig. 2



INDUSTRY DIRECTION
1990'S

Approach new markets dynamically, proactively and creatively

Tailor sales and marketing organizations to marketplace

Fig. 3

AEROSPACE MARKET

Create new ideas

Respond to customers

Fig. 4

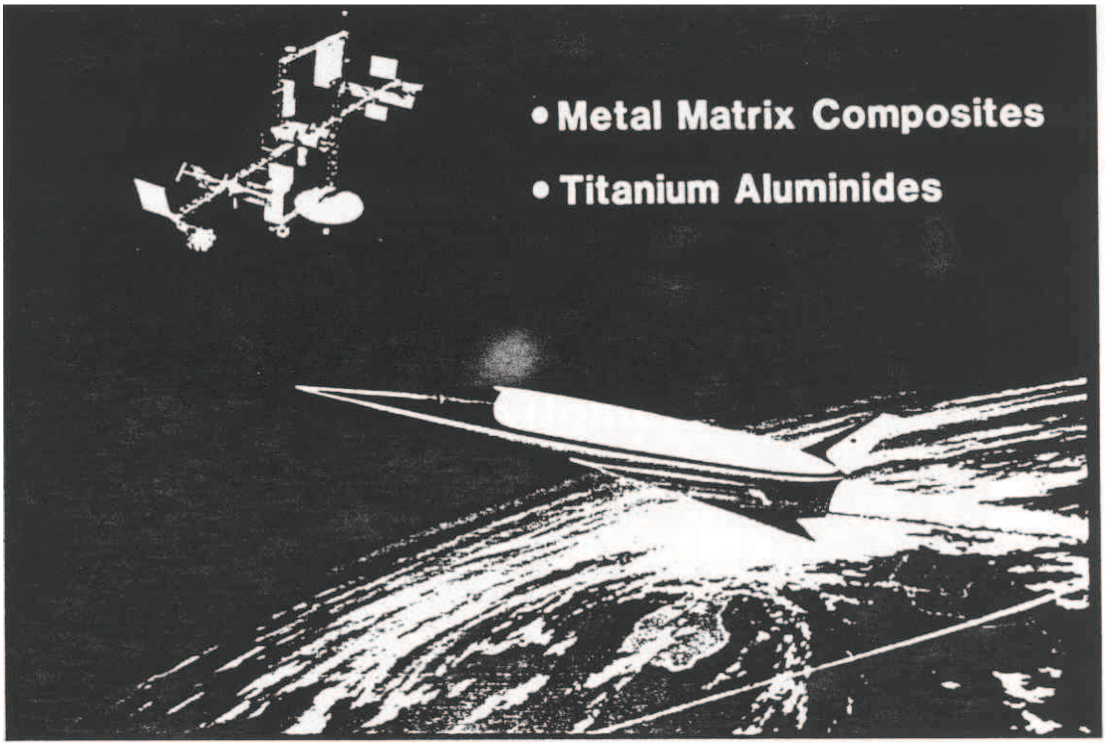


Fig. 5

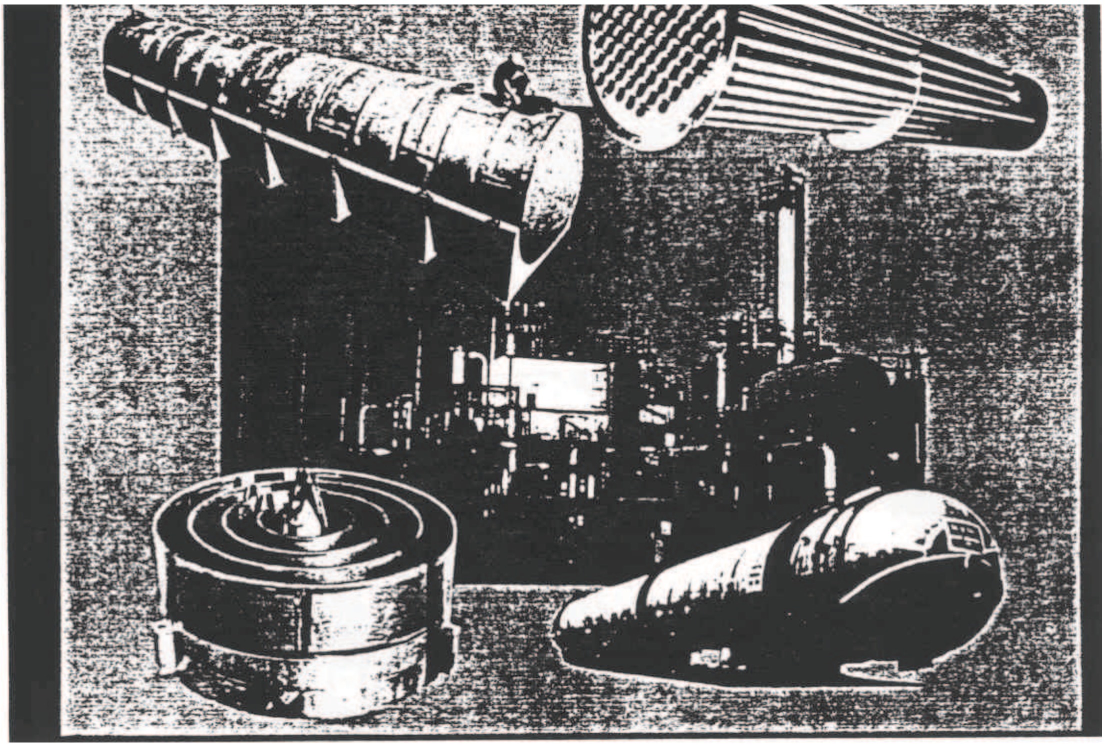
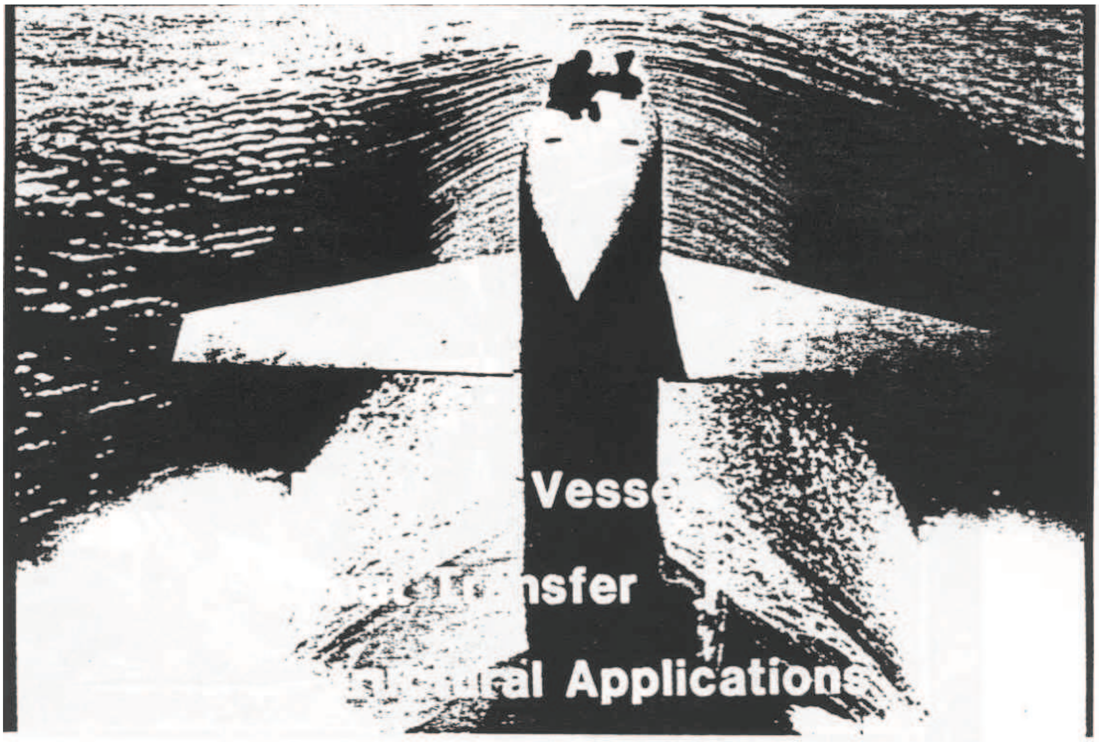


Fig. 6

- Marine/Navy
- Environmental/Pollution Control
- Energy Extraction
- Automotive
- Infrastructure Rehabilitation
- Medical Implants

Fig. 7



[illegible] Vesse

[illegible] Transfer

[illegible]al Applications

Fig. 8

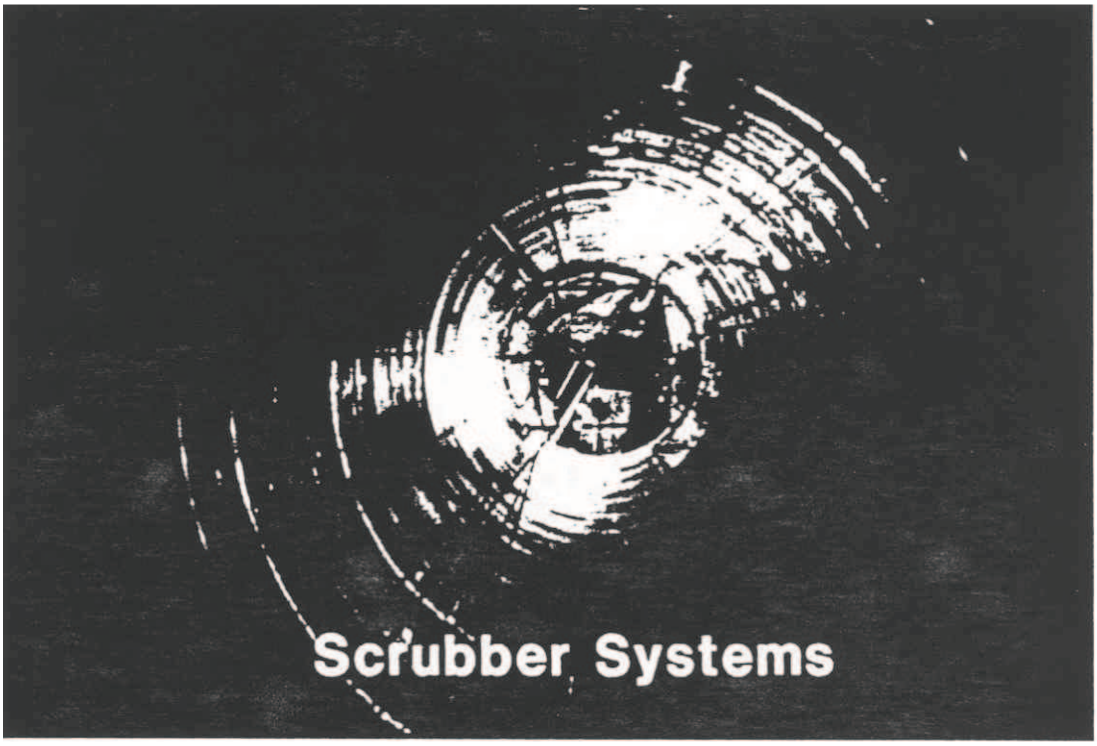


Fig. 9

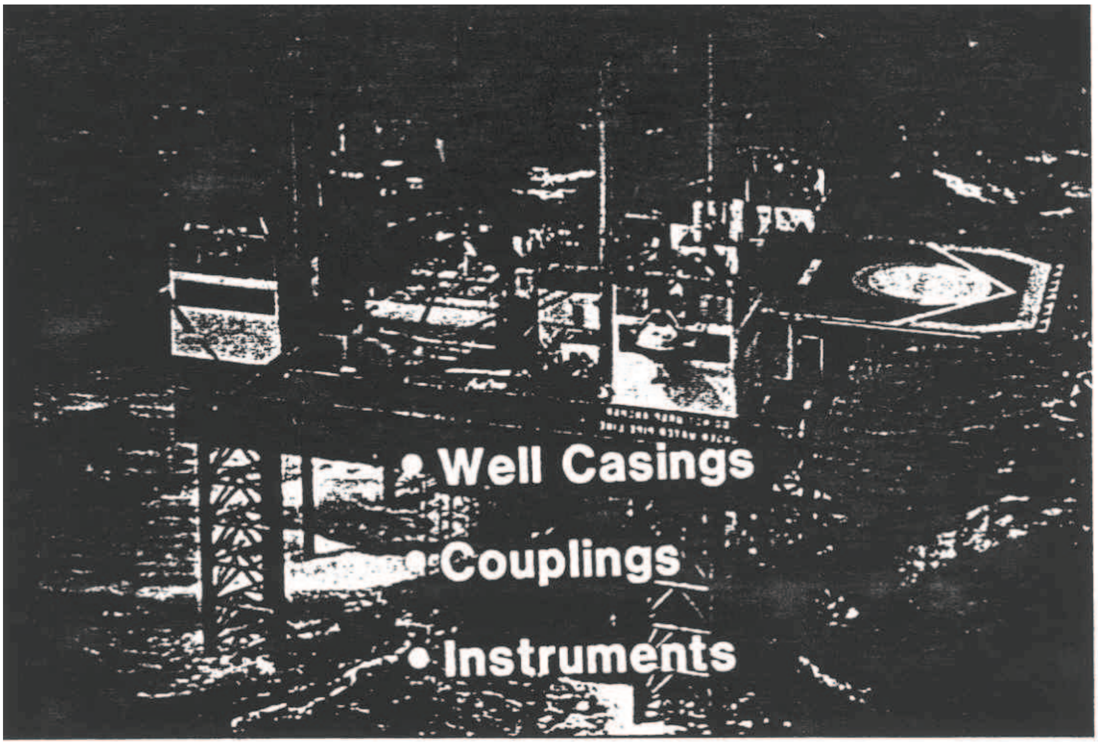
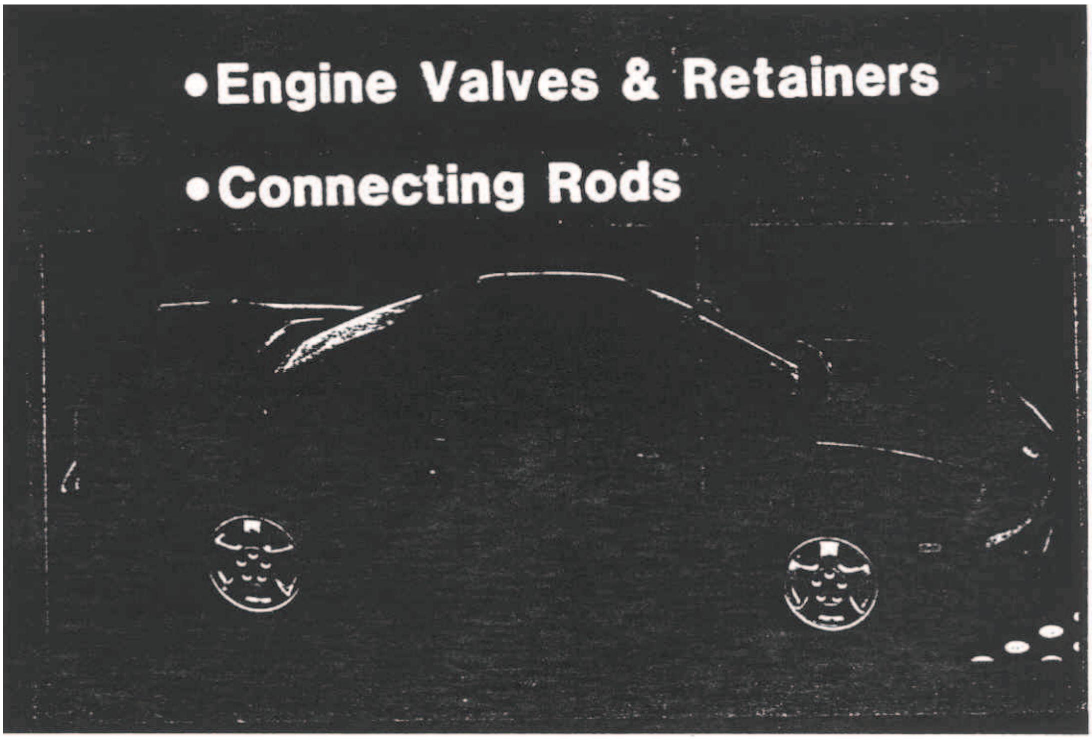
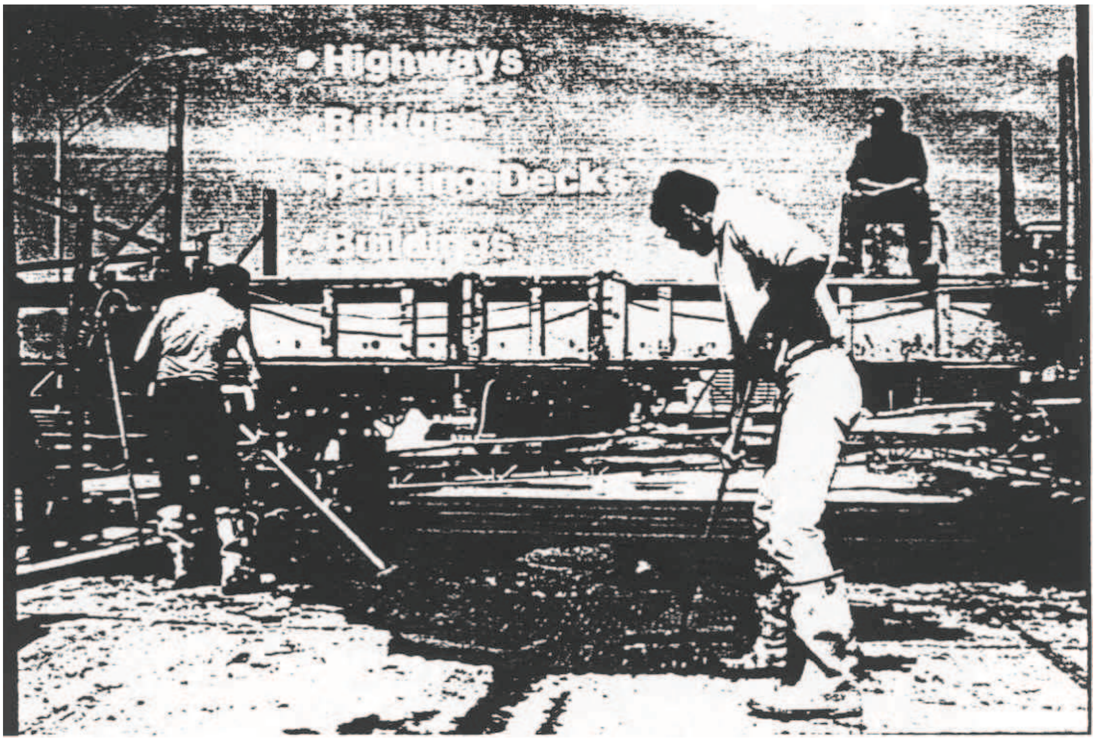


Fig. 10



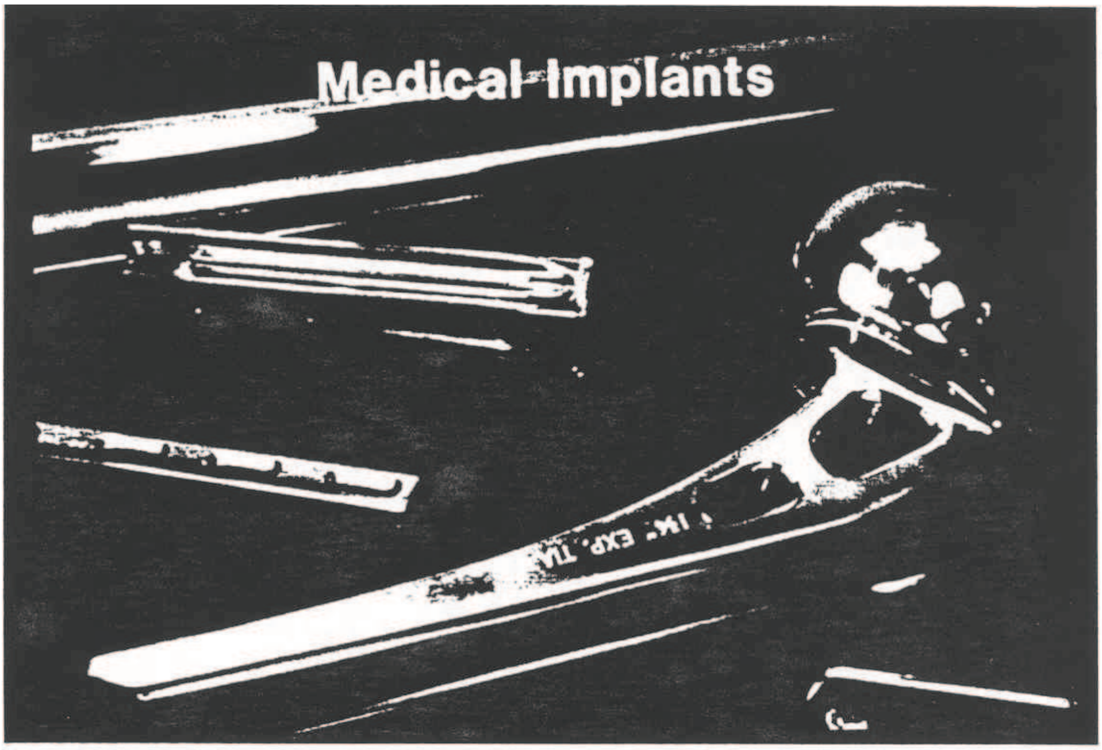
- Engine Valves & Retainers
- Connecting Rods

Fig. 11



- Highways
- Bridges
- Parking Decks
- Buildings

Fig. 12



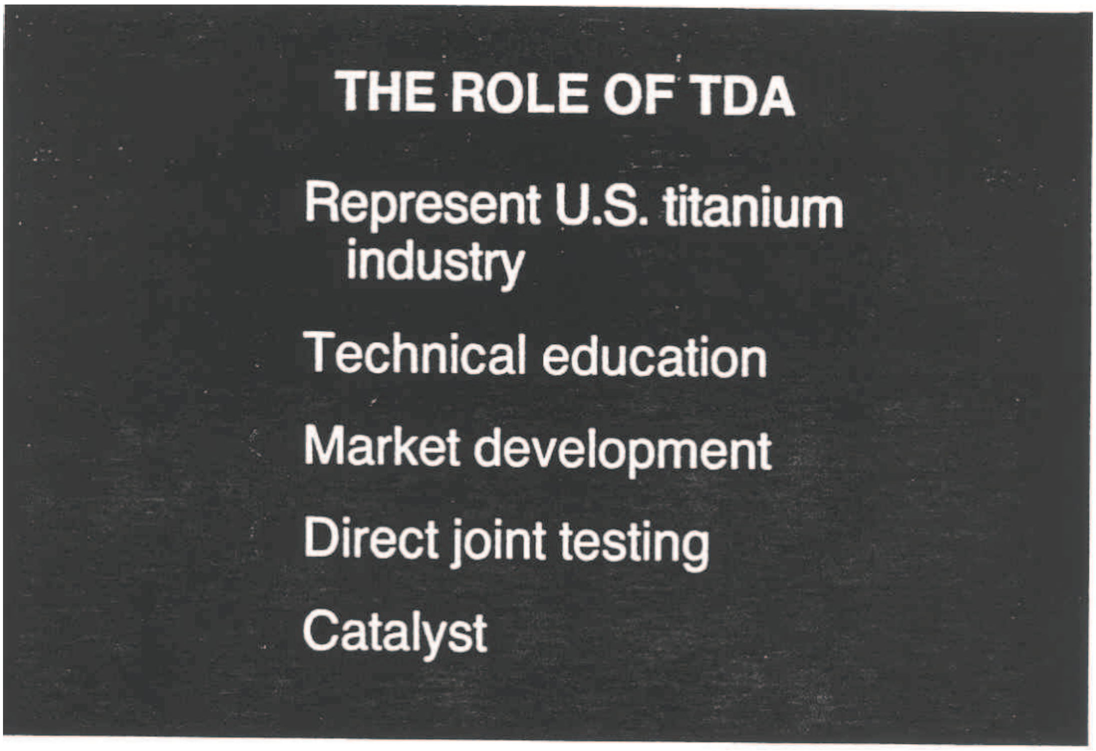
Medical Implants

Fig. 13

NONAEROSPACE MARKETS

- Aggressive approach
- Dedicated technical marketing
- Expert sales force
- Solve customer problems
- Creative style
- Subsidize testing
- Team effort

Fig. 14



THE ROLE OF TDA

Represent U.S. titanium industry

Technical education

Market development

Direct joint testing

Catalyst

Fig. 15

TDA AND JTS COOPERATIVE EFFORTS

Welcome new members worldwide

Address industry environmental problems

Develop new markets

Fig. 16

INDUSTRY METHODOLOGY FOR THE 1990'S

- Reduce raw material costs
- Emphasize new markets
- Educate users
- Increase research budgets
- Continue capital investment
- Expand distribution system
- Reach global markets
- Create an entrepreneurial spirit

Fig. 17

VI INTERNATIONAL MEETING ON TITANIUM

THE DEVELOPMENT OF COMPUTER CONTROL IN TITANIUM SPONGE GRANULE MANUFACTURE

Peter Morcom
Deeside (UK)

THE DEVELOPMENT OF COMPUTER CONTROL IN TITANIUM SPONGE GRANULE MANUFACTURE

Ladies and Gentlemen, my name is Peter Morcom, and I am the Process & Systems Manager of Deeside Titanium Limited, or DTL for short.*

In the next 20 to 30 minutes, I will be discussing the introduction of computer control to the reaction process we employ at DTL to make titanium. Before I do this, I will briefly give details on DTL as a company, and also a resume of the process we use at DTL.

DTL started production in 1981 and is a subsidiary of Rolls-Royce plc with IMI plc as the minority shareholder. DTL produces titanium sponge granules of the highest quality, and these are mainly used in the high temperature titanium alloys manufactured by IMI and utilised in Rolls-Royce aero engines. IMI 834 is the latest high performance titanium alloy produced using DTL material and is used extensively in the Rolls-Royce Trent Engine.

In addition to granules, DTL produce a range of titanium powders.

The process we use is often call the Hunter Process, named after the person who first developed it, and is essentially the same process used previously at the ICI plant which DTL replaced.

The process consists of the following main steps; Raw Material Handling, Raw Material Purification, High Temperature Reaction between Sodium and Titanium Tetrachloride, Removal of product from the Reactor, Crushing, Leaching, Drying and Packing.**

---

* Fig. 1

* * Fig. 2

The main raw materials, Sodium and Titanium Tetrachloride (or TTC for short), are received in rail or road tankers and are stored on site. Both these materials then go through purification processes and are stored in measure vessels ready for introduction into the reaction process.

The reaction process is a batch process and is carried out in a leak tight argon filled enclosed reactor vessel which is placed in a gas heated furnace. Sodium is charged to this vessel and heated. TTC is fed into the vessel over a period of about 30 hours, and the temperature within the reactor can exceed 1000 degrees centrigrade during some stages of the reaction.

During the reaction, close control of process parameters, including reactor pressure, TTC flowrate and furnace conditions, is maintained.

At the end of the reaction, the reactor is transferred to a cooling bay, where water is sprayed onto the outside of the vessel whilst maintaining a positive argon pressure inside.

Once the reactor product (or melt) has cooled to ambient temperature, the melt, which consists of approximately 1 part of titanium to 5 parts of sodium chloride, is removed from the reactor and crushed. The salt is leached out leaving titanium granules which are then dried and packed into drums.

Today, I will be concentrating on the reaction stage of the DTL process.

The reaction process first used at DTL was manually controlled, and was a "Chinese Copy" of that which had been used previously at ICI.

The only process variable data available on the ICI reaction process was that given in their Process Operating Instructions and manually recorded on log sheets by process operators. The information was of limited use as only hourly readings were taken. Therefore, as the reaction process was considered to be critical to the quality of titanium produced, and also the part of the process about which least was known, DTL decided in 1980 to install a sophisticated data logging facility as a first step to introducing full computer control at some time in the future.

Development of the data logging system commenced in 1981 and continued through to early 1983, when the system became fully operational.

The next slide shows a schematic of the data logging system. The data logging system is still in full use, and has been much enhanced to log other process plant areas. The basic design concept, however, remains the same.*

Analogue and digital information tram instruments and control valves associated with each reactor station is collected at regular intervals by a Hewlett Packard mini computer. Weight information tram the sodium and TTC measure vessels is also logged.

Once a reaction batch has been completed the acquired data is compressed using pre-determined deadbands for each process variable monitored, and archived onta disc or tape. Data for each reaction batch will be kept for 25 years to satisfy aerospace requirements.

---

* Fig. 3

The next slide shows the types of reports and information available tram the data logging system.*

Any logged process variable can be displayed or plotted in graphical form for both live and archived reaction batches. Graphics screens are provided for all production, technical development and product assurance personnel. During the automatic data compression routine, approximately 60 process parameters are calculated for each reaction batch, for example, average TTC flow rate, and these can be statistically examined for trends and correlations using in-house developed routines.

Reaction data logging quickly started to help our understanding of the reaction process. The difficulties in getting operators to manually control a relatively complex process in a repeatable way immediately became apparent.

The next slide lists some of the problems in using manual control.**

DTL has always used a five shift system and it soon became clear that different shifts placed different interpretations on the Process Operating Instructions. Also, one of the favourite beliefs on the shop floor was that "If changing a variable made the reaction process run easier, it automatically followed that this must be good for product quality". This, of course, is very rarely true, and certainly does not hold for our process. Anybody adopting this philosophy would not be controlling his process, the process would be controlling him.

---

* Fig. 4

* * Fig. 5

Shift changeovers were al so a problem. During the overlap period, when the previous shift is explaining to the next one what has happened, control parameters can often drift outside control bands. We found that by looking at a plot of a reaction batch, we could identify the shift changeover by the change in trace characteristics.

Changes in process variable settings tended to be large and infrequent, instead of being small and frequent. Consequently reaction control whilst on the whole achieving the average setting required, was most uneven.

The problems with manual control become even more acute when trying to optimise the process. Each time a new set of operating parameters is required to be tested, a temporary set of operating instructions is required. Then there is the problem of communicating these to each shift. Very often, the first few reactions under a new operating parameter regime are a mixture of the old and the new operating parameters. In practice, it has proved impossible to achieve exactly what one set out to achieve when manually controlling the reaction process.

At this stage, it was clear that improvements to the process could only be made with confidence if the variability in the measured process parameters could be significantly reduced, and it was decided to explore the possibility of introducing computer control to the reaction process.

The next slide shows the development stages required to introduce computer control.*

---

* Fig. 6

The first step was to identify which parameters could be controlled satisfactorily, and their interdependence, if applicable. A list of possible control loops was drawn up, and tram this, a shortlist was targetted. From 1983, development effort was directed at improving the performance of these control loops until in 1985, it was possible to manually enter setpoints into the associated controllers and obtain reasonable process control over some process parameters. However, temperature proved more complicated to control as this was affected by both gas firing rate and TTC flow rate and therefore could only be indirectly controlled.

During 1984 and 1985, a number of development reactions were carried out on a comprehensively instrumented reactor station to assess the potential of setpoint control. Development personnel manned the reactions round the clock, liaising with process operators whenever changes to setpoints were required. The results proved very interesting and indicated that automatic setting of setpoints by a computer should be possible.

The decision was made at the beginning of 1986 to convert one reactor station to computer control, and the relevant control loops and hardware were installed. A functional specification for the control software and hardware configuration was developed internally at DTL and circulated for comment amongst interested parties. Suitable analogue and digital output units for interfacing between the Hewlett Packard minicomputer and the individual loop controllers were identified. The interface software specification was written by DTL and developed by an outside software contractor this being the only software developed externally.

The control software was written in FORTRAN 77, a very popular scientific computer language, and this made modifications and enhancements to the program relatively easy for DTL to implement themselves.

Software development was completed in 1986, and following rigorous acceptance testing, the first "live" computer controlled reaction was carried out at the end of 1986.

The next slide shows a schematic of the computer control system.*

The overall design of the reaction computer control system is relatively straightforward. The system is designed on the principle of supervisory loop control. The setpoints of the controllers associated with a reactor station are adjusted by a host computer, in this case, the Hewlett Packard minicomputer, depending on the values of the measured process variable and the stage the reaction has reached. Valve position and control status equipment are also controlled by the computer. The computer sets the analogue and digital output units to the desired values, and these in turn output to the plant systems. The original data logging system was utilised and enhanced to provide the required level of data logging.

---

* Fig. 7

Safety considerations were of paramount importance, and none of the safety systems provided for the manually controlled process were removed or bypassed. The actual outputs tram the analogue and digital output units are monitored by the data logging system and any significant discrepancies cause alarms to sound on the plant. In the event of the computer failing, a special watchdog unit operates an alarm to inform the operators. On each reactor station, a LOCAL/REMOTE switch is provided and an operator can switch tram computer control to manual control at any time during the reaction.

During development of the computer control system, so far, I have only talked about the technical aspects of implementing computer control. The human considerations are equally important, as you ne ed to obtain the full co-operation of the workforce if you want to reap all the benefits.

The next slide shows some of the human considerations.*

Justification to the workforce for the introduction of computer control can be difficult. Computer control has often been an unfortunate expression on the shop floor, and conjures up the spectre of unemployment.

---

* Fig. 8

Fortunately, DTL were able to justify the investment in computer control on the grounds of improved reaction consistency leading to improved overall product quality. Also, at the time DTL introduced computer control, the work torce on reaction had already been cut back to the minimum safety level allowable. This meant that productivity gains were possible if production rates increased as fewer additional operators would be required.

Communication between the implementers and the operators of the system was most important. During the development cycle, operators and shift managers were consulted about the design of the interface between machine and operator and also asked to define what displays they required. Regular meetings were held to keep personnel informed as to the progress of the project.

Training was also most importante DTL place a considerable emphasis on training, as evidenced by recent success in the 1990 UK National Training Awards. All five shifts, including shift managers, were given comprehensive training in the operation of the computer control system and a special simulation program was developed in-house for this purpose. Operating instructions were developed, and these were used during the training sessions.

I am sure that the main reason for the success of the implementation of computer control was the fact that we, as a company, purposely involved the workforce at a very early stage.

During 1987 reactions were run by operators on the converted reactor station. The control program was extensively enhanced to reflect operational experience. Results exceeded expectations, and reactions carried out under computer control were much more consistent with regard to the measured process parameters, than had been the case under manual control.

What was most interesting was that initial operator scepticism had changed to enthusiasm, and they were actually asking the company when computer control would be installed on all the reactor stations.

By the end of 1987, computer control had been installed on all the reactor stations. Minimal control software changes were necessary, as this had been designed to control all the reactor stations right from the start.

DTL had now entered the computer control age.

DTL have now been running reactions under full computer control for almost three years. So, I hear you asking, what, if any, have been the benefits?

If we take the first benefit, CONTINUOUS STATISTICAL CONTROL.* By introducing computer control, all the process control parameters are kept within much tighter bands, and corrective action is automatically taken if a parameter exceeds a pre-programmed value. The computer is continuously monitoring instrument information and making adjustments as frequently as required. If problems occur with drifts in product quality, the reaction process can now be discounted as the direct cause as there is an assurance that the process is being controlled to known parameters. Therefore, effort can be directed at other process areas. This benefit has saved DTL many man hours of problem investigation time, and is a strong argument in itself for introducing computer control.

REPEATABILITY.** The same control setpoints and control logic are applied time after time by the computer to the reaction process. The computer does not know that it is shift changeover time or that it is Monday morning. Differences in characteristics between reactor stations become more marked as the level of control improves. It is even possible to see when the fuel/air ratio on a particular gas burner needs adjusting. Diagnostic routines have been incorporated into the control program that measure the health and reliability of the instrumentation and, in some cases, can compensate for errors. One example of this is the measurement of TTC flow rate. This is measured in two ways, one directly with a flow meter and the other by calculating the average flow rate over a period, by looking at the weight of TTC fed in. The integrated TTC flow rate over the period can be compared to the actual weight of TTC fed in, and an adjustment to setpoint made.

---

* Fig. 9

* *   Fig. 10

REDUCTION IN PROCESS VARIABILITY.* There are many process variables, and I do not want to comment on all of them here. In this slide, I have tabulated some of them. I have compared the characteristics of two populations of reaction batches consisting of about 200 batches each. One population is taken from 1984 when there was no computer control and the other from 1990 when there was full computer control. For process confidentiality reasons, I am unable to give values for the means of each population, but I can give the standard deviation of the means expressed as a percentage. Where the variable is a control variable, this is indicated on the right hand side of the table. As you can see, the variability of the means has been significantly reduced in all cases, even for process variables that are not being directly controlled.

CONTROLLED PROCESS DEVELOPMENT.** Incorporated into the control program is a table of about 50 parameters associated with the control of the process. Each reaction station has its own table of values. During normal production, each table is identical for all the reactor stations, and therefore, all reactions are carried out using the same control parameters and routines. However, to test different sets of process parameters, the table of values for a reactor station can be changed to permit one reaction to be carried out using non-standard conditions. Facilities ara available to obtain a representative sample from the reaction product, and the resultant quality can be assessed. All such work would of course, be covered by appropriate documentation and traceability records to cover aerospace requirements.

---

* Fig. 11

* * Fig. 12

VERSATILITY AND EASE OF MAINTENANCE.* The control program in use today has changed significantly from that first used in 1986. New routines have been added and logic has been modified. Changes have been relatively easy to implement, as the software has been written in FORTRAN 77, a well established high level scientific and engineering programming language. All changes and enhancements have been made in-house at DTL which, of course, has many benefits. The expertise in FORTRAN programming resides in the Process & Systems Department, which is also responsible for process development. Therefore, the people who know what is required from a process change point of view have also the skills and knowledge to make it happen. Changes can be implemented quickly, without having to instruct another company to carry out the modifications, and then probably finding, that they have not given you what you wanted.

IMPROVEMENT IN PRODUCT QUALITY.** In this slide I have tabulated some of the aspects of quality we measure in the finished titanium granule product. I should point out that improvement to reaction process control does not account for all of the product quality improvement as we have made improvements in other areas. However, we believe computer control on the reaction process has made the most significant improvement to quality. The finished product quality comparisons relate to the reaction batches that were the subject of the previous slide. Again, for process confidentiality reasons, I cannot give you actual values, but instead, can give improvements in mean ppm values.

As you can see from the slide the mean values for chloride, iron, oxygen and Vickers hardness between 1984 and 1990 have reduced by 300 ppm, 160 ppm, 100 ppm and 11 points respectively.

---

* Fig. 13

* * Fig. 14

IMPROVEMENT IN PRODUCT QUALITY VARIABILITY.[*] This slide shows the reduction in product quality variability for the same batches shown in the previous slide.

As you can see, the standard deviation expressed as a percentage of the mean value of the populations for chloride, iron, oxygen and hardness is less for batches produced in 1990 than for those produced in 1984 indicating an improvement in product quality variability. Bear in mind that the percentages for 1990 are based on a lower mean value, and therefore, relative to 1984, there has been a very significant improvement in product quality variability.

PRODUCTIVITY.[*]* The average reaction time for 1990 reactions is about 8% less than for 1984 reactions. Also, the number of reactor stations an operator can control has increased very significantly due to the introduction of computer control.

COST SAVINGS. The average energy usage for 1990 reactions is about 10% less than for 1984 reactions. However, the largest cost saving is in the reduction of effort spent in reworking cut of specification batches. The level of rework in 1984 approached 30% at times. In 1990, the level cf rework has been less than 1%.

---

* Fig. 15

* * Fig. 16

During the last 20 or so minutes, I have tried to give you an idea of how the introduction of computer control of the reaction process was achieved, and some of the benefits we have obtained. At present, DTL is in the middle of a reaction process optimisation programme, made possible by the implementation of computer control. Already we are beginning to see further benefits.

In conclusion, I would like to thank you for your attention and hope that you found my talk interesting. I would also like to express my personal thanks to all those at DTL who made computer control of the DTL reaction process a reality and to the Company for giving permission for me to give this talk.

A.P. MORCOM'S PRESENTATION

"THE DEVELOPMENT OF COMPUTER CONTROL IN TITANIUM SPONGE GRANULEMANUFACTURE" LIST OF SLIDES

(1) SLIDE OF DTL
(2) SLIDE OF PROCESS SCHEMATIC
(3) DATA LOGGING SYSTEM SCHEMATIC
(4) INFORMATION AVAILABLE FROM REACTION DATA LOGGING SYSTEM
(5) MANUAL CONTROL PROBLEMS
(6) COMPUTER - CONTROL DEVELOPMENT STAGES
(7) REACTION COMPUTER CONTROL SYSTEM SCHEMATIC
(8) HUMAN CONSIDERATIONS
(9) CONTINUOUS STATISTICAL CONTROL
(10) REPEATABILITY
(11) REDUCTION IN PROCESS VARIABILITY
(12) CONTROLLED PROCESS DEVELOPMENT
(13) VERSATILITY AND EASE OF MAINTENANCE
(14) IMPROVEMENT IN PRODUCT QUALITY
(15) IMPROVEMENT IN PRODUCT QUALITY VARIABILITY
(16) PRODUCTIVITY AND COST SAVINGS

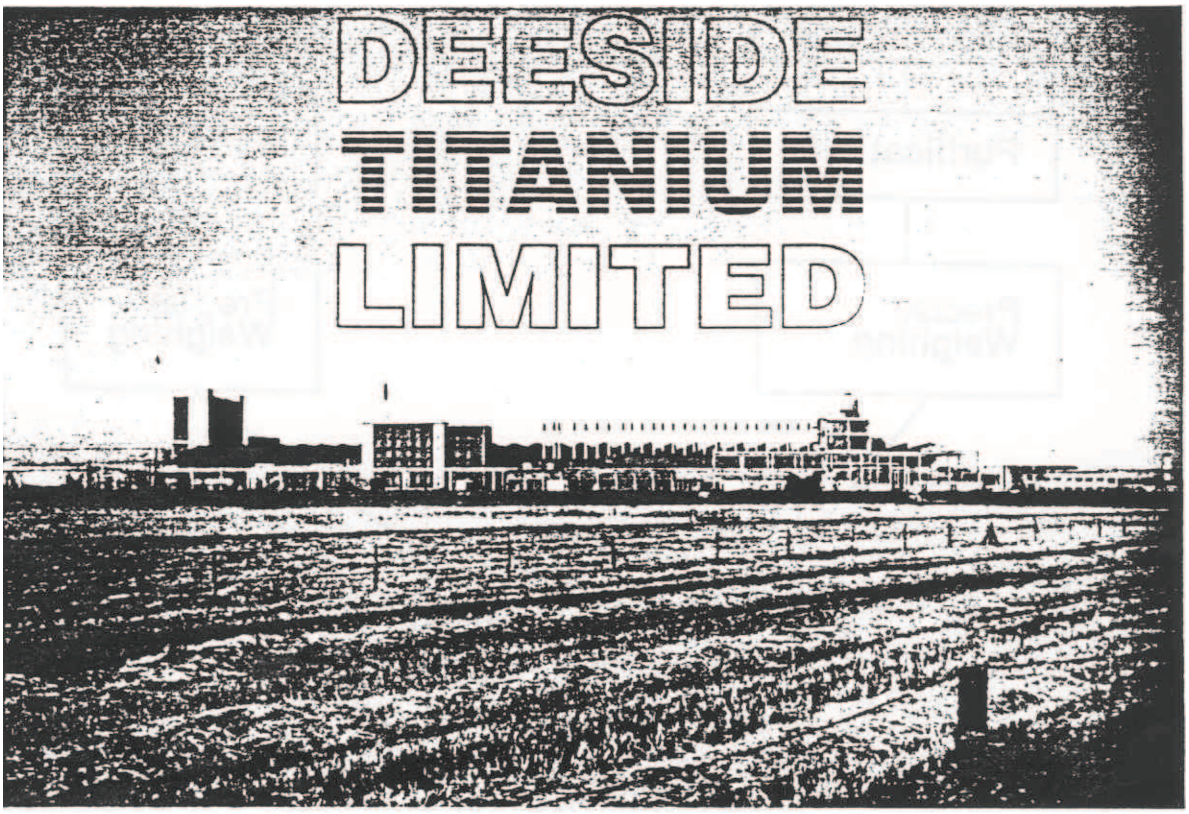


Fig. 1

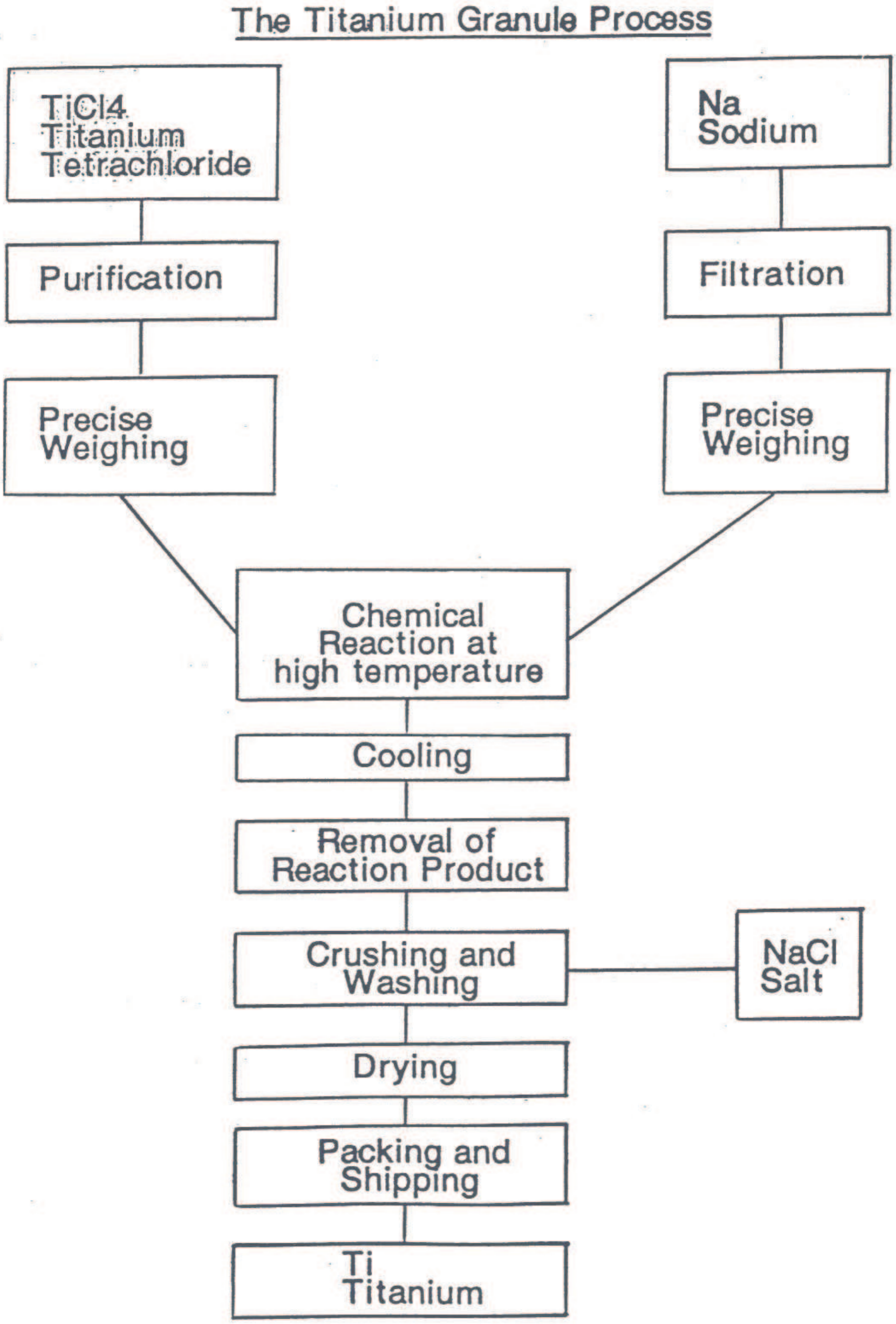

The Titanium Granule Process
TiCl4 Titanium Tetrachloride
Purification
Precise Weighing
Na Sodium
Filtration
Precise Weighing
Chemical Reaction at high temperature
Cooling
Removal of Reaction Product
Crushing and Washing
NaCl Salt
Drying
Packing and Shipping
Ti Titanium

Fig. 2

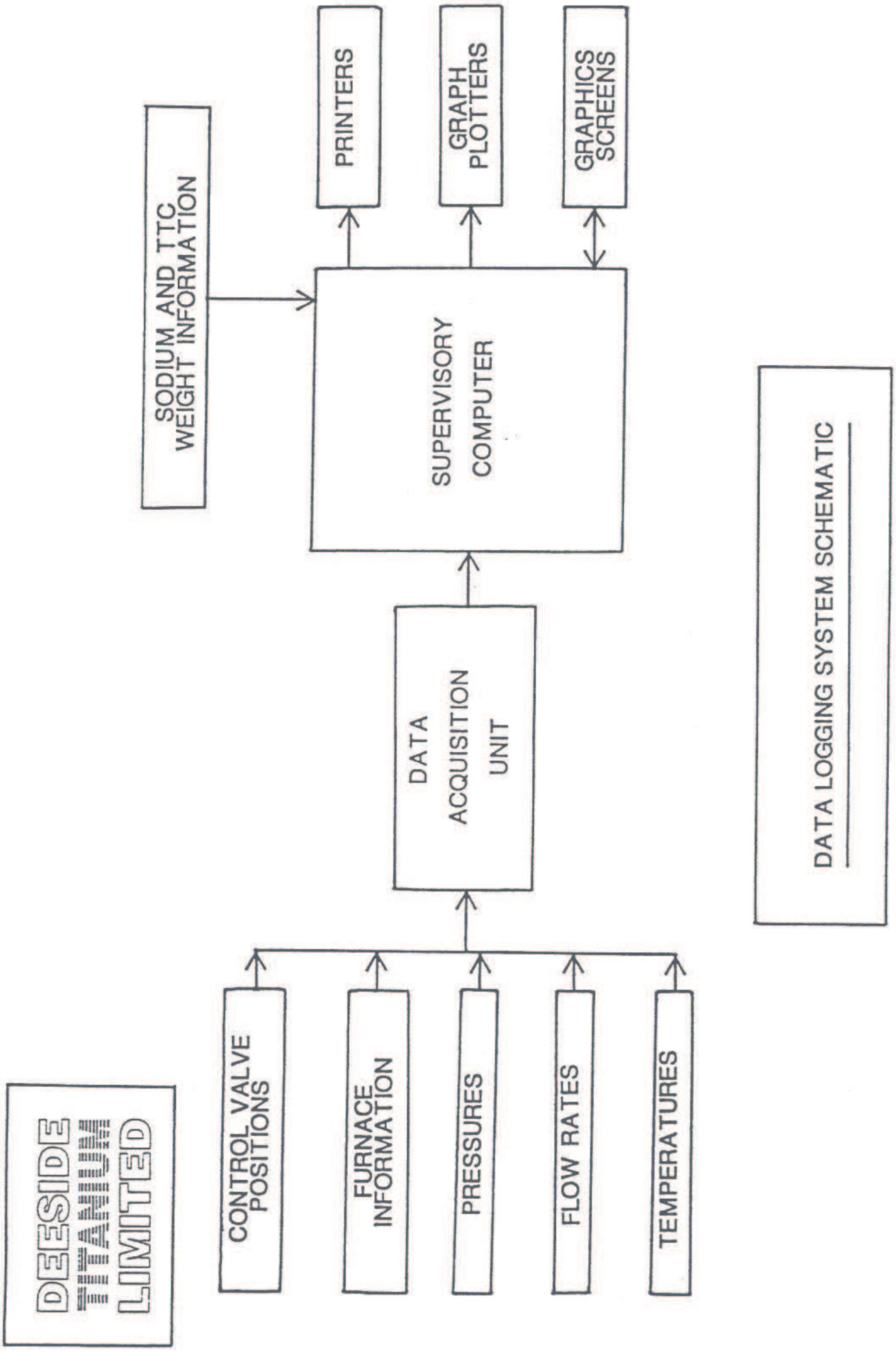

DEESIDE TITANIUM LIMITED
CONTROL VALVE POSITIONS
FURNACE INFORMATION
PRESSURES
FLOW RATES
TEMPERATURES
DATA ACQUISITION UNIT
SUPERVISORY COMPUTER
SODIUM AND TTC WEIGHT INFORMATION
PRINTERS
GRAPH PLOTTERS
GRAPHICS SCREENS
DATA LOGGING SYSTEM SCHEMATIC

Fig. 3

INFORMATION AVAILABLE FROM REACTION DATA LOGGING SYSTEM

CUSUM

Exception Reports

Printout of all logged data

Bespoke statistical routines and reports

Process Variable Trends and Correlations

Historical and On-line graphical displays and plots

Compliance with Statistical Process Control criteria

Fig. 4

MANUAL CONTROL PROBLEMS

Interpretation of Instructions

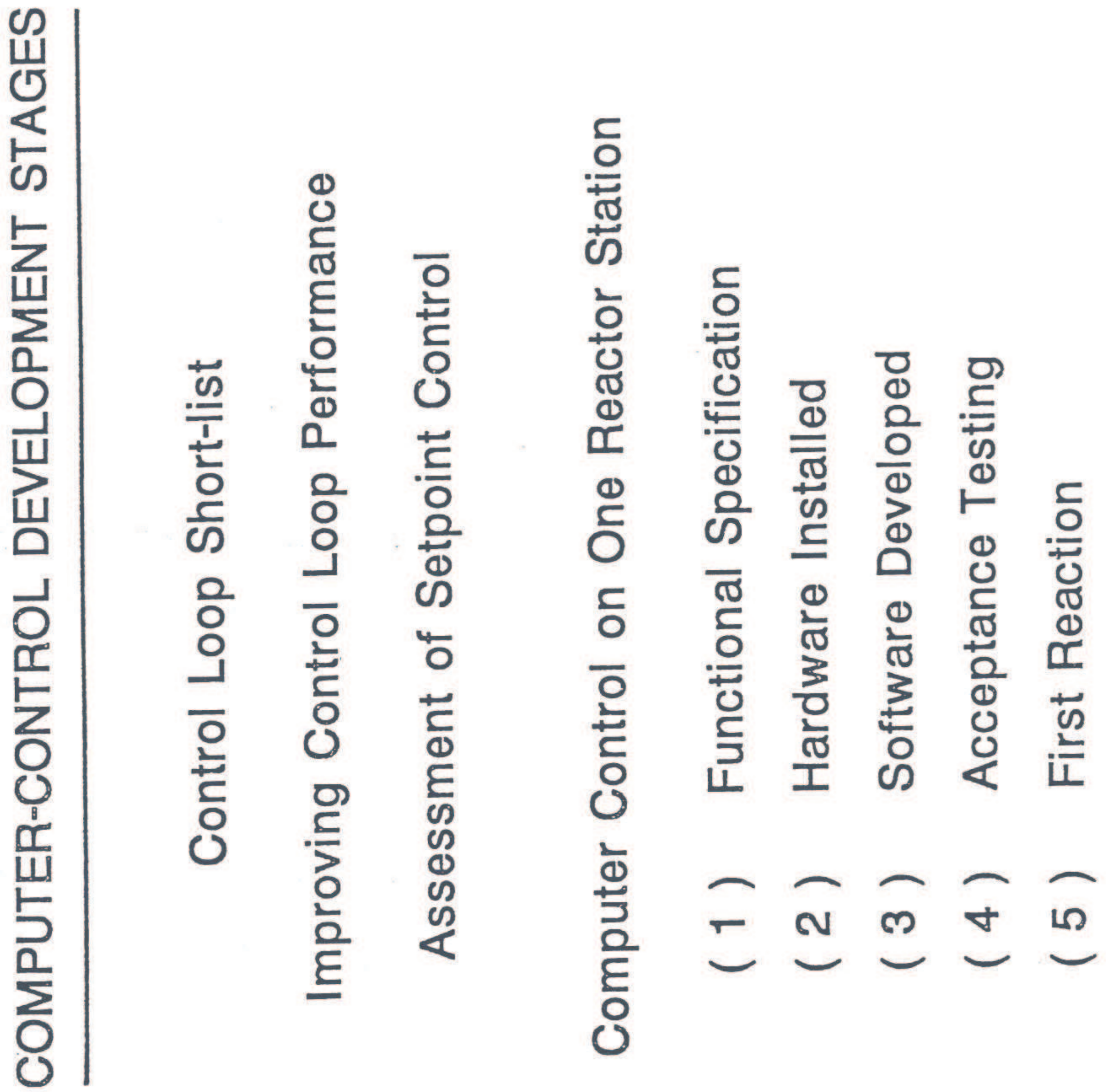
Easier Equals Better

Shift Change-over

Large Infrequent Adjustments

Consistent Process Development

Fig. 5



COMPUTER-CONTROL DEVELOPMENT STAGES

Control Loop Short-list

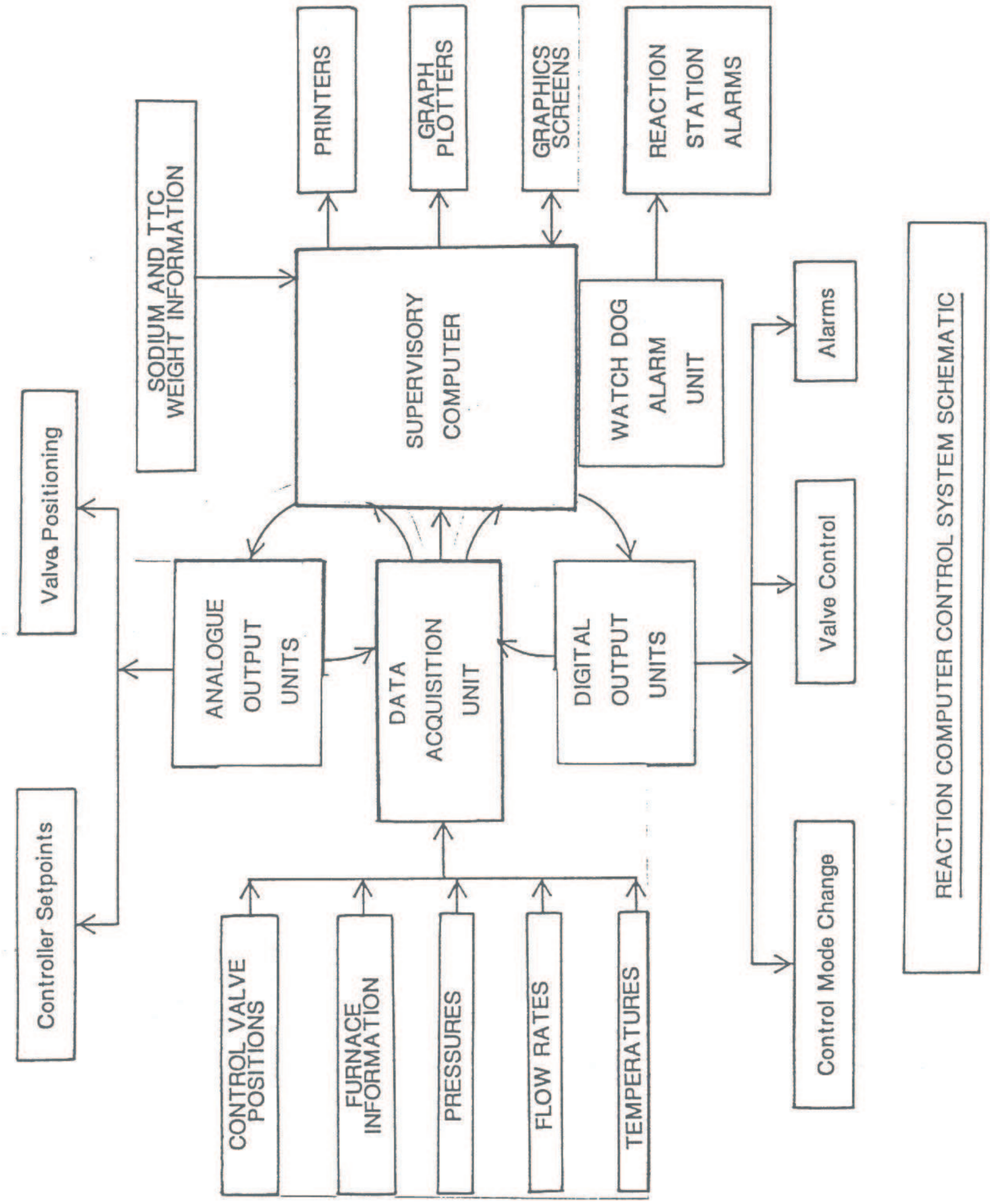
Improving Control Loop Performance

Assessment of Setpoint Control

Computer Control on One Reactor Station

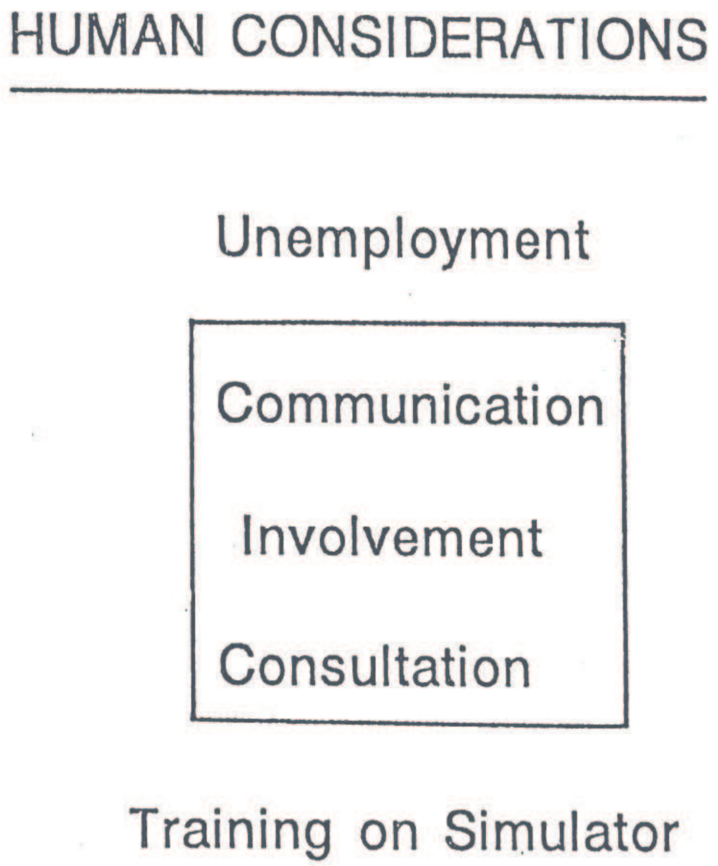
(1) Functional Specification
(2) Hardware Installed
(3) Software Developed
(4) Acceptance Testing
(5) First Reaction

Fig. 6



REACTION COMPUTER CONTROL SYSTEM SCHEMATIC

Fig. 7



HUMAN CONSIDERATIONS

Unemployment

Communication

Involvement

Consultation

Training on Simulator

Fig. 8

CONTINUOUS STATISTICAL CONTROL

Parameters :- Kept within tighter bands

Assurance :- Controlling to known parameters

Saving :- Problem investigation time

Fig. 9

REPEATABILITY

Same control setpoints and logic

Highlights characteristics of Reaction Stations

Diagnostic routines can cope with errors

Fig. 10

REDUCTION IN PROCESS VARIABILITY

		PROCESS VARIABLE							
		TEMPERATURE	REACTION TIME				FUEL GAS USED		SINTER FACTOR
			TOTAL	START	BULK	FINISH	BULK	TOTAL	
STANDARD DEVIATION EXPRESSED AS A PERCENTAGE OF THE POPULATION MEAN	1984	0.7	6.0	9.8	6.3	17.7	28.5	16.3	48.3
	1990	0.1	2.8	7.7	2.8	6.7	14.6	11.1	14.0
RATIO OF 1984 TO 1990 STANDARD DEVIATION		7.0	2.1	1.3	2.3	2.6	2.0	1.5	3.5
CONTROL VARIABLE		YES	NO	NO	NO	NO	NO	NO	NO

TABLE SHOWING COMPARISON OF PROCESS VARIABILITY BETWEEN 1984 AND 1990 REACTIONS

Fig. 11

CONTROLLED PROCESS DEVELOPMENT

Parameters can be set individually for each Reaction Station

Fig. 12

VERSATILITY & EASE OF MAINTENANCE

Software written in FORTRAN 77

Well established "High-level" scientific/engineering programming language

In-house programming skills

Fig. 13

IMPROVEMENT IN PRODUCT QUALITY

CHLORIDE	300
IRON	160
OXYGEN	100

Note: All figures in parts per million

VICKERS HARDNESS	11HV30

TABLE SHOWING COMPARISON OF PRODUCT QUALITY BETWEEN 1984 AND 1990 OUTPUT

Fig. 14

IMPROVEMENT IN PRODUCT QUALITY VARIABILITY

	Standard Deviation of Population as a percentage of the Mean	
	1984	1990
CHLORIDE	13.0	11.4
IRON	37.7	27.7
OXYGEN	14.4	9.6
HARDNESS	5.1	3.8

COMPARISON OF PRODUCT QUALITY VARIABILITY BETWEEN 1984 AND 1990 OUTPUT

Fig. 15

PRODUCTIVITY & COST SAVINGS

Reaction times 8% shorter

One operator can control more reactions

Energy usage 10% less

Rework down from 30% to <1%

Fig. 16

"OPERATING BEHAVIOUR OF AERONAUTIC TITANIUM COMPONENTS"

Francesco Botré

Reparto Chimico Tecnologico
Divisione Aerea Studi, Ricerche e *Sperimentazioni.*
Aeroporto "M. De Bernardi ", 00040 Pratica di Mare - Roma -

Titanium and titanium alloys are nearing the end of their fourth decade of commercial and industrial service. Application of these material's in many different fields is becoming broader and broader year after year. In spite of such a growth, the sphere of applications in which titanium and its alloys have found the maximum employment is still that of aerospace engineering. This is mainly due to the peculiar characteristics of titanium, summarized in figs.1-2, which perfectly match with the need of aerospace technology. In this regard, fig. 3 shows the percentage of titanium, as compared with other elements, in the overall composition of some modern aircraft.

PECULIAR CHARACTERISTICS OF TITANIUM

- Density: 60% of that of steel
- Cost: 130% of that of stainless steel
- Modulus: 55 % of that of steel
- Corrosion resistance higher than that of a stainless steel in most environments
- Forgeable by standard techniques
- Easily castable (although investment casting is preferred)
- Suitable to powder metal technology processing
- Highly joinable (fusion welding, brazing, adhesives, diffusion bonding, fasteners)
- Formable and readily machinable
- Available in a wide variety of types and forms

Fig. 1

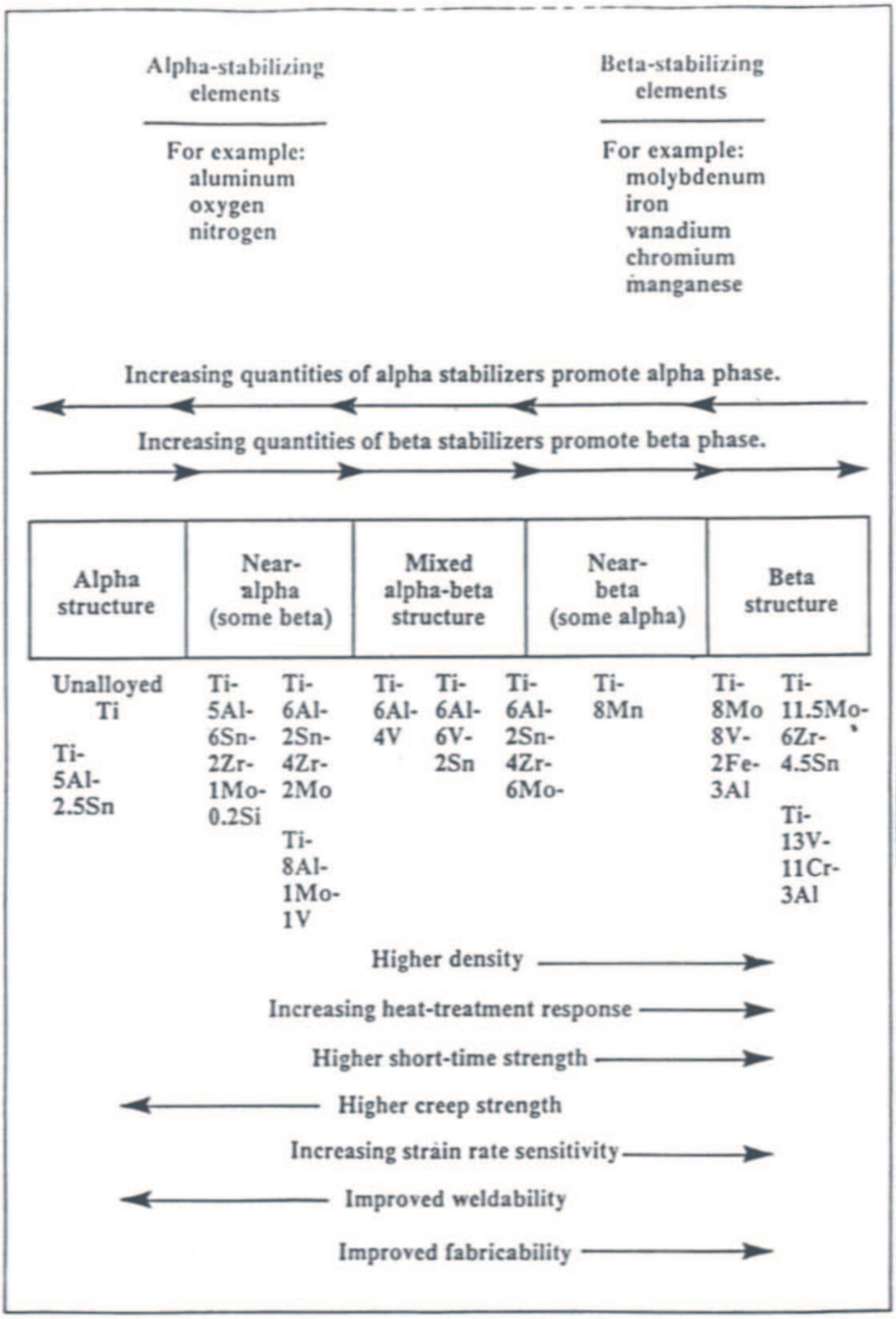


Fig.2: Schematic representation of relationship between structure and technological properties for titanium and titanium alloys.

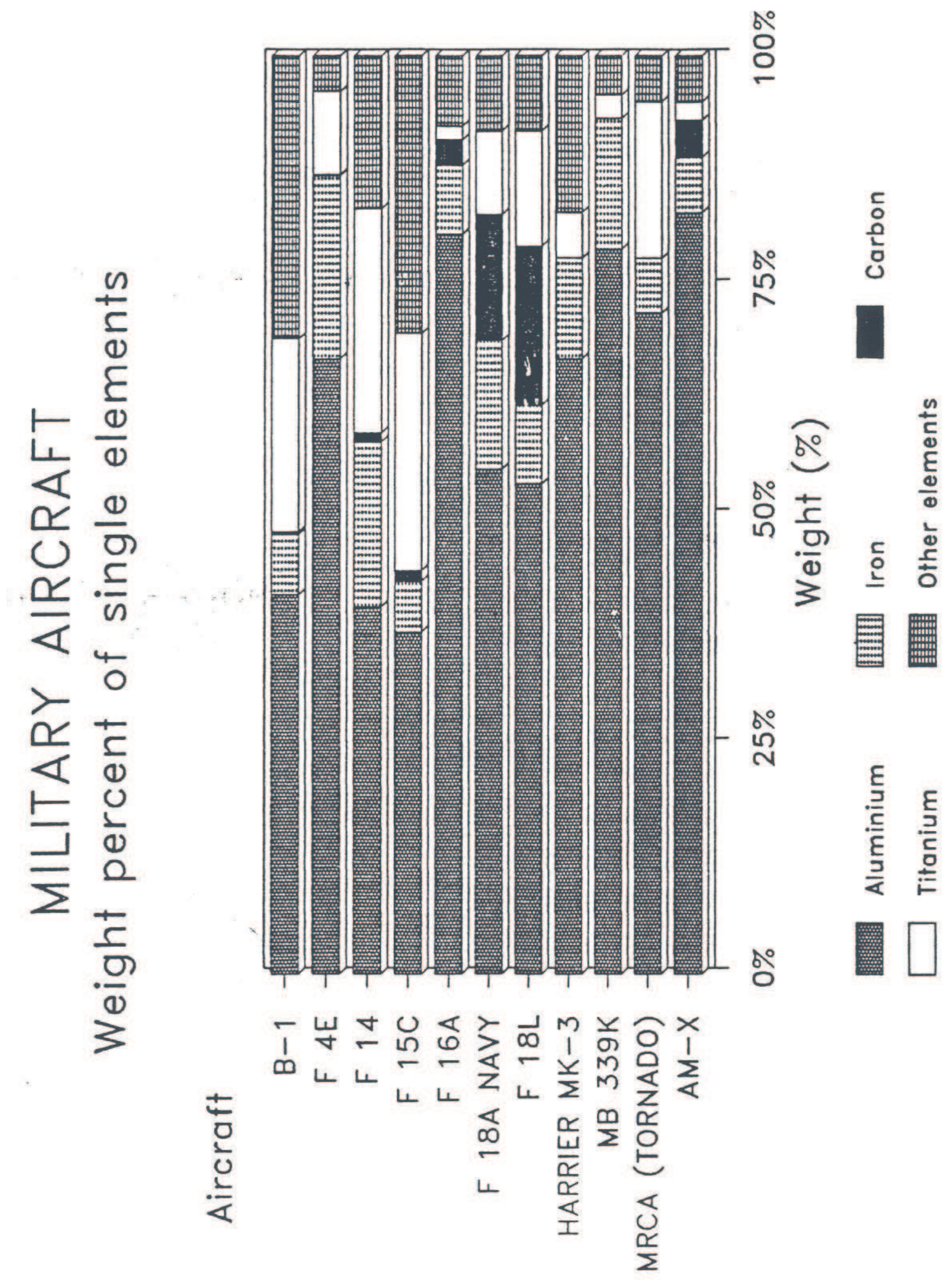

MILITARY AIRCRAFT
Weight percent of single elements
Aircraft
B-1
F 4E
F 14
F 15C
F 16A
F 18A NAVY
F 18L
HARRIER MK-3
MB 339K
MRCA (TORNADO)
AM-X
0%
25%
50%
75%
100%
Weight (%)
Aluminium
Titanium
Iron
Other elements
Carbon

Fig. 3

The purpose of the present investigation is focused on the evaluation of the operating behaviour of titanium components of military aircraft, as detected by the Chemical Research Laboratories of Italian Air Force ("D.A.S.R.S. - Reparto Chimico-Tecnologico", up to 1985 "Direzione Laboratori A.M."), on the basis of all investigations carried out between 1975 and 1990.

The results of the present review are therefore limited to all those failures and inconvenient which were not merely solved at the level of the Peripheral Bodies, but that instead required deeper and more detailed investigations.

Fig. 4 shows the main stages of the general procedure to be followed in failure investigation.

It appears clear that every single stage has to be modulated according to the specific failure under examination. It follows that there is not a step that is a *priori* more important than another: a procedure or a testing that can be definitive to clarify the fracture mechanism of a particular failure can be trivial for another and *vice versa.* It is only the experience that can suggest what step can be critical and what step could be passed by.

The following four cases show how all these guidelines. are applied practically.

GENERAL PROCEDURE IN FAILURE ANALYSIS

- Collection of background data and selection of samples
- Preliminary examination of the failed part:
  visual examination and record keeping
- Nondestructive testing
- Selection, identification, preservation and/or cleaning
  of all specimens
- Macroscopic examination and analysis of surface phenomena:
  fracture surface
  secondary cracks
- Microscopic examination and analysis
- Selection, preparation, examination and analysis of
  metallographic sections
- Chemical analyses: bulk
  local
  surface corrosion products
  deposits or coatings
- Mechanical testings
- Determination of failure mechanism
- Analysis of fracture mechanics
- Testing under simulated service conditions
- Analysis of all the evidence, solving of contradictions,
  formulation of conclusions (including recommendations)
- Final report

Fig. 4

1st Case: (commercially pure Ti)

The defects had been revealed by liquid-penetrant inspection, and localized below the thread of all the three forks (see fig. 5). All the defects were ascribed to the rolling process. The validation of the hypothesis came from the examination of the metallographic specimen (fig. 6), which shows the orientation of the grains around the crack. This kind of defect is not particularly dangerous, but nonetheless it was taken out to avoid any misinterpretation in following inspections.

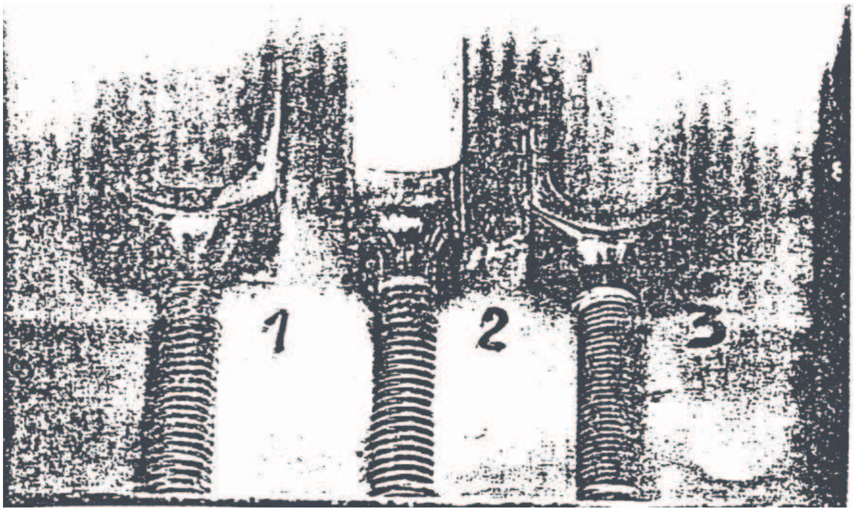


Fig. 5

Fig. 6

2nd Case: (Ti-6Al-4V alloy)

The fracture, localized at the groove of the fourth lowest thread (fig.7), was produced by the growth of a fatigue crack, whose initiation was in the correspondence of sharp tool marks, shown in fig. 8, which caused also the erosion of the other three threads. The SEM examination of the fracture surface was also useful to record the typical fatigue striation (fig.9). Fig.10 shows the microstructure of the material.

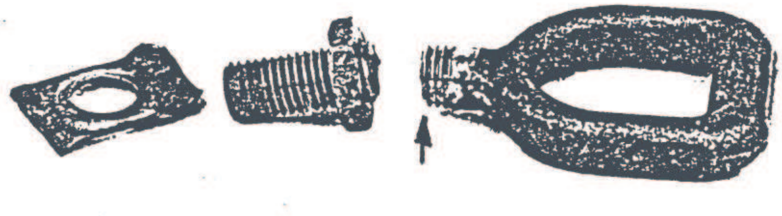


Fig. 7

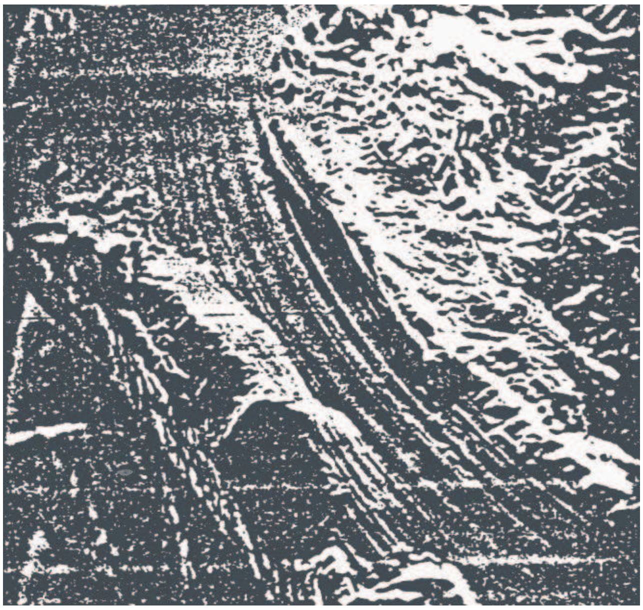


Fig. 8

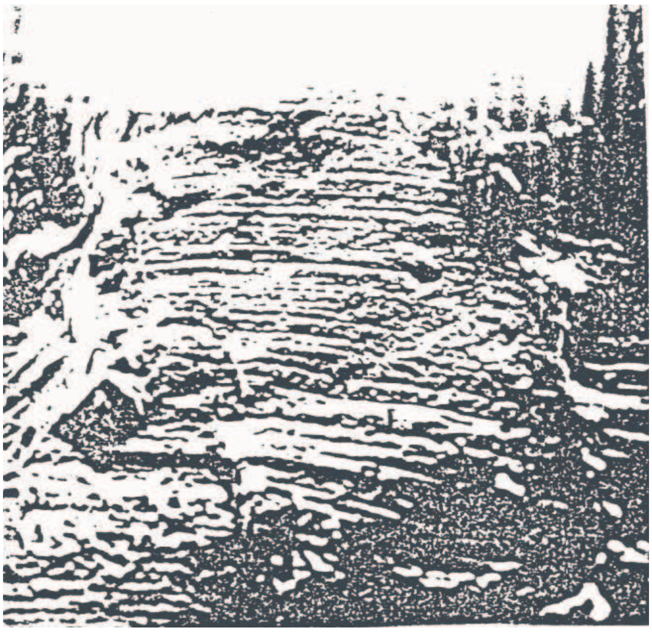


Fig. 9

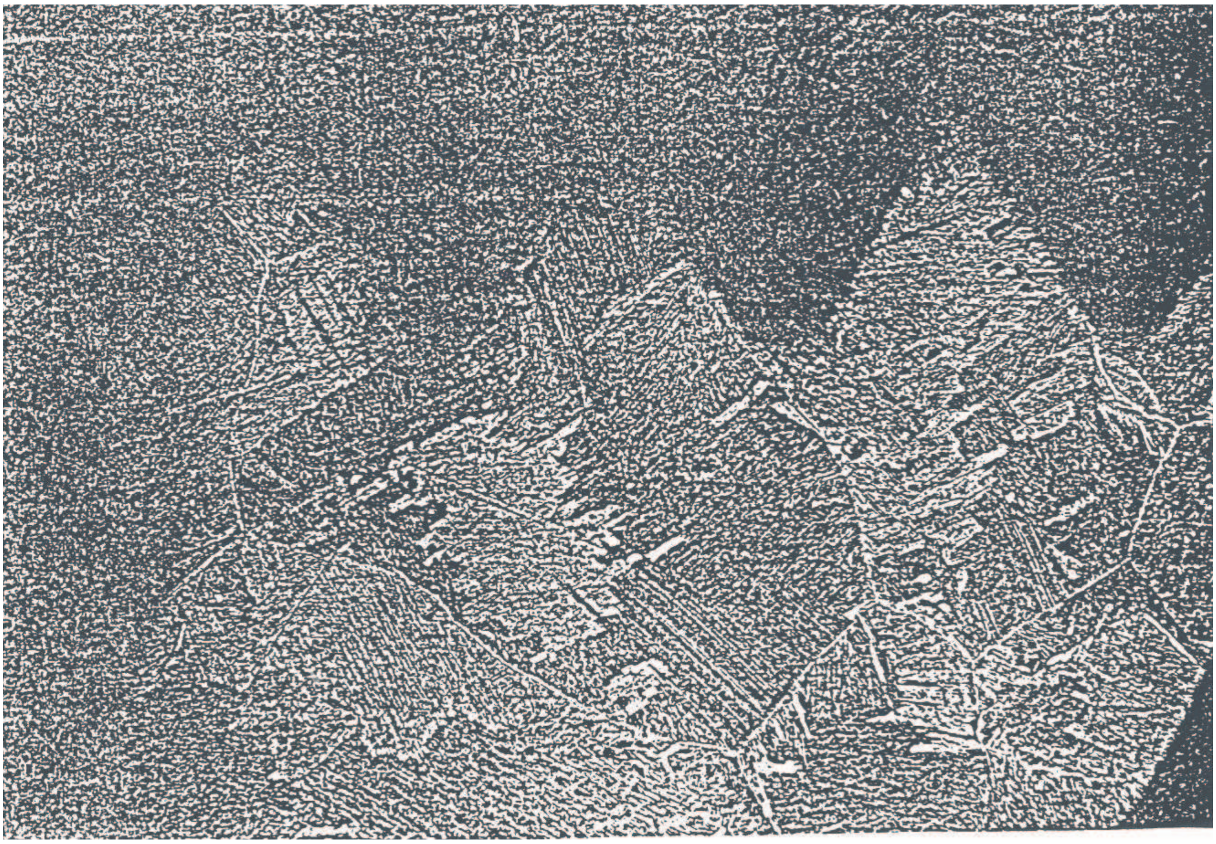


Fig. 10

3rd Case: (Ti-6Al-4V alloy)

This component of a transport aircraft was suspected to be cracked in correspondence of the arrows of figs. 11-12. A careful examination by a stereoscopic microscope, and, more important, the examination of the metallographic section (figs. 13-14) allowed us to exclude the presence of crack, and to ascribe the surface defect to the action of a tool.

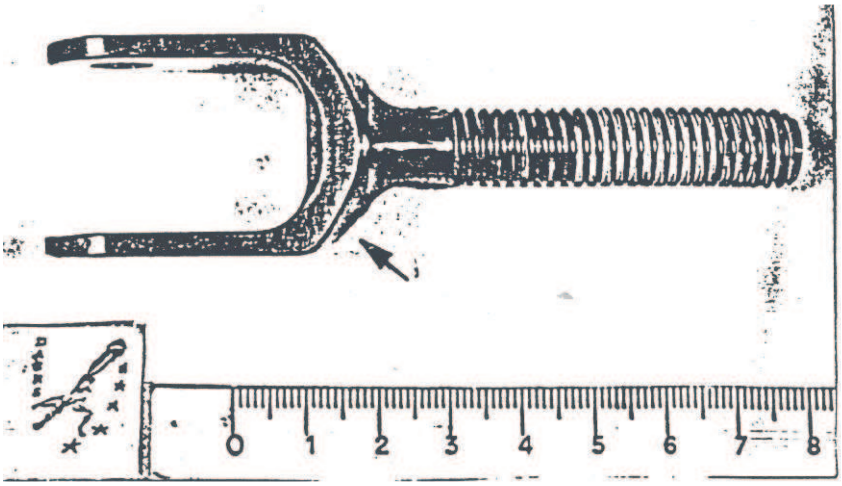


Fig. 11

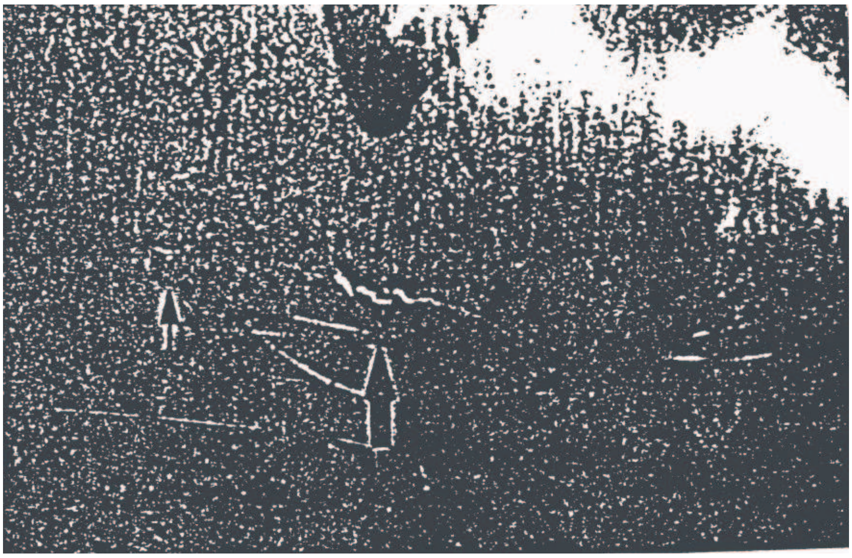


Fig. 12

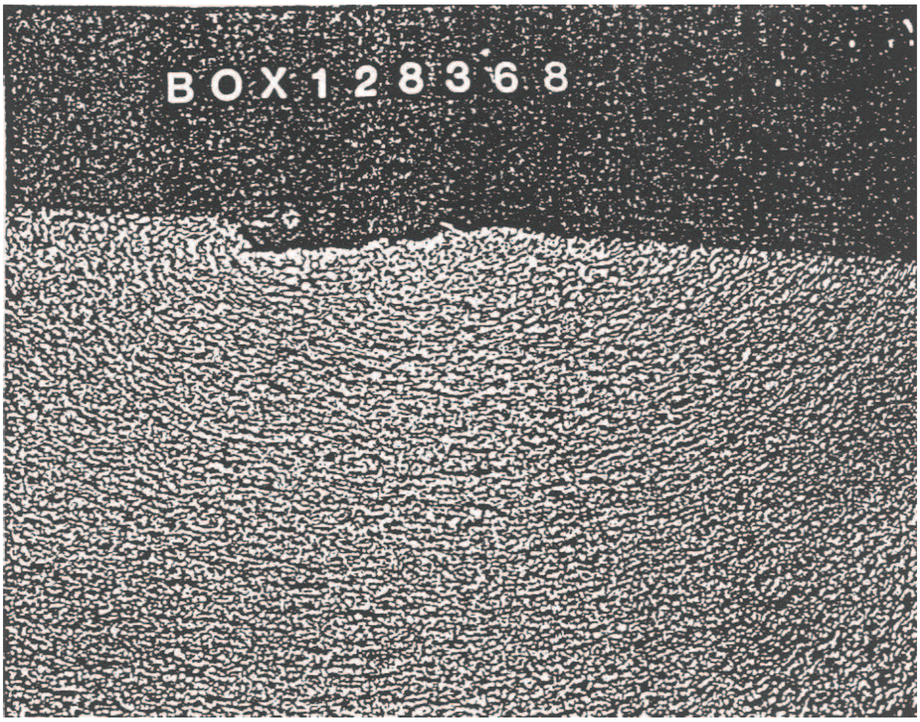


Fig. 13

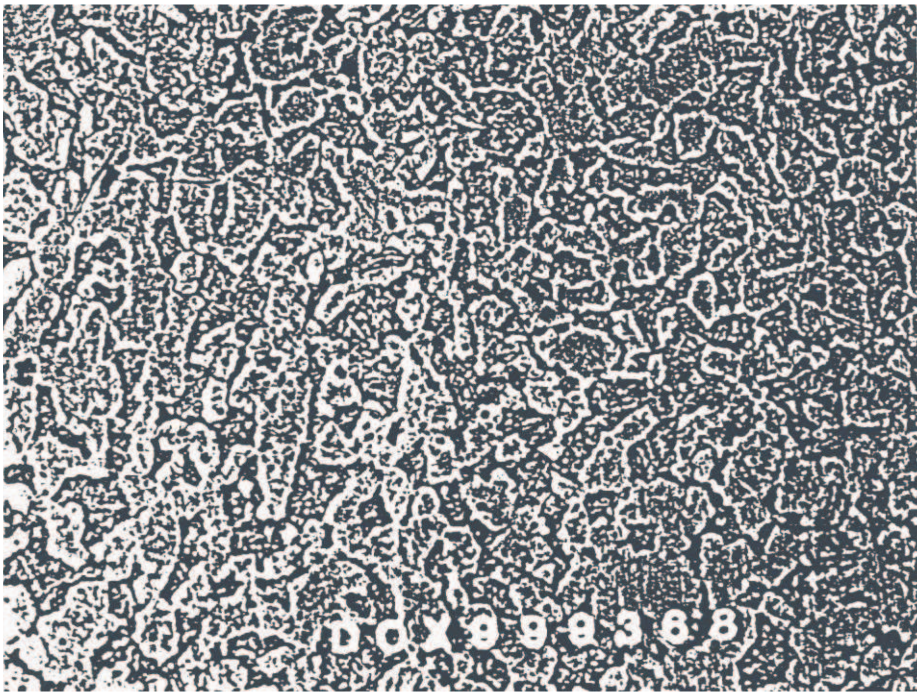


Fig. 14

4th Case: (Ti-6Al-4V alloy)

The failure of the structure shown in fig.15 began with the fracture of the posterior hinge (fig.16), being the fracture of the anterior hinge due to tension, with a component of torsion, overload (fig.17). Therefore the anterior hinge has been thoroughly examined with different techniques. On the fracture surface (fig.18) have been identified the typical striations due to the growth of a fatigue crack (figs.19-20): the cyclic loading is in this case to be ascribed to vibration, deriving from the imperfect closing of the panel. This inconvenient is a direct consequence of the too strict tolerance limits taken into account in the designing of this particular: it follows that even a lightly defective assembly can be responsible of the previously described vibrations.

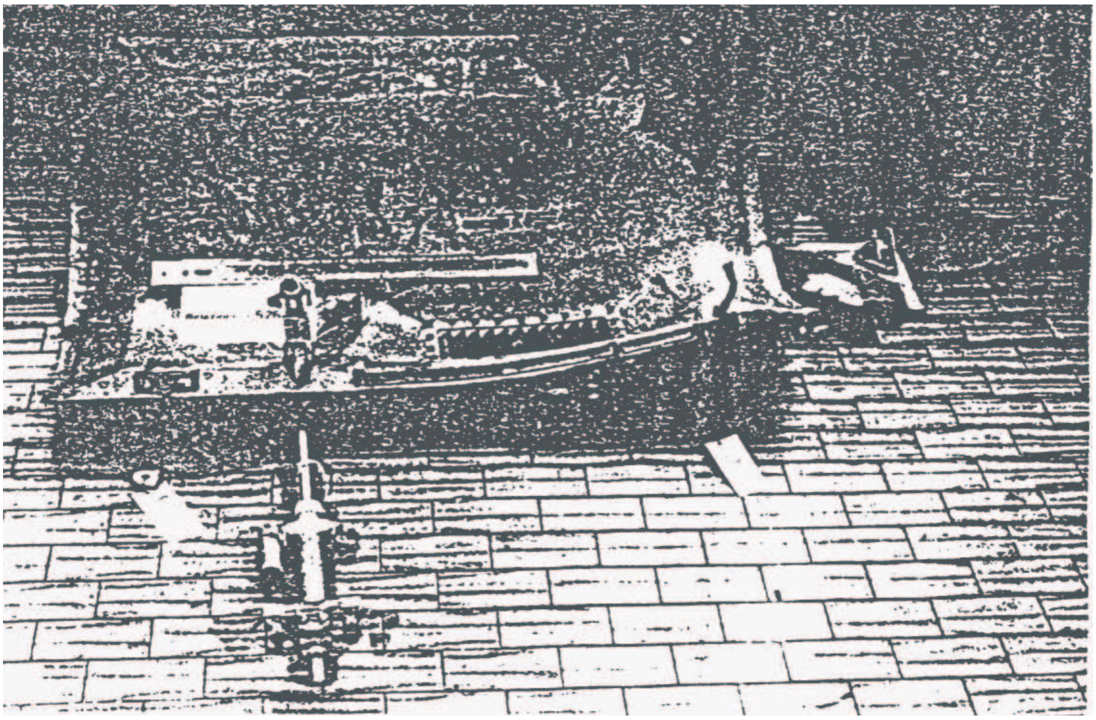


Fig. 15

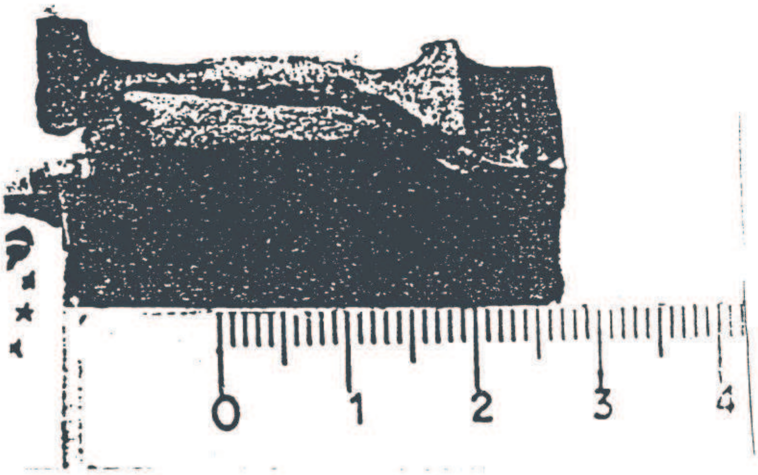


Fig. 16

Fig. 17a

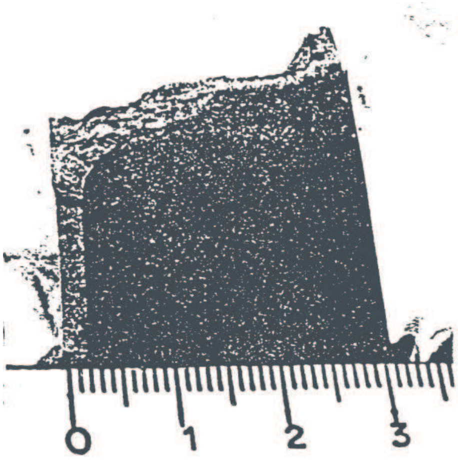


Fig. 17b

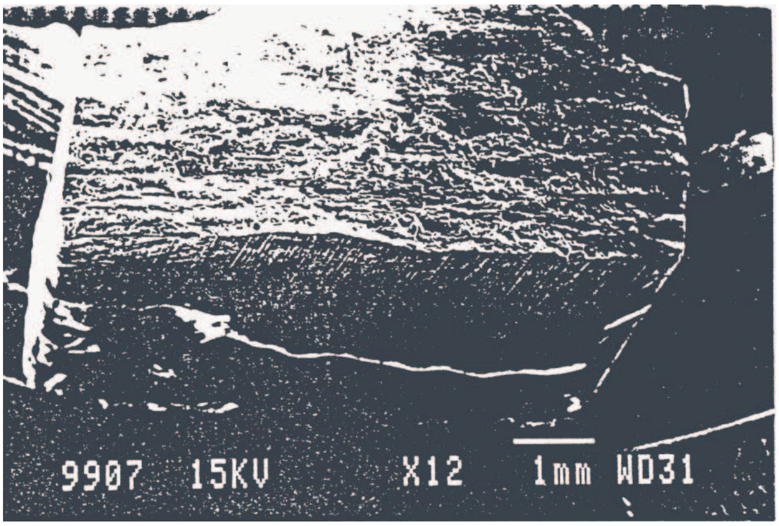


Fig. 18

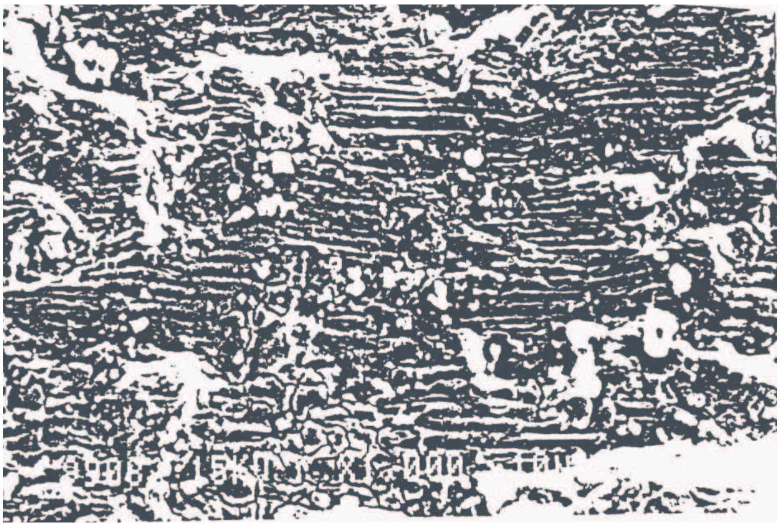


Fig. 19

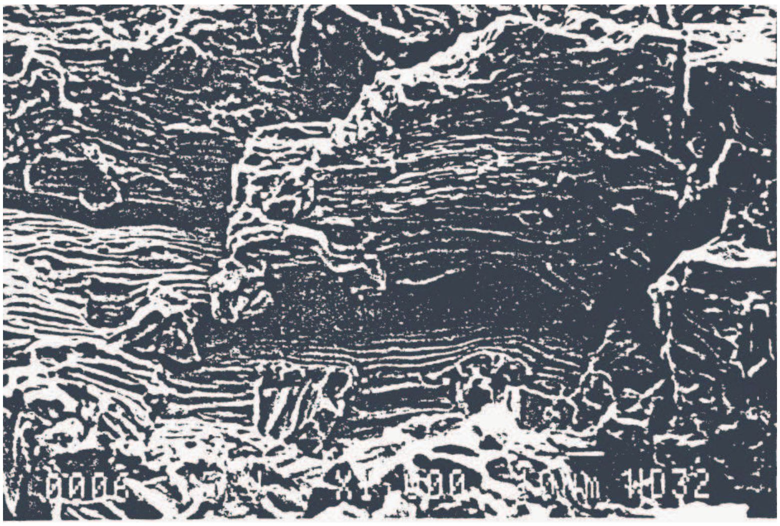


Fig. 20

Conclusions

Some relevant indications can be evinced tram the data here presented.

First of all, it is evident that the number of failures involving titanium components is extremely small; moreover it appears even smaller if compared to the number of failures of other metallic components.

In addition to this, it has to be taken in the due account that the present study is limited to military aircraft, whose operating conditions are generally extremely severe, and cause stress concentrations definitely higher than those acting on civilian aircraft.

Finally, it is worthwhile to highlight that all failures here presented and discussed are induced by factors that are not directly concerned with a reduction of the technological properties of the material; indeed, causes of failure have to be inquired into design errors, detective production and incautious and/or improper use of the component under investigation.

In conclusion, the present results once more confirm the extreme suitability of titanium and titanium alloys for aerospace applications.

Acknowledgement:

The author is extremely grateful to Dr. Giuseppe Magnani, for his precious assistance in the realization of the present work.

References

1. "Titanium and Titanium Alloys -Source Book" M.J.Donachie Jr. (Ed.), ASM, 1982 (4th printing, 1987)
2. "Titanium: a Technical Guide" M.J.Donachie Jr. (Ed.), ASM, 1988
3. "Metals Handbook, 9th Edition, vol.11: Failure Analysis and Prevention" ASM, 1986
4. G.Oddone "Guida all' interpretazione delle caratteristiche morfologiche delle superfici di frattura al microscopio elettronico a scansione" Ragno Editore, Roma, 1981.

Powder Titanium Fabrication Processes, Economics and Market Applications

by

Michael J. Trzcinski

Presented at the Sixth International Meeting on Titanium

23 November 1990 Turin - Italy

Michael J. Trzcinski
Advanced Materials Management
2567 Fenwick Road, Cleveland, Ohio 44118 U.S.A.
Telephone: 216 932 0104
Telefax: 216 371 0835

Powder Titanium Fabrication Processes, Economics and Market Applications

Purpose: The purpose of this paper is to provide information showing how products can be made successfully from powder titanium, and identify issues associated for use of the material. This information is given to help companies engaged in powder titanium supply, fabrication, and end use better focus their efforts. This paper will

1. Describe the major fabrication technologies, and some properties being achieved.
2. Discuss the economics of selected processes.
3. Present products made from these processes that are a commercial success, and describe potential applications.

Much of this information is based on the experiences obtained by the author while General Manager of Clevite's Titanium Business.

Powder Titanium, Manufacturing Processes and Properties

Powder metal manufacturing methods are used successfully for many materials in high volumes. The success of the powder metal industry in general required the effort of material suppliers, equipment manufactures, powder metal parts producers, and design engineers. A great deal of the infrastructure developed for the powder metal industry is available for use in manufacturing powder metal titanium components. Fabricating titanium products from powder metal methods has had limited success in terms of the number of commercial product applications. Why?

The major manufacturing methods presently developed for powder titanium can be grouped into the following major categories:

- Commercially pure titanium.
- Blended elemental titanium.
- Prealloyed titanium and hot isostatically pressed.
- Prealloyed titanium other.

Titanium powders available to be used are sponge fines, hydride-dehydride powder, and prealloyed powder. Sponge fines used for titanium parts fabrication have been those produced from the sodium reduction process for making sponge. These sponge making processes produce 7-12 percent of their material in a particle size -100 mesh suitable for powder metal parts. The cost of sponge fines is less than half the cost of wrought titanium. The quality of the material for fatigue critical applications is not acceptable for most applications. However, fatigue endurance limits are achieved. Of all titanium powder used in the world for structural parts, titanium sponge fines made from the sodium reduction processes represent the largest commercial success. See table 1.

In an effort to provide higher quality titanium powder, the hydride-dehydride process was developed to produce powder from wrought alloy titanium material. The price of these powders is 3 to 5 times higher than wrought titanium.

Processes were developed to produce prealloyed titanium powder in a spherical shape. The powder produced is of high quality as is the costs which are 4-5 times more expensive than wrought titanium. In addition, the manufacturing methods to use spherical titanium powders is the most expensive of all powder metal fabrication processes.

Powder morphology has a great affect on the economics of a finished part. Morphology determines the type of manufacturing process which can be used, and the properties attainable. In addition, the quality and availability of titanium powder can help or hinder the commercial use of components made with powder titanium.

Titanium based powder can take on one of two powder shapes: irregular or spherical. *The first shape, an irregular or a circular shape,* allows a compact to be formed by:

- Mechanical die pressing.
- Cold isostatic pressing.
- Plasma Spraying.
- Direct powder rolling.
- Hot isostatic pressing (HIP).
- Extrusion.

The first three methods are used on a routine basis for production of parts. The economics of these methods have been accepted by design engineers. The first two methods represent cost reductions versus wrought metallurgy. Plasma spraying offers unique processing capabilities.

A spherical shape titanium powder produced by gas atomization or rotating electrode method can not be fabricated by traditional high volume powder metal methods such as mechanical die pressing, direct powder rolling or cold isostatic pressing. The particles can not be molded with sufficient green strength for handling prior to sintering. Spherical titanium powders can be used by:

- Coatings Plasma Sprayed, and Sintered.
- HIP.
- Powder cloth process.

The irregular shape titanium powder has demonstrated unique metallurgical capabilities by allowing a sintered density greater than 95 percent to occur. In the case of one process, MR-9, 99 percent density is achieved after vacuum sintering. Blending an irregular shaped master alloy with irregular shaped titanium will result in a rapid diffusion of the master alloy into the titanium during vacuum sintering, and result in densities greater than 96 percent. The state of the art is to use minus 100 mesh titanium powder with a master alloy of minus 400 mesh (40) micron size. After blending, parts are pressed to 85 percent green density and vacuum sintered. In the case of commercially pure titanium a 85 percent green density will sinter to 92 percent.

Commercially Pure Titanium Processes

The manufacturing methods used for commercially pure titanium products are the same methods used for blended elemental titanium. The difference is that no master alloys are added. The process for making parts from titanium powder involve cold pressing the powder into a shape (green part) and then vacuum sintering the part. Standard powder metal equipment used for fabrication include mechanical die presses, cold isostatic presses and rolling mills. Low cost sponge fines processed by high throughput powder metal equipment produces parts that are used mainly for the chemical resistant properties of titanium. Fasteners and filters are routinely produced by these methods. Specialty products such as knife handles and watch cases are made from C.P. titanium powder.

Blended Elemental Titanium

Blended elemental titanium technology developed from the availability of low cost titanium powder, sponge fines, and the availability of high throughput standard powder metal equipment. Two companies started work on blended elemental titanium technology in the 1960's and pioneered the technology into commercial product applications. These companies are Clevite Industries, and Dynamet Technologies. In addition to these companies The Materials Research Laboratory at Wright Patterson AFB sponsored, funded and evaluated material from these two companies.

Blended elemental titanium is the blending of a irregular shaped titanium powder with a master alloy powder. To make a Ti-6Al-4V alloy, a master alloy consisting of 60 percent aluminium and 40 percent vanadium is blended in proper proportion to yield the desired alloy chemistry. In addition small amount of other materials may be added to adjust the final product chemistry. For example, iron, or copper, may be added as alloy constituents. Powder titanium dioxide may be added to increase the oxygen content of the final material. Recently, Dynamet Technologies achieved metal matrix composites by additions of titanium carbide to the blended elemental process.

The companies that make near net shape components from sponge fines have managed to take a material (sponge fines) whose chemistry is considered inferior to ingot metallurgy and make it a commercial success. This has occurred because of dramatic cost savings in the range of 50-70 percent.

There are three basic processes for achieving full density using irregular shaped titanium powder in a blended elemental process:

1. CHIP Process.
2. MR-9(c) Process.
3. Forged Powder Metal Preforms.

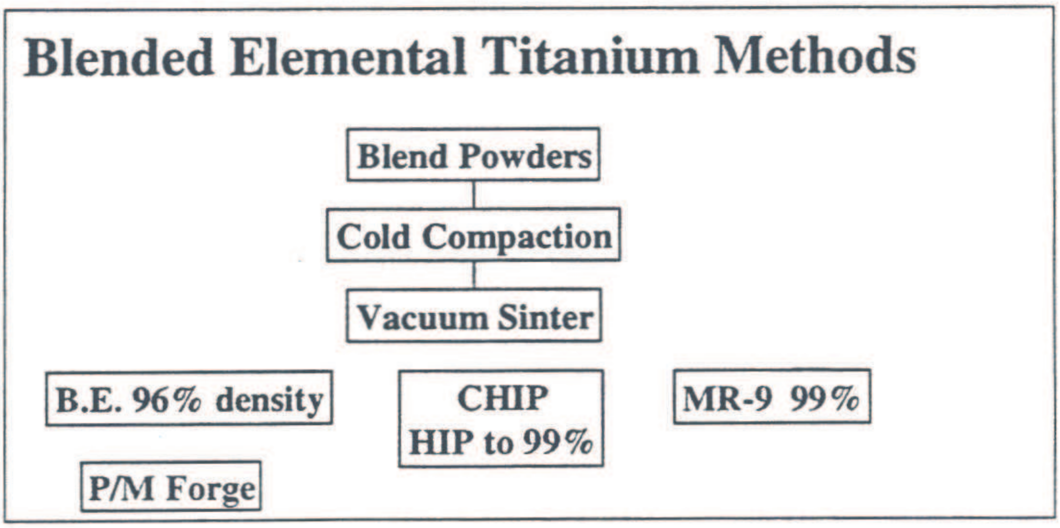
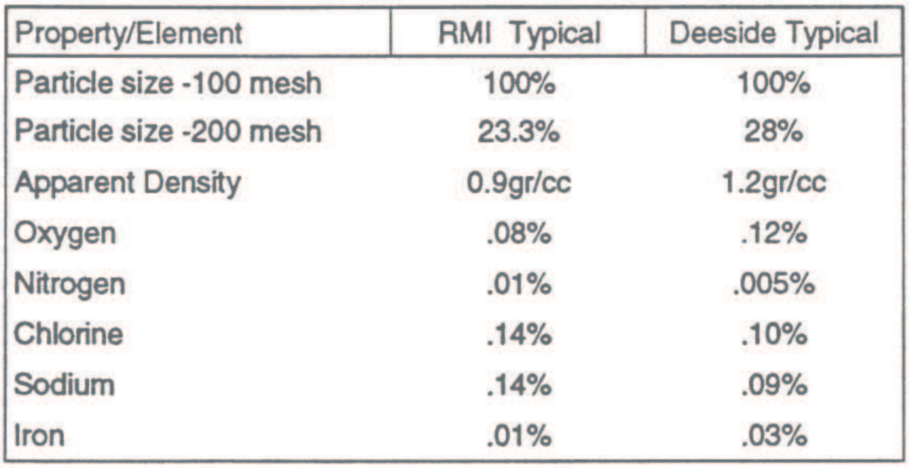


Table 1: Comparison of Major Properties: AMI and Deeside Sponge Fines (Rer. 1)



Property/Element	RMI Typical	Deeside Typical
Particle size -100 mesh	100%	100%
Particle size -200 mesh	23.3%	28%
Apparent Density	0.9gr/cc	1.2gr/cc
Oxygen	.08%	.12%
Nitrogen	.01%	.005%
Chlorine	.14%	.10%
Sodium	.14%	.09%
Iron	.01%	.03%

Sponge fines are the predominant titanium powder form used for blended elemental applications, however electrolytical, Hydride-dehydride titanium powders and other methods are being evaluated.

CHIP Process

The CHIP process, takes advantage of the fact that interconnected porosity does not exist at densities greater than 95 percent. In the CHIP process a powder metal component that has achieved a green density of at least 83 percent is vacuum sintered at 1260 degrees Celsius (2300 degrees Fahrenheit) for four hours. After sintering, a density greater than 95 percent is achieved. The ability to achieve sintered densities greater than 95 percent allow the use of a hot isostatic press to further consolidate the part to greater than 99 percent. In the case of Clevite's MR-9(c) process hot isostatic pressing is not required. If the parts are not 99 percent dense after sintering and higher density and the associated properties are required, the parts can be batched processed in a HIP cycle without canning. On parts 2-4 pounds in weight and volumes of 500-1000 pieces per HIP cycle, HIP costs per piece range from $4-10 per part. The powder metal fabricator can send his component to a company that specializes in HIP'ing and thereby not have to invest in a HIP unit.

MR-9 Process

Clevite developed and patented a blended elemental powder titanium process MR-9. Based on proprietary processing techniques they achieve sintered densities greater than 99 percent and achieve high mechanical properties and a fatigue endurance limit. The MR-9 process does not use HIP'ing or forging to achieve the high densities. Sponge fines from RMI, Deeside Titanium, and chlorine free titanium powder from Osaka Titanium have been used successfully in the process. Clevite has licensed the MR-9 process to Exotic Metals Inc. a division of Masco Industries, and to a Japanese company.

Great interest has been shown in the automotive industry for the MR-9 process because it allows the use of high volume powder metal manufacturing methods. It is the lowest cost process for making titanium connecting rods in volumes of 100,000 pieces or more.

Forging Powder Metal Preforms

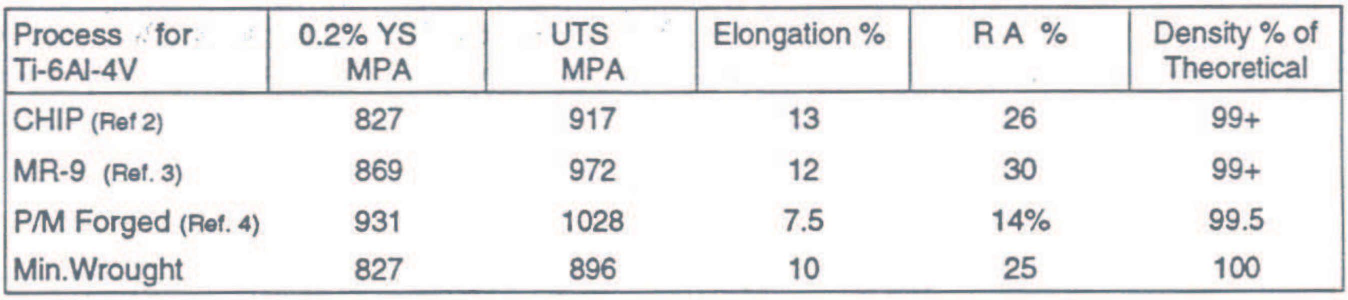
Forging powder metal preforms is emerging as a potential process for making parts. Dynamet Technology has completed process and economic studies with Alcoa Forging Division in Cleveland, Ohio. The powder forging process developed to date for powder titanium includes the following major steps:

- Blending titanium powder with master alloy.
- Cold pressing a part to 85 percent green density.
- Vacuum sintering (96-99 percent density achieved).
- Forging reduction.
- Final finishing(descaling, machining etc.).

A combination of powder metal and forging has resulted in manufacturing cost reductions for certain part geometries. Benefits achieved by the combination of processes are:

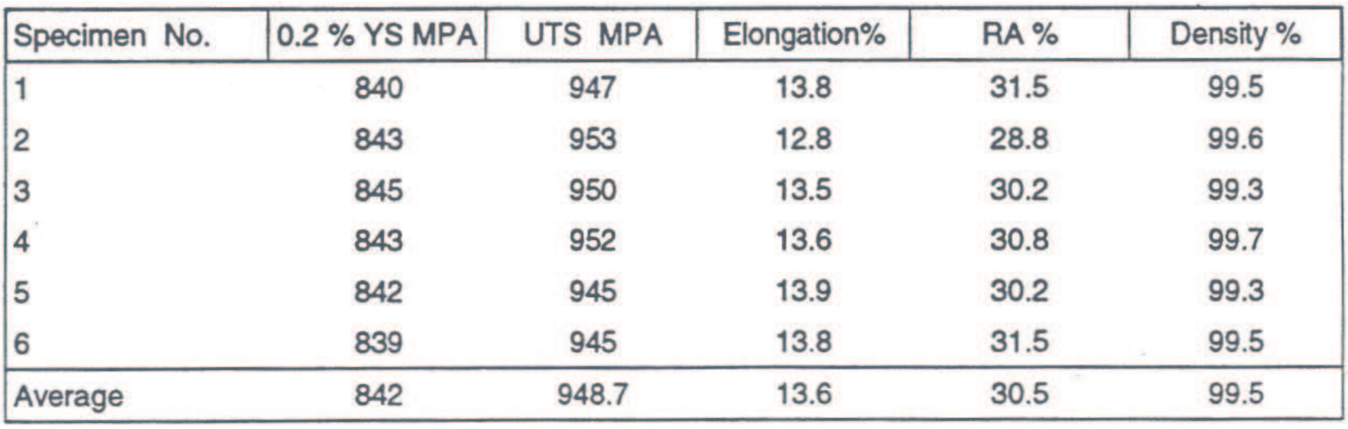
1. Improved shape making capability from cold isostatically pressing.
2. Lower material starting cost if sponge fines are used.
3. Reduction in the number of forging dies required too one die.
4. Increased material utilization.
5. Increasing density of the powder metal part to 99 percent.

Table 2: Blended Elemental Titanium Properties Using Sponge Fines



Process for Ti-6Al-4V	0.2% YS MPA	UTS MPA	Elongation %	R A %	Density % of Theoretical
CHIP (Ref 2)	827	917	13	26	99+
MR-9 (Ref. 3)	869	972	12	30	99+
P/M Forged (Ref. 4)	931	1028	7.5	14%	99.5
Min.Wrought	827	896	10	25	100

Table 3: TI-6Al-4V Tensile Specimens Using Deeside Titanium Ltd. Sponge Fines



Specimen No.	0.2 % YS MPA	UTS MPA	Elongation%	RA %	Density %
1	840	947	13.8	31.5	99.5
2	843	953	12.8	28.8	99.6
3	845	950	13.5	30.2	99.3
4	843	952	13.6	30.8	99.7
5	842	945	13.9	30.2	99.3
6	839	945	13.8	31.5	99.5
Average	842	948.7	13.6	30.5	99.5

Sample Microstrucure Blended Elemental Ti-6Al-4V Using Deeside Titanium Sponge Fines
Figure 1

Direct Powder Rolling

In the early 1980's Clevite pioneered direct powder rolling of titanium alloy foil. At that time the interest was for monolithic applications. Material could be rolled continuously. Coils could not be sintered in a vacuum furnace and needed to be cut to lengths equal to the length of the furnace. Very successful results were achieved. Cost estimates for rolling titanium alloy foil were five times material costs. In todays cost that would result in $U.S. 77 per kg. ($35 per lb.). Present high alloy titanium fail produced by acid etching (Chemtronics) or rolling and annealing (Texas Instruments) is $ 1,100 - 2,200 per kg. Now there are needs for foil in composite applications.

Use of Spherical Titanium Powder Technology

In an effort to increase the material properties of powder titanium the U.S. government funded major programs to develop high purity powder by funding a titanium gas atomization. TGA, rotating electrode process, REP, and plasma rotating electrode process, PREP. These processes provided high purity powder in a spherical shape. The powder is an order of magnitude, 3 to 5 times, more expensive than the wrought titanium, and 10 times more expensive than sponge fines.

In addition to the premium cost of material, the manufacturing processes needed to fabricate the spherical powder is more expensive than traditional powder metal compaction and processing techniques. A combination of high material costs high fabrication cost require a complicated part geometry to make the process competitive with investment casting or wrought metallurgy. The HIP process offers design engineers unique shape making capability with high material utilization.

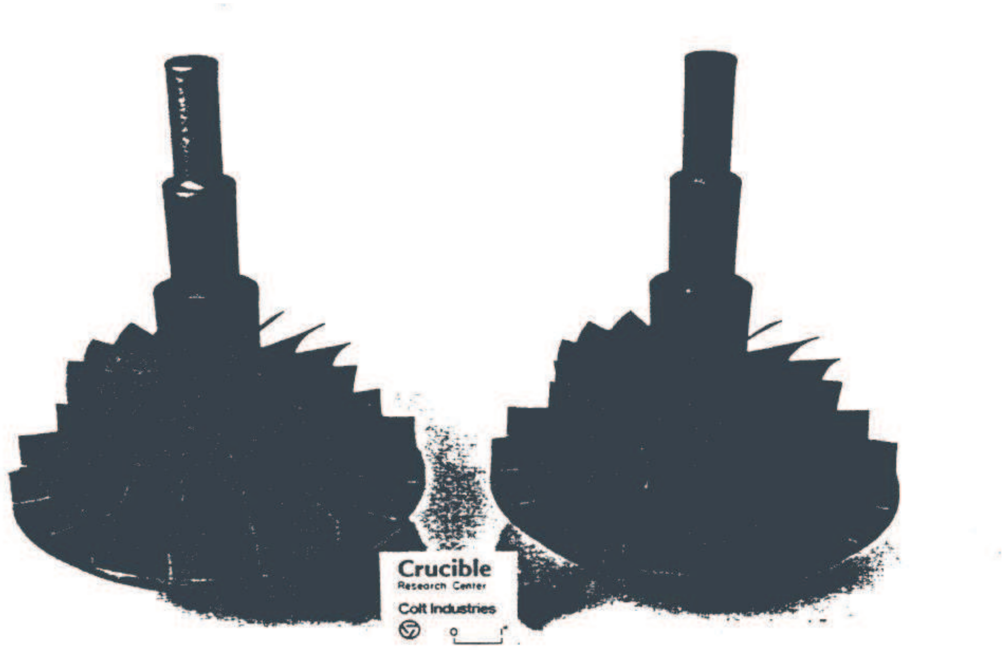
Tooling technology developed for shape making include MBB's electroforming container technology, Crucible Research Center's ceramic mold process, and Kelsey Hayes rapid omni-directional compaction, ROC.

Applications that have proven successful for spherical titanium powders are applications that require the specific powder form in order to achieve desired material characteristics. Two successful applications are plasma sprayed coatings and sintered powder coatings. Both are used for medical prosthetic implants.

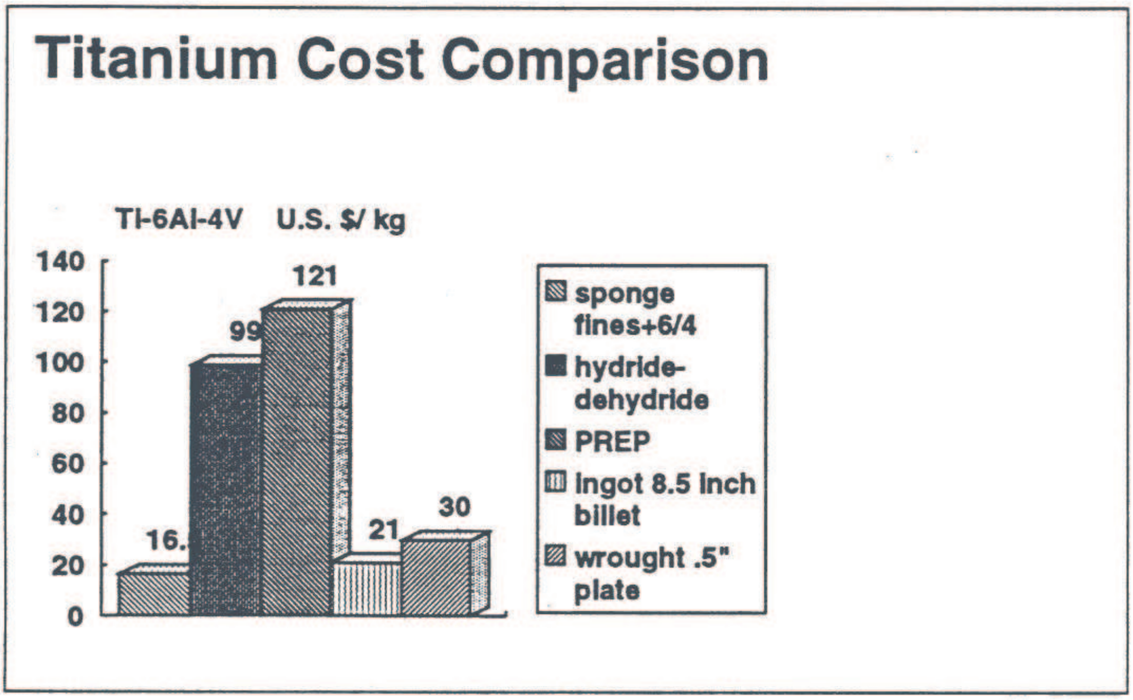
In the U.S. the two largest suppliers of spherical titanium powders are Nuclear Metals and Crucible Research Center. Nuclear Metals utilizes PREP, Plasma Rotating Electrode Process and Crucible Research Center, has developed a TGA, Titanium Gas Atomization Process.

Both TGA and PREP show a great potential for use in making titanium aluminides. Present titanium aluminide materials are difficult to fabricate using wrought metallurgy. The more difficult the titanium aluminide alloy is to process by ingot metallurgy, the greater the advantage for processing by powder metal methods. In addition to near-net shape fabrication, these processes have the ability to provide the necessary feed material for plasma spraying titanium aluminides. Plasma spray processes are being developed for advanced composite applications.

Crucible Materials Corpo Ceramic Mold Process: Alpha 2(T-14Al-21Nb wt%)
Figure 2



Powder Cloth: In addition to the processing methods mentioned PREP titanium aluminide powders are being processed by a powder cloth process. NASA Lewis has fabricated intermetallic matrix composites using titanium aluminide powder dispersed through a binder of PTFE, poly(tetraflouroethylene). Using 3-5 percent weight volume of PTFE allows a web to be formed by fibrillation. The web of PTFE provides a means of rolling the resultant material into thin strips (0.15 - 0.20 mm).



A Case Study: Manufacturing Economics for Blended Elemental Titanium

Since blended elemental titanium has been proven to be highly cost effective, two cost models will be discussed. One model will deal with using a cold isostatic pressing method to make a missile housing. A second example will summarize the manufacturing economics of making a titanium connecting rod in high volumes using a mechanical die press.

In this paper cost information will be provided based on the following exchange rates:

U.S.	U.K.	Germany	Japan	Italy
1.00	0.51	1.49	130	1120

Source : Wall Street Journal, November 9, 1990. Rates as of late N. Y. Trading November 8,1990

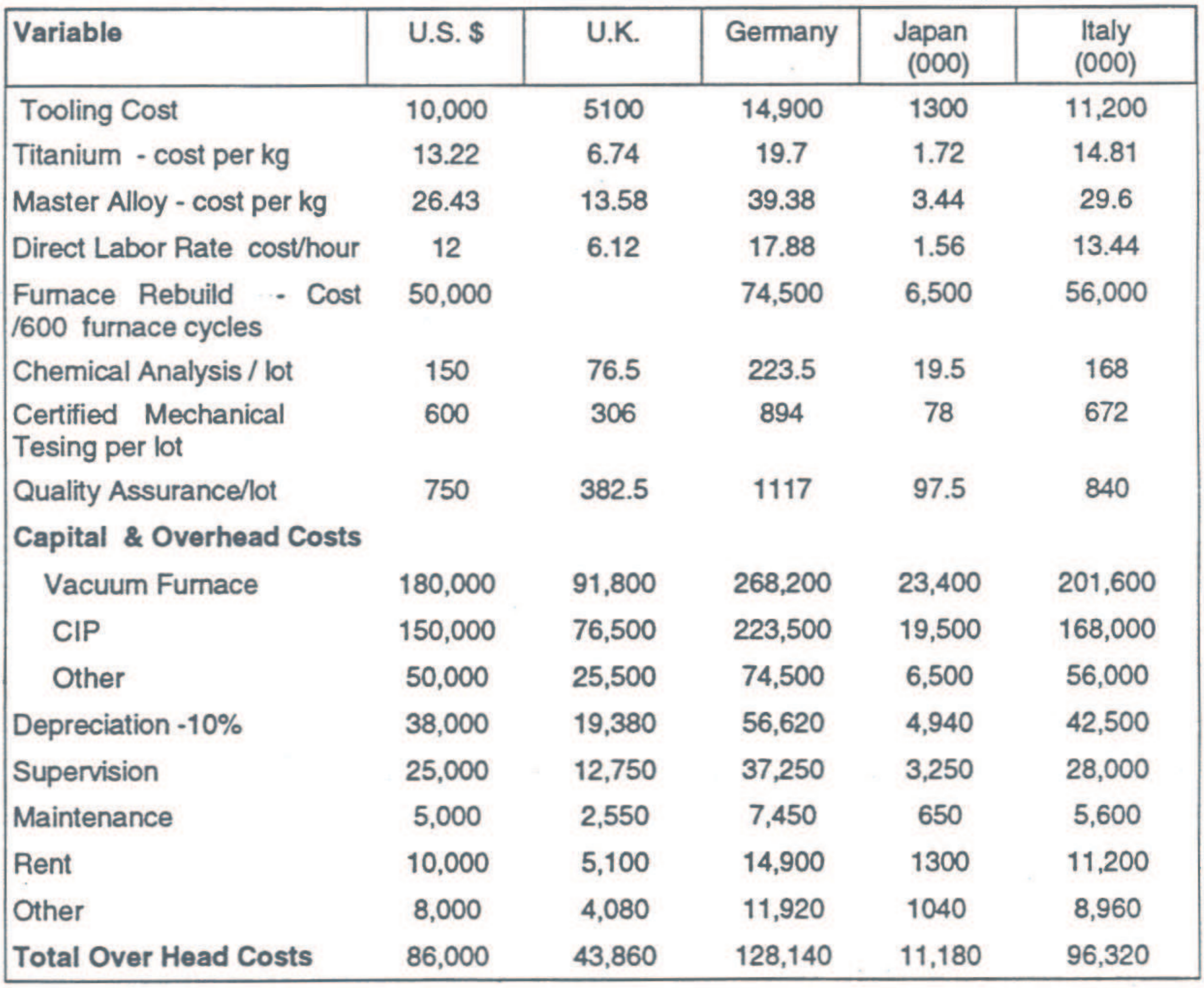
Case One: Ti-6Al-6V-2Sn Housing Blank, See Figure 3

Material Property Requirements for Application:

- 862 MPA - Yield Strength Minimum at a .1% offset
- 3.0% - Elongation minimum
- 13 % - Reduction of area, average value
- 6ft/lb. - Minimum V-notch charpy impact at-40 degrees Fahrenheit

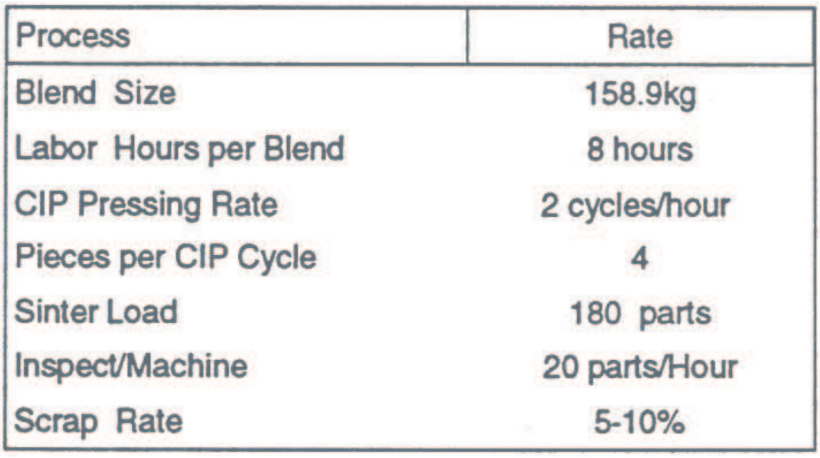
Quantity:	10,000 pieces per year
Part Weight:	967 grams

Cost Rates for CIP Housing



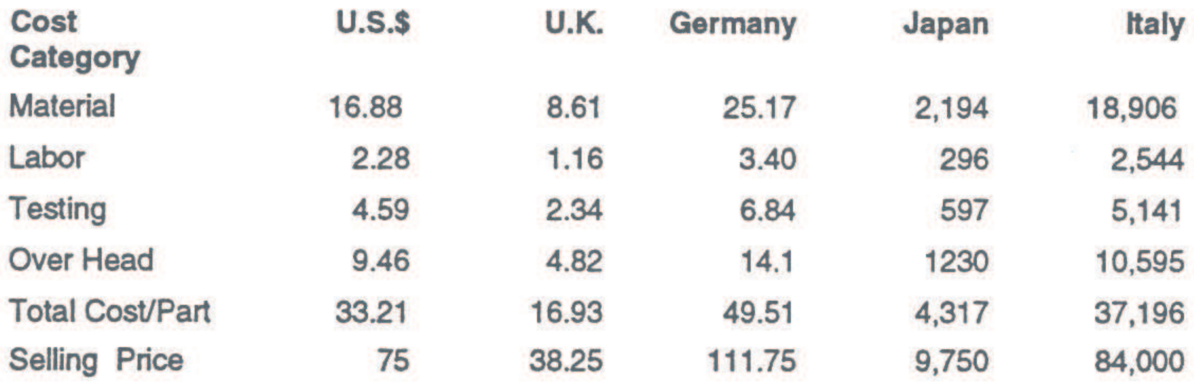
Variable	U.S. $	U.K.	Germany	Japan (000)	Italy (000)
Tooling Cost	10,000	5100	14,900	1300	11,200
Titanium - cost per kg	13.22	6.74	19.7	1.72	14.81
Master Alloy - cost per kg	26.43	13.58	39.38	3.44	29.6
Direct Labor Rate cost/hour	12	6.12	17.88	1.56	13.44
Furnace Rebuild - Cost /600 furnace cycles	50,000		74,500	6,500	56,000
Chemical Analysis / lot	150	76.5	223.5	19.5	168
Certified Mechanical Tesing per lot	600	306	894	78	672
Quality Assurance/lot	750	382.5	1117	97.5	840
Capital & Overhead Costs					
Vacuum Furnace	180,000	91,800	268,200	23,400	201,600
CIP	150,000	76,500	223,500	19,500	168,000
Other	50,000	25,500	74,500	6,500	56,000
Depreciation -10%	38,000	19,380	56,620	4,940	42,500
Supervision	25,000	12,750	37,250	3,250	28,000
Maintenance	5,000	2,550	7,450	650	5,600
Rent	10,000	5,100	14,900	1300	11,200
Other	8,000	4,080	11,920	1040	8,960
Total Over Head Costs	86,000	43,860	128,140	11,180	96,320

Manufacturing Rates for CIP Housing



Process	Rate
Blend Size	158.9kg
Labor Hours per Blend	8 hours
CIP Pressing Rate	2 cycles/hour
Pieces per CIP Cycle	4
Sinter Load	180 parts
Inspect/Machine	20 parts/Hour
Scrap Rate	5-10%

A computer model using a Lotus 123 language was developed with the information mentioned above for a missile housing. This part was very successful at replacing a 2,043 gram forging. A 52 percent material savings was achieved. The following summarizes the major cost categories of the model:



Cost Category	U.S.$	U.K.	Germany	Japan	Italy
Material	16.88	8.61	25.17	2,194	18,906
Labor	2.28	1.16	3.40	296	2,544
Testing	4.59	2.34	6.84	597	5,141
Over Head	9.46	4.82	14.1	1230	10,595
Total Cost/Part	33.21	16.93	49.51	4,317	37,196
Selling Price	75	38.25	111.75	9,750	84,000

Note: The properties for the product mentioned above were achieved without hot isostatically pressing. Using the CHIP process for the above product would add approximately $5, (2.5 U.K. Sterling), (7.5 German D.M.), (650 Japan Yen), (5,600 Italy Lire).

This product is routinely produced. A material savings of over 52 percent was achieved and a tremendous cost reduction. The near-net shape part allowed for a reduction in final machining costs. This part is a good example of using low cost sponge fines with standard powder metal fabrication methods.

Cost Summary For Titanium Connecting Rod

In the past five years Clevite received a lot of attention for it's MR-9 process from major automobile manufactures. The automotive industry has evaluated alternative methods for achieving increased fuel economy and reduced noise, shock and vibration in four-cylinder engines. A known means of accomplishing this goal is through lightweight, high-temperature/high-strength engine components. Full dense blended elemental material was supplied for testing and evaluation. Connecting rods were fabricated using both the CIP and mechanical die press technology. The fatigue endurance limit of sponge fines for the application matched the existing iron based connecting rods and provided for a minimum of a 35 percent weight savings.

To demonstrate the cost effectiveness of the process for high volume applications, the writer developed an economic model using Lotus 123. The cost model included a dedicated facility over a ten year period. Based on this cost model the MR-9 process proved to be the most competitive titanium technology for achieving significant weight reduction. The information below summarizes the price attainable given the current price of sponge fines, quality of titanium powder available, and the current state of the art for powder metal titanium fabrication. **See Figure 4**

Quantity:	1 million pieces per year
Part Weight:	340 grams
Pressing Rate:	4 parts per minute using a 500 ton press.
Price of Sponge Fines:	U.S. $ 11.56/ kg (U.K. 5.90/kg) (Germany 17.22/kg) (Japan1503/kg) (Italy 12.947/kg)

The selling price required to justify a dedicated facility for making titanium connecting rods is :

• US $	7.5 - 8.0 per part
• U.K.	3.83 - 4.08
• Germany	11.18 - 11.92
• Japan	975 - 1,040
• Italy	8,400 - 8,960

The major cost items affecting the high volume production of titanium connecting rods are the price of sponge fines, and the vacuum furnace capacity. A vacuum furnace represents a considerable investment and is a batch process with complete degassing and sintering cycle of at least 12 hours. Existing sponges fines meet the fatigue requirements and offer the lowest cost material and an optimum fatigue endurance limit for the cost. Chlorine free titanium powder at the same price of sponge fines would dramatically increase the performance of the finished part and allow for less material to be used. Ford Motor Company has evaluated the use of titanium in the main part of the connecting rod and use of steel in the cap end. This approach minimizes the use of an expensive material.

Product Applications For Powder Titanium

Commercially Pure Products: C.P. titanium products are made by mechanical die pressing, cold isostatic pressing and powder rolling. Products produced currently include chemical resistant fasteners, filters, knife handles, watch cases, and coatings for medical applications.

Blended Elemental Titanium Products: The major applications for blended elemental titanium exist in non-man-rated weapon systems. Missile housings are produced to densities of 96 - 99 percent, depending on the application. Components are produced for the Sidewinder, Seeker and Stinger Missiles.

Prealloyed Titanium Products: Titanium powder made by the PREP, TGA and hydride-dehydride process are used in coating applications for medical prosthetic implants. Coatings are applied by plasma spray and vacuum sintering.

Major Applications under development: Major applications for powder titanium under development include automotive engine components, MMC missile fins, and plasma sprayed coatings for composites. In addition powder titanium capabilities developed for the TGA and PREP process are being used to provide titanium aluminide powder for advanced applications.

Summary

The use of powder titanium for structural parts has evolved due to the availability of low cost sponge fines and standard powder metal fabrication techniques. In addition design engineers were educated to the capabilities of the various technologies. High purity powder titanium in spherical forms is used successfully in coating applications.

Major factors limiting a broader use of the available technologies are educating design engineers to the materials and capabilities, and the cost and availability of titanium powder. Lowering the cost of sponge fines or the availability of improved powder at prices equal to wrought titanium will make these technologies more competitive.

Acknowledgements

The author wishes to acknowledge Dr. Vladimir Moxson, President of Advanced Materials Products Inc., Mr. Brian McTieman, Director Superalloy and Titanium Products, Crucible Compaction Metals, Stan Abkowitz, President of Dynamet Technologies, Cliff Bugie Manager, Research and Development of Dynamet I nc., Walt Orloff, Product Development Engineer, Ford Motor Company, Ed Brosius, Manager Engineering, Tiex Metals Inc (Masco Industries).

References

1. Product Specification Material published by Deeside Titanium Ltd., and RMI.
2. S. Abkowitz: in 'powder metallurgy of titanium alloys', (ed. F.H. Froes and J.E. Smugereresky), 291-302; 1980, Warrendale, PA, Metallurgical Society of AIMR.
3. E. Brosius, J. Malek, N Petek, and M. Trzcinski, Clevite Industries, Blended Elemental Powder Titanium for Automotive Applications; Symposium on Titanium Products and Applications; Titanium Development Association, October 1986. Copies available through M.J. Trzcinski, 2567 Fenwick Road, Cleveland, Ohio 44118 USA.
4. A. Charkrabarti, G. Kuhlman, Alcoa Forging Division, S. Abkowitz, Dynamet Technologies Inc., Paper presented at 1990 Advanced Aerospace Materials/Process Conference (AEROMAT) 21-24 May 1990, Long Beach California.
5. J. W. Pickens Sverdrup Technology, Inc, NASA Lewis Research Center Group, and R. Noebe, G. Watson, P. Brindley, and S. Draper, NASA Lewis Research Center, Cleveland, Ohio; Fabrication of Intermetallic matrix Composites by the Powder Cloth Process; 13th Annual Conference on Composite Materials and Structures, sponsored by the American Ceramic Society, Cocoa Beach, Fl, January 18-21, 1989.

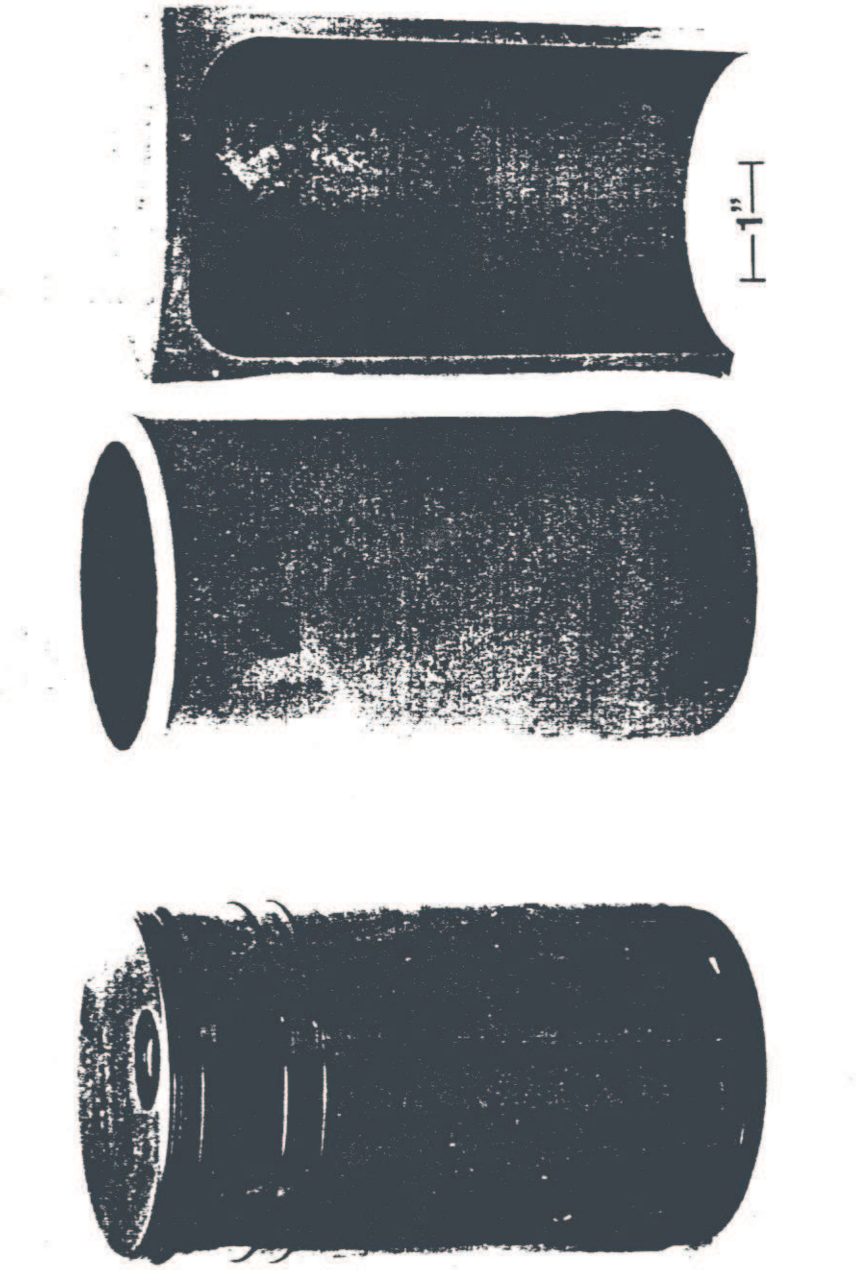


Fig. 3 – P/M Ti-6Al-6V-2Sn housing blank

Fig. 4 - P/M Ti-6Al-4V connecting rod

VI MEETING INTERNAZIONALE SUL TITANIO

“TITANIO E ARCHITETTURA”

Carlo Pession
Studio Pession (Italia)

TITANIO E ARCHITETTURA

Va innanzitutto premesso che l'uso del Titanio in edilizia è abbastanza recente e scarsamente diffuso.

Le regioni di questo ridotto impiego vanno ricercate soprattutto nella distorta immagine che spesso il Titanio presenta: meteriale sofisticato per applicazioni sofisticate, di uso prevalentemente militare, strategico e comunque sempre metello molto costoso.

Per tutte queste regioni il Titanio è parso poco adatto ad usi edili. Ma una più attenta analisi delle sue caratteristiche e dei rapporti costi-benefici ci induce e capire che viceversa il Titanio è materiale adatto ad impieghi architettonici ed applicabile su vasta scala nel campo dell'edilizia. E ciò eminentemente per il suo peso specifico (specie se paragonato agli acciai), per le sue peculiarità tecnologiche che consentono nel ridotto dimensionamento un risparmio dei manufatti, per il fatto che esso non richiede alcuna manutenzione e soprattutto perché, essendo non corruttibile, la sua vite utile è molto più lunga di quella degli altri materiali tradizionali.

La prima comparsa ufficiale del Titanio nell'edilizia avviene in Giappone nel 1971 come materiale di coperture. Sempre in Giappone, specie dopo il 1983, sono evidenti alcuni casi di maggior rilievo, soprattutto per merito della **Titanium Association of Japan** che ha promosso su scala più vasta l'uso del Titanio anche per impieghi edili. In Europa e negli Stati Uniti l'uso del Titanio in edilizia è invece ancora relativamente scarso.

In Italia possiamo citare come interventi di rilievo l'applicazione del Titanio nel restauro conservativo della **Colonna Antonina** di Roma e nelle opere di recupero delle **Fontana di Trevi** dove si sono usati elementi di Titanio per il fissaggio delle varie parti marmoree del monumento.

Un altro caso d'uso del Titanio nelle opere di restauro è stato l'intervento di conservazione del **Partenone** eseguito nel 1983 con applicazione di varie tonnellate di Titanio semplice o composto nelle sue leghe.

E' importante ricordare che la progettazione deve oggi tenere in somma considerazione il mutamento avvenuto nell'atmosfera e ciò in particolare nelle città. Le condizioni di progetto che venivano poste negli anni 70/80 sono infatti mutate a seguito della maggiore aggressività dell'ambiente: oggi vanno previsti materiali con grandi capacità di resistere alle azioni corrosive delle atmosfere metropolitane.

Per quanto riguarda le **qualità strutturali** del Titanio va precisato che esse sono straordinariamente efficaci dal punto di vista tecnologico ma, data la scarsa conoscenza dei sistemi di lavorazione applicati all'edilizia ed il ridotto approfondimento sul rapporto costo/beneficio, il Titanio, sotto la veste strutturale, pare al momento meno applicabile degli altri materiali concorrenti.

E ciò succede per quello che potremmo definire il **fattore forma.** Ciò significa che a parità di forma il Titanio può sembrare **meno vantaggioso di altri materiali.** Ma se fosse progettato in relazione alle sue reali peculiarità tecniche, cioè con una **propria forma** esso potrebbe diventare eccezionalmente **efficace con adatti profili resistenti**.

Il Titanio avrebbe potuto svolgere ottimamente un ruolo strutturale in manufatti come quelli illustrati nelle fotografie 1 e 2 (Londra), 3 e 4 (Parigi: scala del Nuovo Louvre progettata dall'Arch. cino-americano M.PEI), 5 (Parigi: mancorrente del nuovo edifico delle Villette)

All'**interno degli edifici** il Titanio presenta caratteristiche interessanti sia per il suo aspetto che per le sue straordinarie capacità meccaniche e viene pertanto usato prevalentemente nella progettazione di elementi di design e finitura, dove l'incidenza della voce costo è inferiore per le ridotte dimensioni degli oggetti.

Per le sue caratteristiche il Titanio è applicabile però con maggiori vantaggi **all'esterno** degli edifici e specie in ambienti aggressivi come ad esempio ambienti metropolitani e marini. E' in questi luoghi che egli meglio esalta le sue caratteristiche.

All'esterno il Titanio viene usato prevalentemente per **coperture, faldalerie, pluviali e pannelli di rivestimento.**

Nei nuovi fabbricati industriali della Ginatta in Settimo Torinese (foto 6: elaborazione computerizzata del nostro progetto dei capannoni industriali) il Titanio verrà applicato come **copertura piana** composta da lastre nervate di lunghezza fino a mt. 30 e larghezze pari a 33 e 48 cm (foto 7).

Tali lastre verranno accostate ad incastro con un sistema a scatto che fungerà anche da condotto di drenaggio per l'eliminazione dell'acqua (foto 8). Il tutto non è mai perforato, consente il libero movimento degli elementi durante le dilatazioni, è pedonabile ed è priva di ponti termici. L'impiego del Titanio in questo caso rende possibile a parità di caratteristiche un risparmio nello spessore delle lastre. La sua elasticità consente, anche sotto forti carichi, una ottimale pedonabilità. La sua lavorabilità elevata ha consentito inoltre piegature con raggi di curvatura piccolissimi come per esempio il profilo per l'eliminazione dell'acqua (foto 8).

Infine le prerogative di **stabilità chimica** fanno ritenere che la durata della copertura sarà pressoché illimitata, anche in condizioni proibitive. In merito poi al costo, più elevato di circa un 20% rispetto al rame, si può affermare che esso è compensabile dal valore di **rottamazione** finale, che nel caso del Titanio, si conserva particolarmente elevato.

Nel caso delle **pannellature** di facciata il Titanio viene usato in sostituzione dei materiali attualmente presenti sul mercato quali: alluminio, lamiera d'acciaio, alucobond, pietra e ceramica.

Va premesso che **l'alluminio** ha il vantaggio che si estrude facilmente, ma presenta lo svantaggio della difficile planarità e un altrettanto difficile saldatura. Il Titanio è perfettamente planare e facilmente saldabile. L'alluminio va comunque trattato, mentre il Titanio non necessita di un trattamento protettivo.

La **lamiera d'acciaio** si può saldare ma, deve essere protetta con trattamenti che possono presentare deterioramenti nel tempo.

Bisogna ricordare che **l'elettrocolorazione e la zincatura** deperiscono in modo non costante se riferite alle quattro differenti esposizioni cardinali e la **porcellanazione**, che dura maggiormente, rende la superficie esterna dei pannelli delicata agli urti.

L'**alucobond** assomma ai problemi già visti per l'alluminio problemi di infiammabilità.

Pietra e ceramica presentano evidenti problemi di peso, specie in edifici di elevata altezza.

Vedi i casi del Grand'Arche di Parigi rivestito esternamente di pietra (foto 9) e della Nuova Opera di Parigi in cui l'architetto canadese Ott ha accostato vari tipi di rivestimento: alluminio, pietra e acciaio inox (foto 10 e 11)

Il Titanio invece presenta i seguenti vantaggi:

eccezionale durabilità senza trattamenti aggiuntivi in qualsiasi ambiente aggressivo;

estrema leggerezza a parità di caratteristiche meccaniche che consente risparmi economici e di peso (ad esempio per l'utilizzo nei grattacieli);

saldabilità con conseguente eliminazione di viti e o chiodature di tenuta in vista.

Qualora il Titanio venga poi applicato in coppia con altri metalli il problema della conseguente creazione di coppie galvaniche è risolto dalle stesse guarnizioni che realizzano il **taglio termico**.

Il taglio termico infatti oltre che onnullare i ponti termici assolve contemporaneamente la funzione di separazione dei materiali (Titanio e acciaio, Titanio e alluminio) eliminando alla radice la nascita di possibili correnti elettriche. (foto 13-14)

Per tutta questa serie di vantaggi ci pare quindi che il Titanio possa con grandi benefici sostituire l'alluminio, acciaio, alucobond e pietra.

Bisogna ora esaminare se i vantaggi tecnologici descritti abbiano un riscontro negativo sul piano del costo.

Analizziamo il maggior costo dovuto all'applicazione di Titanio in facciate strutturali (foto 15-16: una totale complanarità esterna con struttura di supporto interna) e continue (foto 17-18-19: struttura portante posta all'esterno).

Esaminiamo prima la facciata strutturale e poniamoci nella condizione che esso si presenti totalmente vetrata.

Supponendo di sostituire al vetro pannelli di titanio dello spessore di 8/10, (ipotizzando per una superficie pari a circa il 50%) l'analisi effettuata fornisce il seguente risultato: la facciata strutturale vetro-Titanio è più cara della facciata strutturale vetro-vetro di circa il 40%. Ma va tenuto conto che in questa percentuale è compreso un maggior onere (circo 10%) dovuto al telaio interno più complesso in caso d'uso del Titanio; ciò in quanto oggi il materiale reperibile sul mercato non supera il metro, mentre per il vetro si possono ottenere ampiezze maggiori. Possiamo quindi affermare che il maggior onere è contenibile in una **quota di poco superiore al 30%**.

Effettuando ora lo stesso confronto nella facciata continua otteniamo che il maggior costo anche in questo caso non supera il 30%.

Per tutte le questioni fino a qui affrontate (durevolezza, incorruttibilità, leggerezza, proprietà meccaniche e maggior costo che non supera soglie di accetabilità), abbiamo scelto il Titanio come materiale generale di rivestimento esterno dei **Nuovi Blocchi Uffici della Ginatta in Settimo Torinese** (foto 20-21-22). Qui il Titanio sarà usato come tamponamento della parte centrale dove si presenta in pannelli di 100x200 e spessore 8/10 e come pannello di facciata ventilata sulle zone curve laterali (blocchi scale, servizi, e cavedi tecnici).

Abbiamo anche proposto il **Titanio** come rivestimento di un edificio che stiamo costruendo in Giappone e che sorgerà in un parco esposizioni e fiere dove l'edificio principale progettato da Maky (foto 23-24), si presenta totalmente rivestito in pannelli di alluminio trattati con una elettroverniciatura protettiva.

Ricordo che ci troviamo in una delle città al mondo con una maggiore aggressività atmosferica ed in più ci troviamo ad un passo dal mare. L'edificio oggi mi pare perfetto. Ma non possiamo dire lo stesso dello SPIRAL BUILDING di Maky costruito a Tokyo nel 1983 (foto 25-26): dopo sette anni si notano **evidenti problemi di degenerazione** della pellicola superficiale di elettrocolorazione applicata su pannelli speciali dello spessore di 0,5 mm (foto 27: particolare del pannello).

Ritengo che se Maky avesse usato Titanio avrebbe ottenuto migliori risultati con spessori inferiori, quindi senza necessità di trattamenti e con una incidenza di spesa poco rilevante.

E' questa la ragione che ci ha spinti a proporre per il nostro edificio la totale ricopertura del Titanio della facciata verso il mare (foto 28) e parziale delle altre facciate in vetro e titanio (foto 29) e pietra, cemento e Titanio (foto 30).

Fotografie non incluse.

VI INTERNATIONAL MEETING ON TITANIUM

TITANIUM TUBE ASSEMBLIES FOR AEROSPACE APPLICATIONS

Eric Schoeps
Sierracin Corporation Europe

SIERRACIN CORPORATION EUROPE
30 bis, rue du Vieil Abreuvoir - 78100 Saint Germain en Laye (France)
Tél. (1) 30 87 04 04 Fax (1) 30 87 03 84 Télex 689791 F

"TITANIUM TUBE ASSEMBLIES FOR AEROSPACE APPLICATIONS"

1. Introduction - (1)

   When modern aircraft such as Boeing 747-400, 757/767 or Airbus A-320, 330/340 take off or land, then the instant power for functioning (2) the flaps originates from the hydraulic system in the wings.

   When landing gears such as the one for A-330/340 (3) unfold or withdraw or hit with great force the runway and the pilot brakes - then hydraulic tubing made of 3AL-2.5 V Titanium is part of the effort.

   When engines such as the V-2500 (4) or the new military engine EJ200 for the European Fighter carry fuel, lubricants and hydraulic oil from one component to the other in an ambient temperature of up to 200°C, then the tubing is again made of Titanium alloy.

   Why this extensive use of not only Ti-tubing, but sheets, forgings, fasteners and other components instead of the traditional steel, may it be high-strength or stamless? The reasons are basically 2 - fold :

   1. Excellent "weight to strength to cost ratio" in comparison with steel. At similar strengths Titanium is 45% lighter than steel (5). This picture shows the yield strength to weight ratio of aerospace tubing. The density of steel is around 7.90, Titanium is 4.45.

   2. Stainless steel corrodes in the extremely hostile environment of an aircraft. Titanium 3AL 2.5V with normally only 0.15 % iron, never does.

2. A few remarks on the metallurgy and production of 3AL-2.5V tubing:

   Whereas the 6AL-4V alloy is known throughout the industry for forgings, (6) sheets and structural tubing, 3AL-2.5V seems to be the right alloy for internally pressurised tubing. As the formula says, it contains approx 3 % Aluminium, 2.5 % Vanadium. Depending on the heat treatment this seamless tubing has a typical minimum yield strength of 105.000, 95.000 and 75.000 psi with elongation values between 16 and 28 %.

   The melting point is 1700°C and the beta transus 935°C. Tensile properties at +350°C and -200°C vary less than with other aircraft tubing.

   (7) The manipulation of microstructure + cristallographic texture during production has become a burning issue lately. Tangentially textured tubing thins the walls in

bends. More radial texture results in less tube thinning, but reduces the tube diameter. Extensive test series have shown, however, that too much radial texture is not good for fatigue resistance either. The contractile strain ratio or CSR number a is measurement of the tubing crystallographic texture. The CSR number is the ratio of diametral strain to radial strain which occurs when tubing is pulled to a 4 % tensile strain. The higher the CSR number, the more radially textured the tubing is. The CSR test, as standardized by AS 4076 is in wide use in industry today. Round robin testing between different laboratories showed a standard deviation of only 0.04 units. Studies have shown that tubing with a CSR of between 1.3 and 2.3 has the best fatigue performance.

(8) Let us talk briefly about the production cycle of seamless Titanium tubing.

- The ingot is melted and remelted usually with the so-called "consumable electrode vacuum arc" method.

- The ingot is then transformed into a bar of approx 200 mm dia by forging and reheating to 1150°C and 900°C. The oxygen-enriched surface layer is then ground off and a hole drilled to arrive at the extrusion billet or hollow of 65 to 90 mm OD.

(9)
- The tube reduction cycle then starts which is also called rocking or cold pilgering. The hollow is elongated over a tapered, stationary mandril and over 2 grooved and tapered rolls which move back and forth. The hollow is rotated and advanced in small increments at the beginning of each stroke. In such a way, the 10 - 22 mm thick hollow is reduced in 5 to 6 cycles to a wall thickness of 0.5 mm and less.

- Between the 5th or 6th reduction steps the tube has to be annealled at 700°C in vertical vacuum ovens to prevent oxidation. The final heat treatment is particularly important because it softens the work-hardened tube to the right mechanical characteristics per specification. The finished tube is then straightened, grid blasted, polished, acid-pickled and rinced.

- Naturally the tubing is inspected during the production cycle. The final inspection consists essentially of a 3d-UT inspection which means that not only flaws are detected with an ultrasound method, but OD and wall thicknesses are measured over the whole length of each tube. Then a micro processor calculates the ID dimensions. If any of these 3 dimensions are out of the preset tolerance range, the non-conform area is automatically sprayed with colored ink. The times of measuring the tubes with a micrometer at both ends are definitely over.

- Each tube lot is tested for conformance to applicable specifications and laboratory samples are retained. These tests may include tensile, burst, chemistry, microstructure, CSR, bending, flaring and flattening.
After a last visual inspection and marking, the tubes are sleeved, packed and sent aut. If any technicians amongst you want to know further details on the metallurgy and the production of 3AL-2.5V tubing, then you will be interested to know that SANDVIK-SSM has recently published the 3rd edition of its "Engineering guide".

3. When the Titanium tubing goes through a last visual inspection, we tubing manufacturers are proud of the elegant, mat-grey finish, the cleanliness and shine in the tube ID. But in fact, straight tubing is only the starting material for the functional part; the tube assembly.

   a) After arrival at the airframe or engine manufacturers plant, the tubing is cut to size, deburred and then bent.

      In comparison with industrial steel or aluminium, bending of Titanium tubing has some particularities

      - it must always have a bending mandril (10)

      - the spring back which is virtually nil in soft steel or aluminium tubing, 2-3 % for high-strength steel such as 21-6-9, is approx 10 % for Titanium tubing depending on tube size, wall thickness and actual elongation and yield strength. The theoretically calculated overbending is usually verified by bending samples of each new tubing lot.

      - Titanium tubing is particularly prone to surface scratches which imposes more careful handling. Scratched tubing can lead to premature fatigue failures.

      - Heat makes Ti-tubing more maleable only from 400°C onwards (11).

      - As the bending forces with Titanium are greater then with Alu or steel, the bending machines, mandrils, tools, lubrication and the operators skill have to be somewhat better than with comparable corrosion resistant tubing such as 21-6-9.

      However the bending speed is roughly the same as for stainless hydraulic tubing which is approx 20-30 sec. and the ovalisation 3% max. as compared 5% for other aeronautic materials.

      After bending, the lubricant is removed either by hot steam or projected Trichloréthylène.

   b) The next step is then the attachment of a fitting to the bent tubing. A great variety of attachment methods is available (12)

      - orbital welding is very suited, although delicate and expensive mainly because of the X-ray inspection

      - brazing was used for example on CONCORD, but has been replaced by welding since, because of the higher joint strength obtained

      - internal roller swaging is used by all US fighter aircraft and the Airbus. The advantage in comparison with welding is that the tubing is not weakened through heat and the results can be easily measured with gages after swaging

- the same goes for external swaging, known as the Permaswage method, manufactured by Deutsch and Sierracin

- Cryofit is produced from shape-memory metal and retracts at room temperature or when the heat of a torch is blown at it.

- Rynglok is a recent development of Aeroquip which seems to yield excellent results mainly in super high pressures. The principle is to slide a ring over a sleeve which crimps and holds the tube.

The next 3 (13,14,15) tables show actual fittings used in US and European hydraulic and engine installations. Apart from the attachment of the fitting to the tubing which is always the more critical part, you will notice that the metric and inch fittings are pretty well standardised with regard to the interface concept

- 60° interface for engines
- 24° ISO or MS for civil and military aviation
- 8 1/2° lipseal interface for sophisticated applications and virtually only in military aircraft.

In the last 20 years so-called "Permanent" fittings (16) such as Permaswage or Sierraswage are in use on many aircraft.

- They allow for much cleaner and shorter installation design.

- Eliminate axial and radial stresses induced by adverse manufacturing and installation tolerances, because these fittings can be swaged in situ.

The bench-produced tube assemblies are then proof-pressure tested and installed. Permanent fittings swaged in the aircraft can only be checked by pressurising the whole hydraulic circuit at working pressure.

4. Hydraulic tubing in Titanium has been used in the U.S.A. since the early 70s on aircraft such as the C-5A, F-14, F-15 and by Boeing since 1981 with the 757/767. With the exception of Concord, Europe followed only 5-10 years later with the SAAB SF-340, the Airbus A-320, E.F.A. and AV8-B. Today virtually all new, somewhat sophisticated projects in the U.S.A. and Europe contain Titanium tubing in various circuits.

   The delay of the introduction of titanium resulted in that the European material specifications such as the ABS5004 for Airbus (17), MBBN 6001 for E.F.A. and the future RR Spec. are more sophisticated and user-friendly then the somewhat dated US Specs. AMS 4944/4943.

   (18) This is a simple illustration which shows the tolerances of the "internal diameter" of 3/8 tube

   - the US Spec. AMS 4944 has a large tolerance range resulting from +15/-5 % on the tube wall thickness

- the Airbus tolerance range is more limited

- the dark columns in the middle show the actually achieved ID measurements in series production at SANDVIK in the last 3 years.

What is a user-fiendly tube?

. Close ID tolerances for better mandril fit
. Garanteed OD, ID and wall thickness measurements through ultrasonic inspection over the total length of each tube
. Limitation of the tube wall eccentricity to 8-10 % for better welding
. Radial texture of 1.3 -2.3 CSR in order to guarantee optimum fatigue performance and forming characteristics.
. Elongation values of at least 17 % for small, 22 % for bigger tube.

5. Next time you sit in an aircraft and your stomach feels uncomfortable with too rapid climbing or descent or a rough ride in the clouds, let me take at least the fear away that could creep into your hearts.

Hydraulic tube assemblies are tested to much rougher conditions than could ever happen in reality.

Example :

- Burst pressure of a tube assembly must be at least 4 times the working pressure. It is typically 5 to 6 times.

-6 samples are flexture-fatigue tested 10 million cycles to imitate the 15/20 years life span in 3 days

(19)
- 90° bends per this illustration are impulse tested 200.000 cycles at 1.5 working pressure in 135 °C and -55 °C, just in case the aircraft should ever have to land on the North pale and take off again within an hour. This picture shows an impulse test set-up for EN fittings and tubing. This test is taking place at this very moment at Pirelli-Italia for the E.F.A. project.

- In addition tube samples are submitted to thermal shock, stress corrosion, life tests, reusability and tensile resistance.

And a whole armada of technicians in production, inspection, flight testing, quality assurance and maintenance make certain that the quality of the test samples is reproduced without exception in production and maintenance of the aircraft.

Relax tired traveller, relax. The aircraft people are looking after your safety.

There are other types of aircraft tubing. Example:

- stuctural tubing, made of 6AL-4V which is usually welded into place

- welded, thinwalled tubing which is used in larger diameters for airconditioning or other low pressure circuits

6. There are naturally non-aircraft products made from 3AL-2.5V Ti-alloy too. Examples :

   - golf shafts (20) with better resistance to torque and twisting than carbon fibre or high strength steel.

   Golf fans swear that Ti-shafts is the best thing since the invention of the wheel.

   - In Tennis rackets (21) the non-twist properties of Titanium are particularly appreciated.

   - Racing and mountain bike fanatics are becoming more and more aware of the sultability of hard titanium tubing. The frame is welded.

   - Titanium is particularly suited for medical application as for bone and teeth screws, wheelchair frames, implants of many types (22). This drill handle is made from regular Aircraft tubing. It is transformed by "superplastic forming" at 900°C into the most suitable, ergonometric shape.

   Titanium was selected because of

   . the excellent superplastic properties of 3AL-2.5V
   . its lightness wich is essential in dentistry
   . the agreable, warm feel of titanium vs chromed steel
   . the antiseptic properties of titanium
   . and price (no complex milling and rectification)

8. Conclusion :

   (23)
   10 years ago titanium was at least 5 times more expensive than quality stainless aircraft tubing. Today the ratio is reduced to approx 60 to 100 %. As the tube costs only about 5 % of the price of a finished tube assembly, the actual cost increase for a Titanium tube assembly vs a stainless tube assembly is 5 % too or approx $ 120 per kg. Airlines pay per economised kg up to $ 2000. This is why Titanium will find more and more applications in weight and fuel-sensitive Aircraft design.

   Other new materials such as Kevlar or carbon fibre have certainly a variety of uses but seem less suited for internally pressurized tubing.

I will be pleased to answer questions you might have with regard to Titanium tubing and tube assemblies.

Thank you for listening.

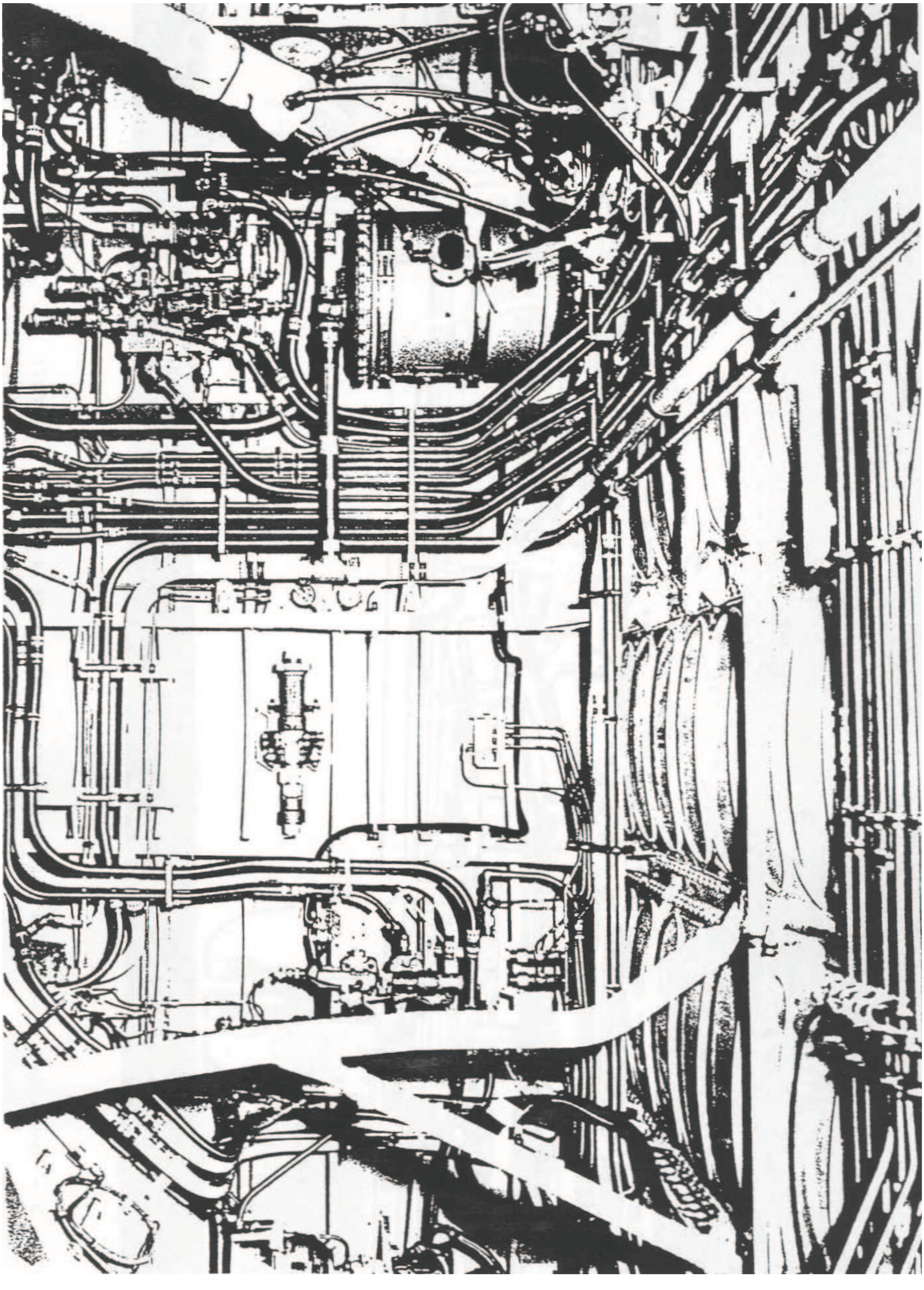


Fig. 1 – View of hydraulic system in a modern aircraft

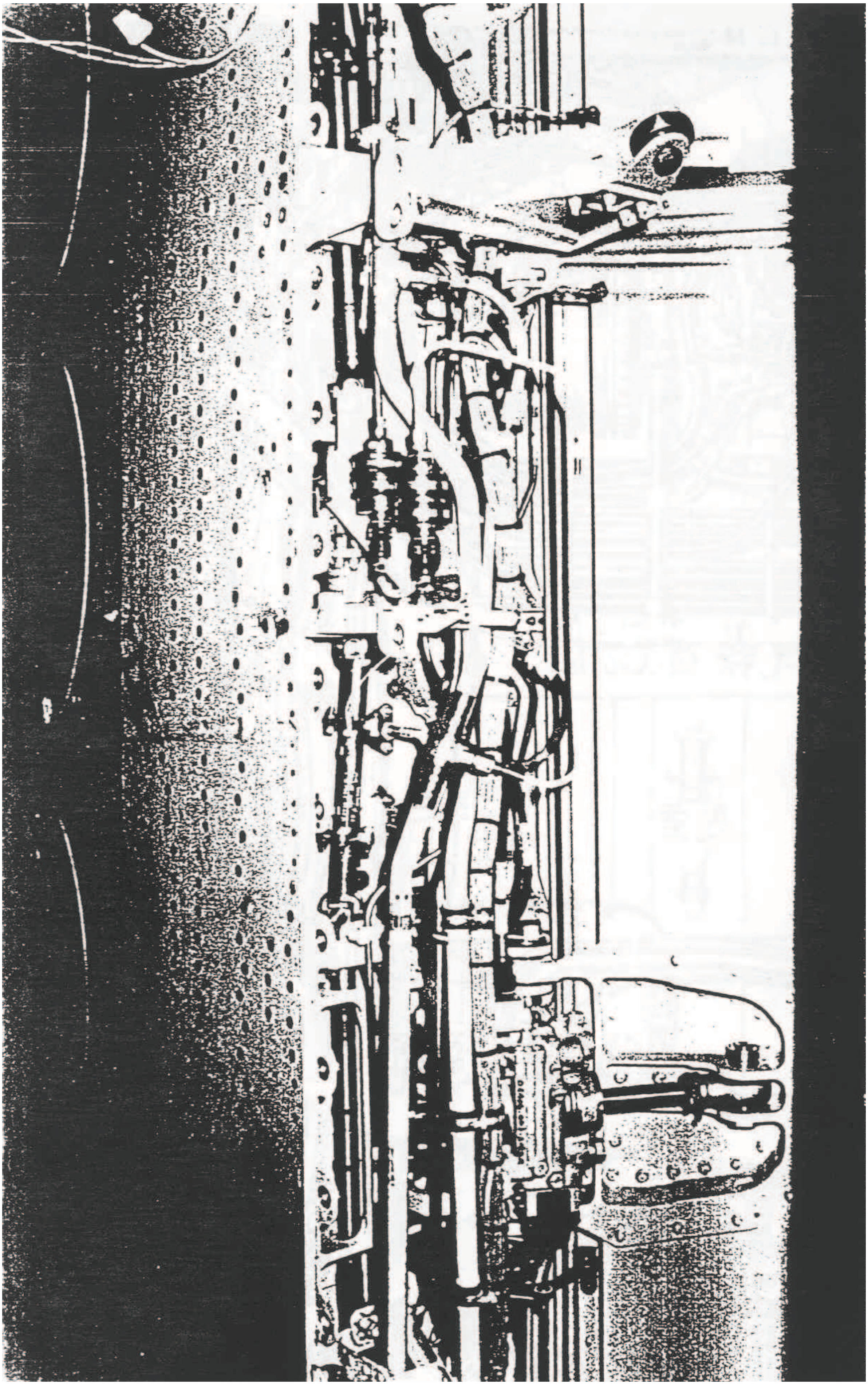


Fig. 2 - Hydraulic system for functioning the flaps of a modern aircraft

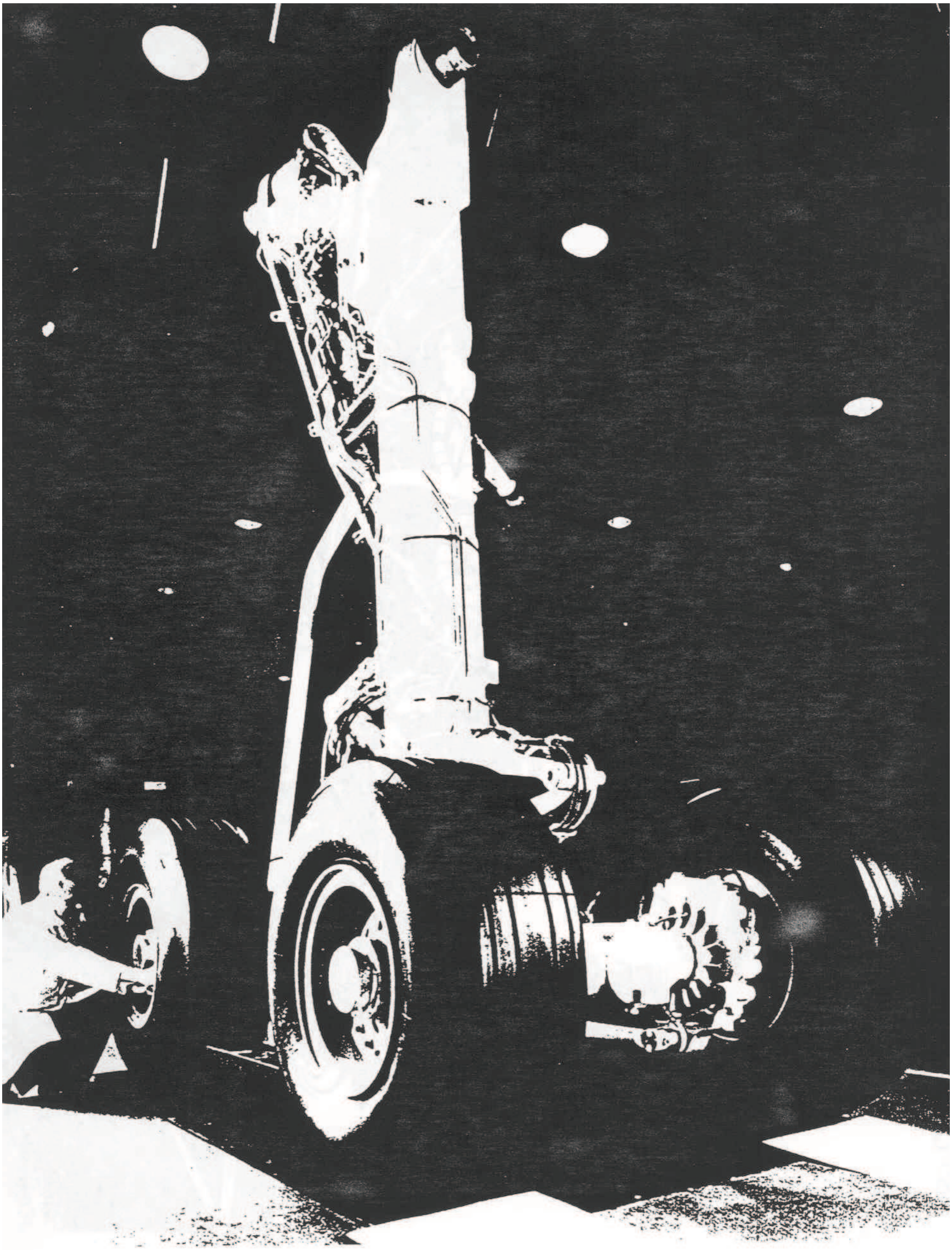


Fig. 3 – Landing gear of a Airbus A-330

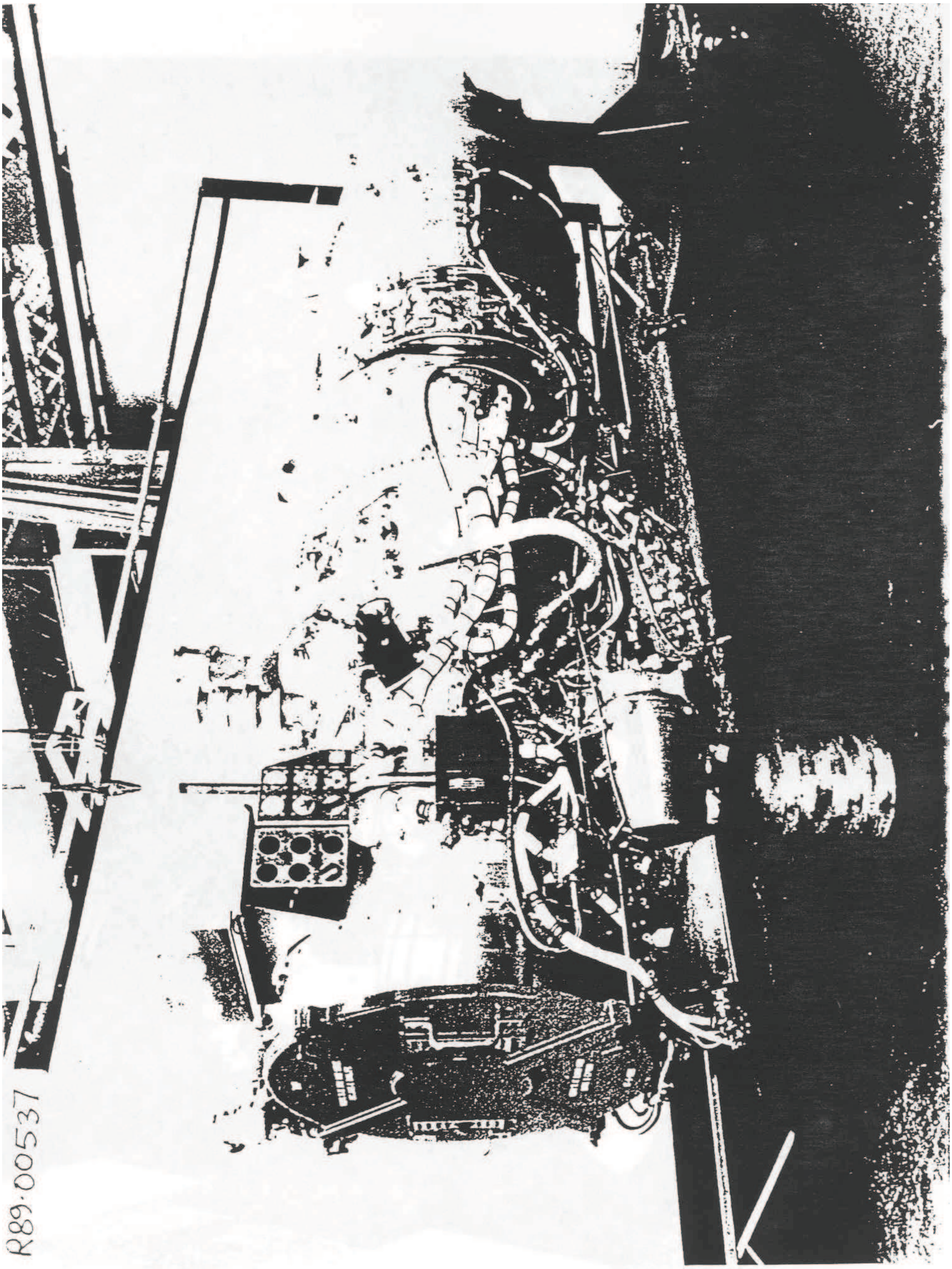


Fig. 4 - V-2500 engine assembly

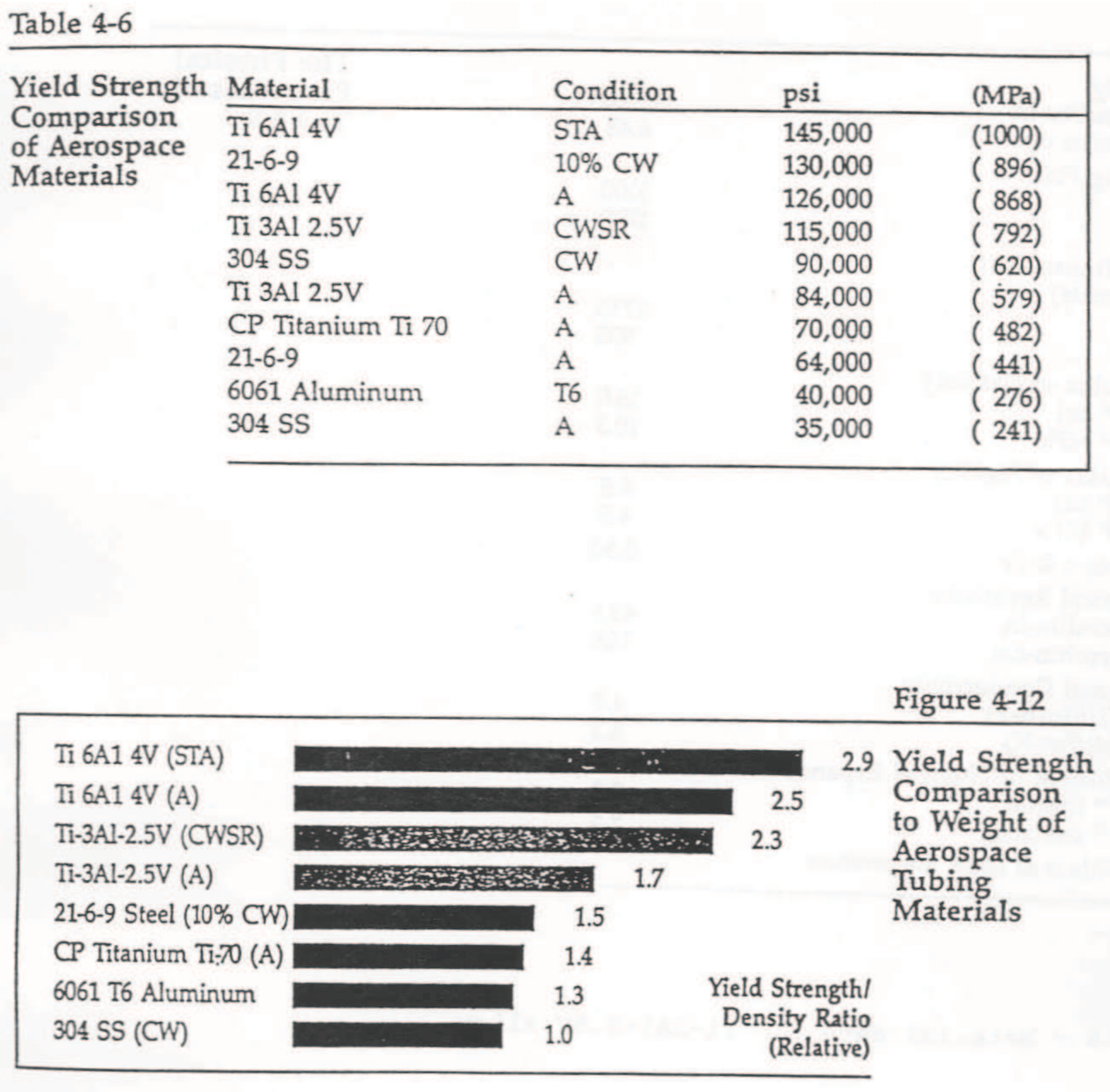


Table 4-6

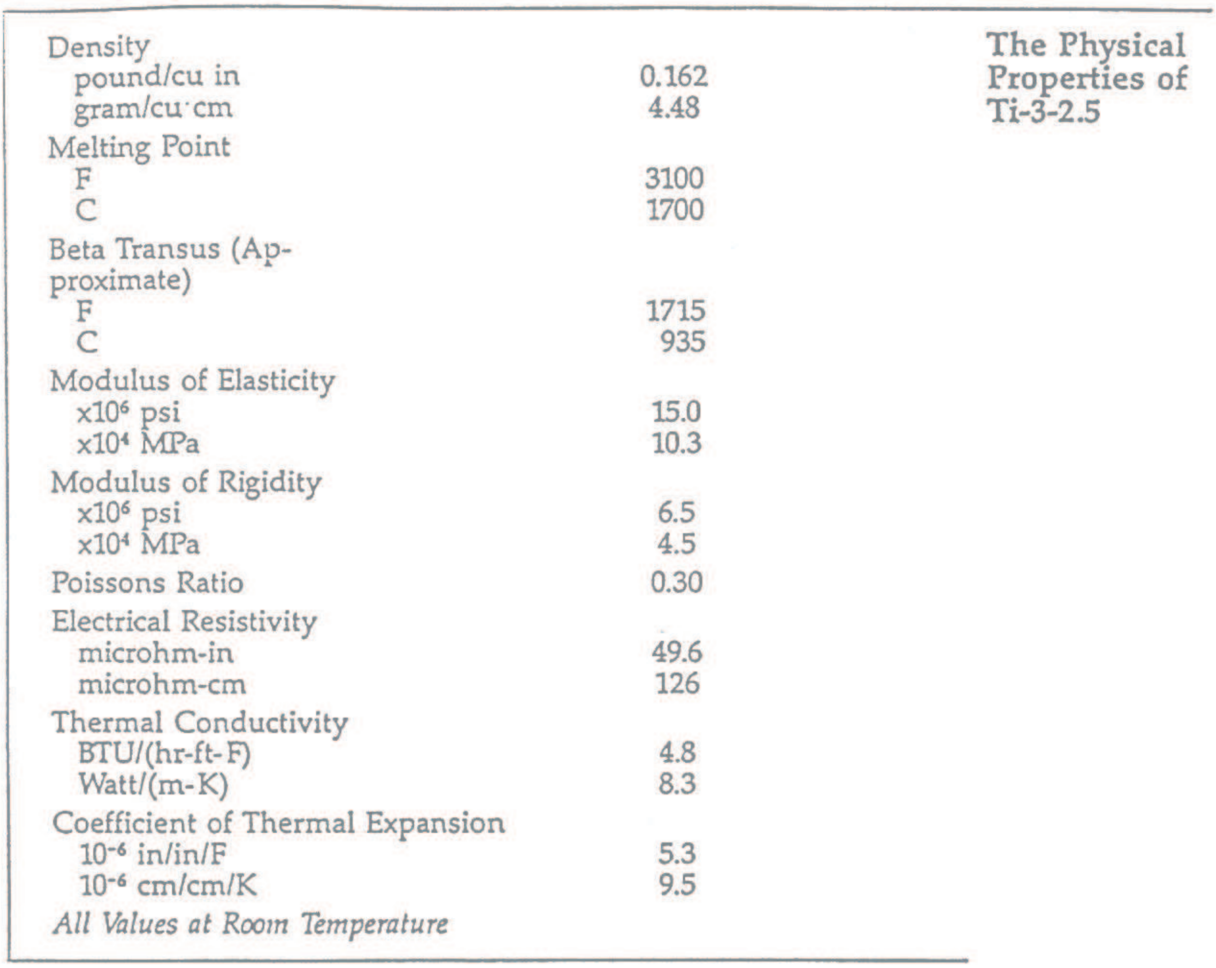
Yield Strength Comparison of Aerospace Materials

Material	Condition	psi	(MPa)
Ti 6Al 4V	STA	145,000	(1000)
21-6-9	10% CW	130,000	(896)
Ti 6Al 4V	A	126,000	(868)
Ti 3Al 2.5V	CWSR	115,000	(792)
304 SS	CW	90,000	(620)
Ti 3Al 2.5V	A	84,000	(579)
CP Titanium Ti 70	A	70,000	(482)
21-6-9	A	64,000	(441)
6061 Aluminum	T6	40,000	(276)
304 SS	A	35,000	(241)

Figure 4-12

Yield Strength Comparison to Weight of Aerospace Tubing Materials

Fig. 5 - Strength data for some tubing materials



The Physical Properties of Ti-3-2.5

Density	
pound/cu in	0.162
gram/cu·cm	4.48
Melting Point	
F	3100
C	1700
Beta Transus (Approximate)	
F	1715
C	935
Modulus of Elasticity	
x10^6 psi	15.0
x10^4 MPa	10.3
Modulus of Rigidity	
x10^6 psi	6.5
x10^4 MPa	4.5
Poissons Ratio	0.30
Electrical Resistivity	
microhm-in	49.6
microhm-cm	126
Thermal Conductivity	
BTU/(hr-ft-F)	4.8
Watt/(m-K)	8.3
Coefficient of Thermal Expansion	
10^{-6} in/in/F	5.3
10^{-6} cm/cm/K	9.5

All Values at Room Temperature

Fig. 6 - Material data for Ti-3Al-2.5V alloy

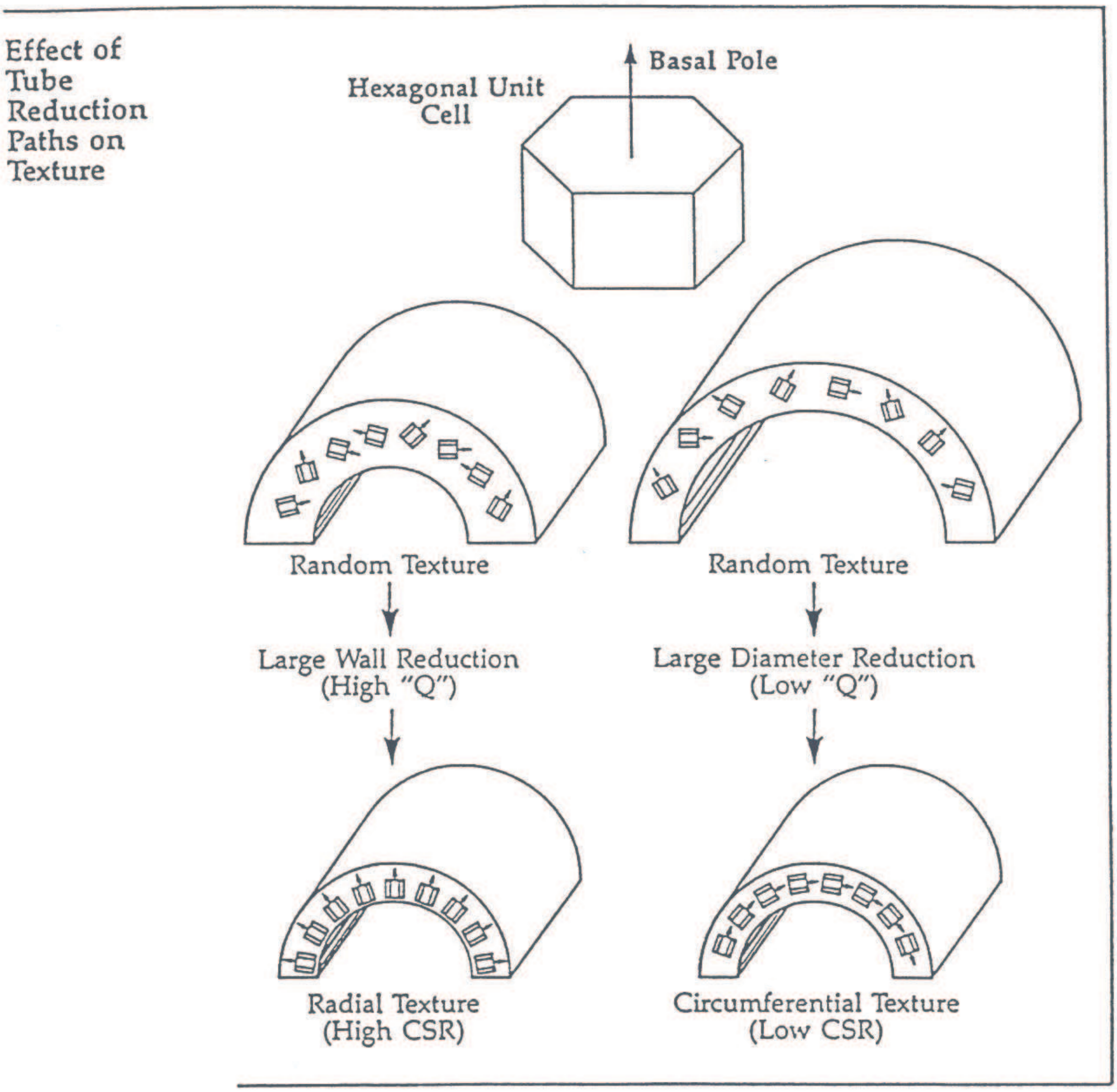


Fig. 7 - Effect of the tube reduction path on texture

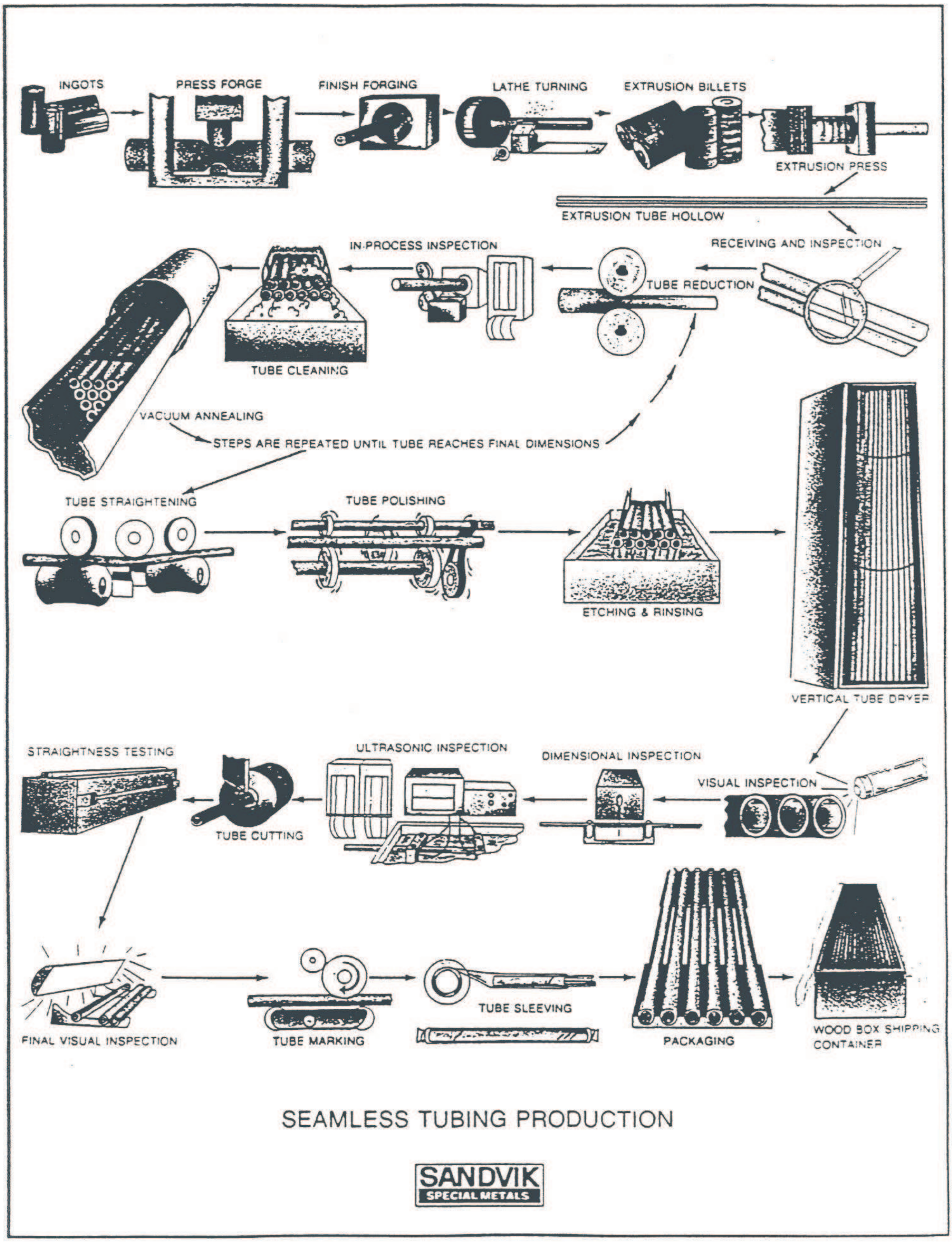
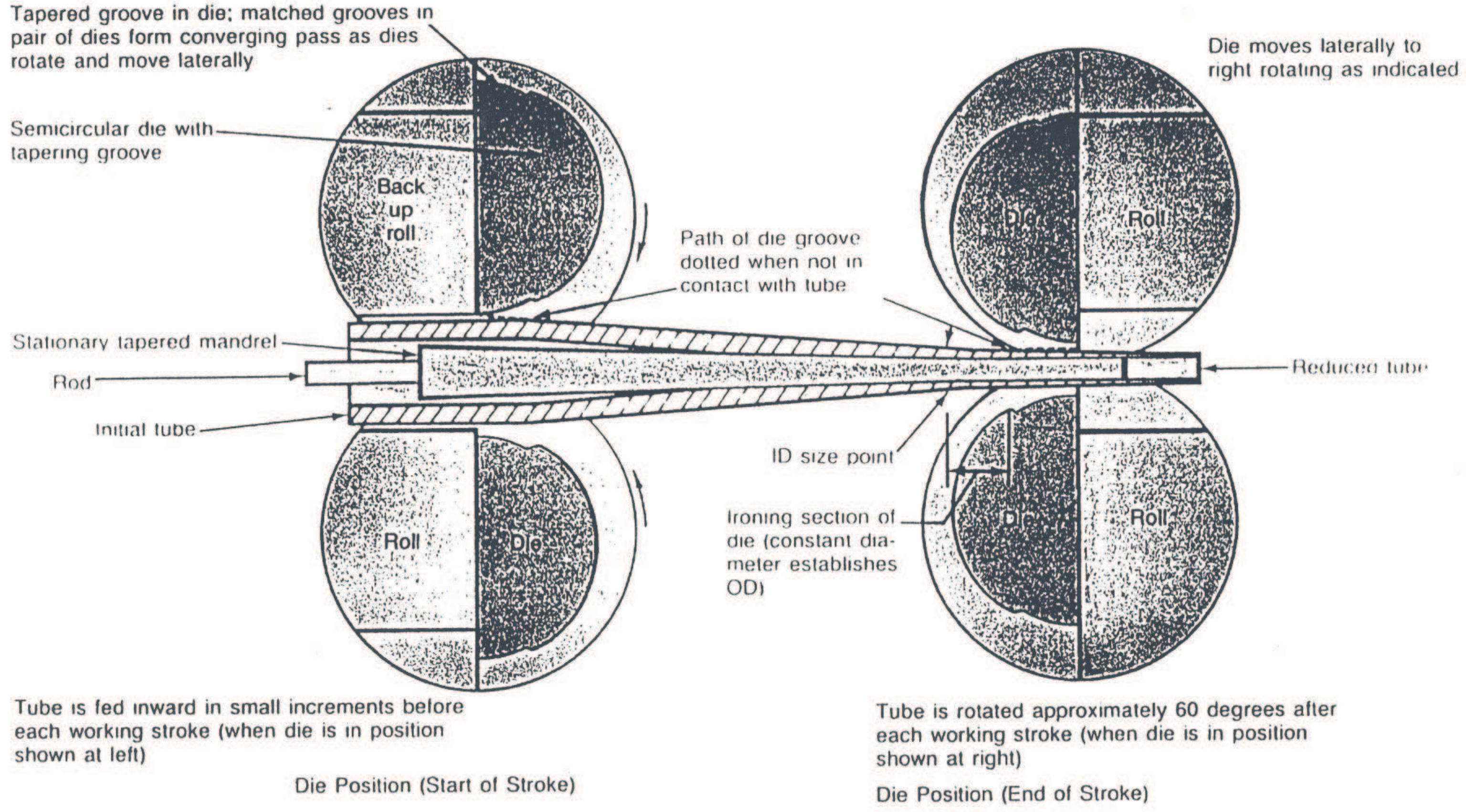


Fig. 8 – Ti-3Al-2.5V seamless titanium tubing production cycle

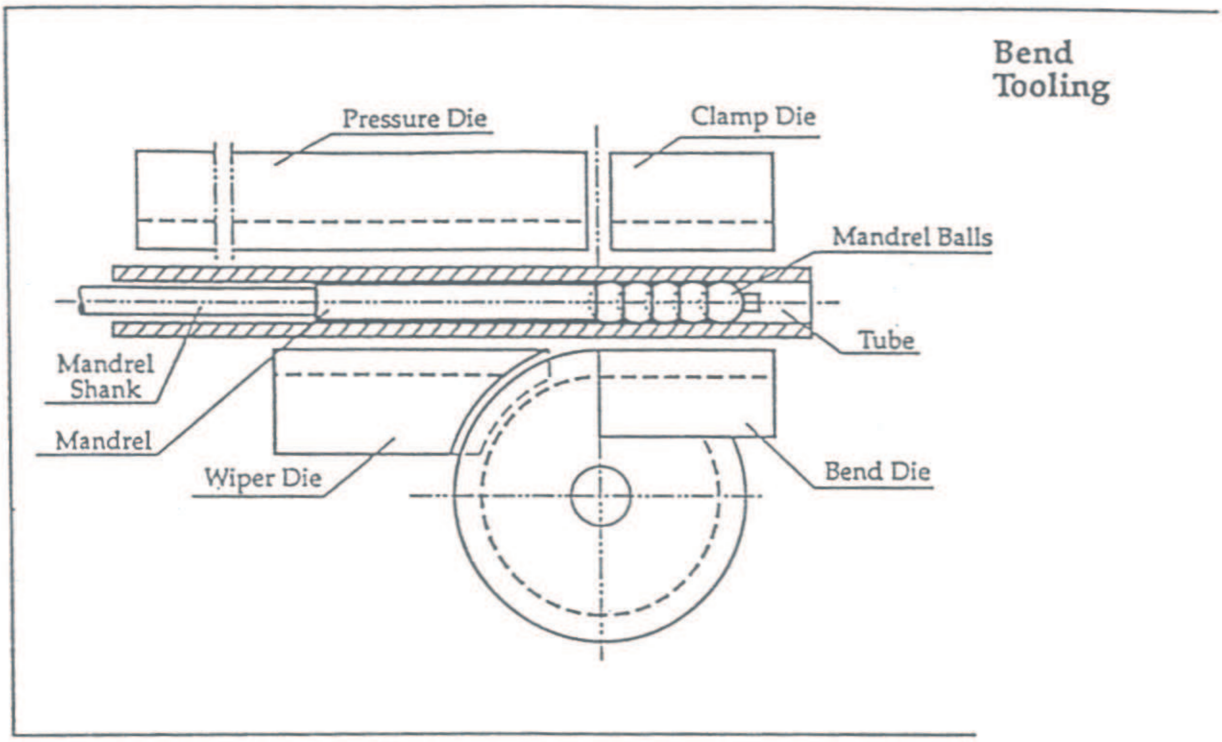
VERTICAL SECTION THROUGH TUBE REDUCER AT START AND END OF REDUCTION STROKE



Vertical section through the tube reducer shows dies at start and end of stroke. Because of the compressive forces and incremental working, tube reducing provides much greater reductions than die drawing.

SANDVIK
SPECIAL METALS

Fig. 9 - Tube reduction cycle: diagram of the cold pilgering



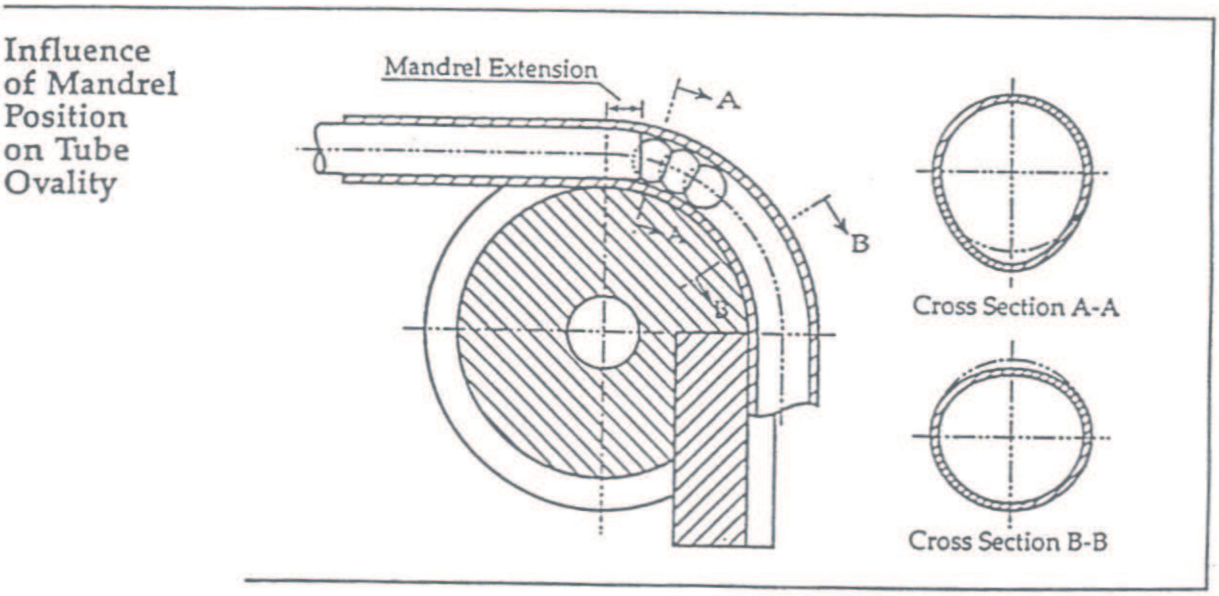


Fig. 10 - Titanium tube bending tools

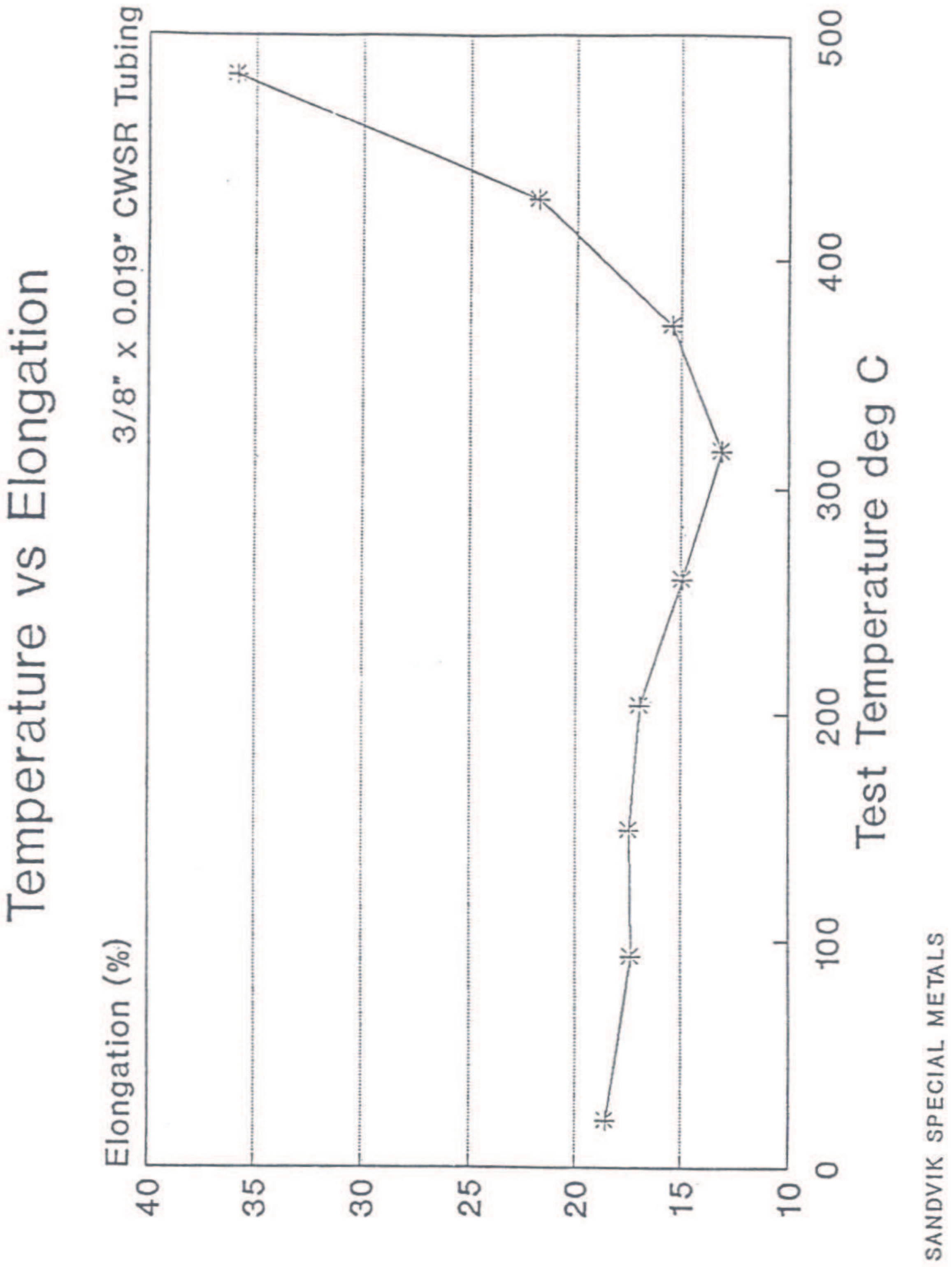


Fig. 11 - The effect of temperature on ductility of Ti-3Al-2.5V tubing

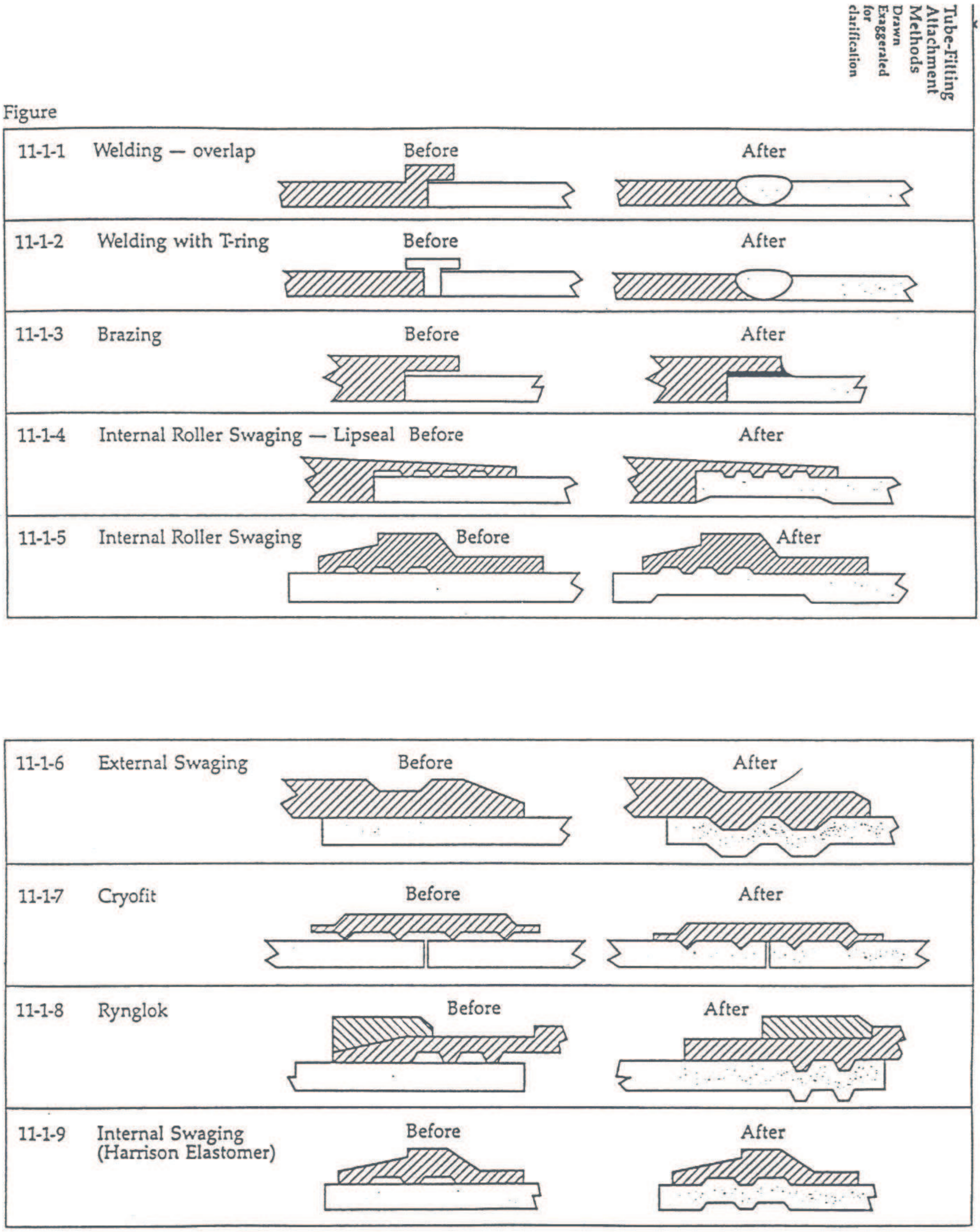


Fig. 12 - Tube-fitting attachment method

AIRCRAFT FITTINGS FOR 3AL-2.5V TUBING - Inch fittings - welding brazing

(All welded fitting systems have developped a range of shaped fittings with welded ends which are not shown in this list).

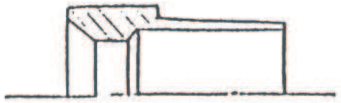
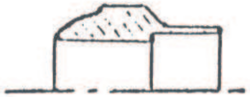
Fitting type	User P/N	Interface	Pressure level	Applications
	P + W/JAEC MS 9483 (Sierracin interchange EP0038T)	37°	engine	F100, V-2500
	General Electric	60°	engine	GE 404
	Boeing AS 1581 (Sierracin interchange 35211)	24°	3000 psi	Boeing 757/767
	Aerospatiale BAE	45°	4000 psi	Concord

Fig. 13 - Actual fittings used

AIRCRAFT FITTINGS FOR 3AL-2.5V TUBING - Inch fittings rolled

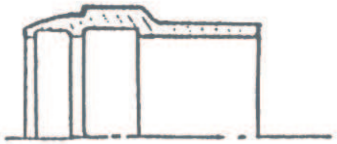
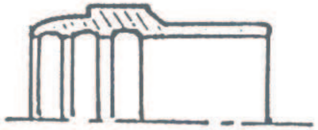
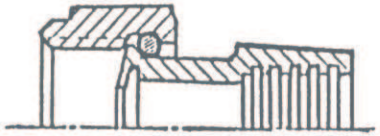
Fitting type	User P/N	Interface	Pressure level	Applications
	Boeing BACS13BX (Sierracin 35235VXX)	24°	3000 psi	Repair, Production back-up
	Airbus 35211/12 ASNA 3759	24°	3000 psi	A-320 A-330 A-340
	Resistoflex Aeroquip Sierracin/Harrison 35247	8 1/2°	3000 psi 4000 psi	F-15, F-18, B1, B2 Space Shuttle AV-8B

Fig. 14 - Actual fittings used

AIRCRAFT FITTINGS FOR 3AL-2.5V TUBING

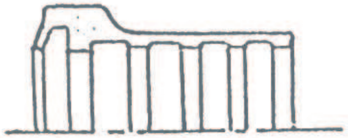
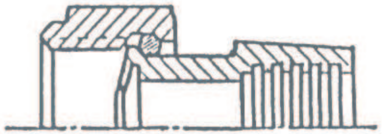
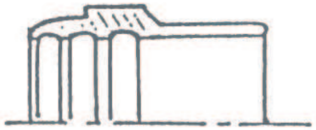
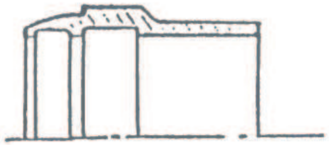
Fitting type	User P/N	Interface	Pressure level	Applications
		-- Metric fittings rolled		
	Sierracin P/N 38536	8 1/2°	4000 psi	(adapted to MBBN-EN-specifications)
	Aeroquip Resistoflex	8 1/2°	4000 psi	
	Sierracin P/N 58512	24°	5000 psi	possibly repair
		-- Metric fitting - expander swaged - Tube T40		
	Dassault 74741 (S/H 38512)	24° ISO	4000 psi	Mirage 2000

Fig. 15 - Actual fittings used

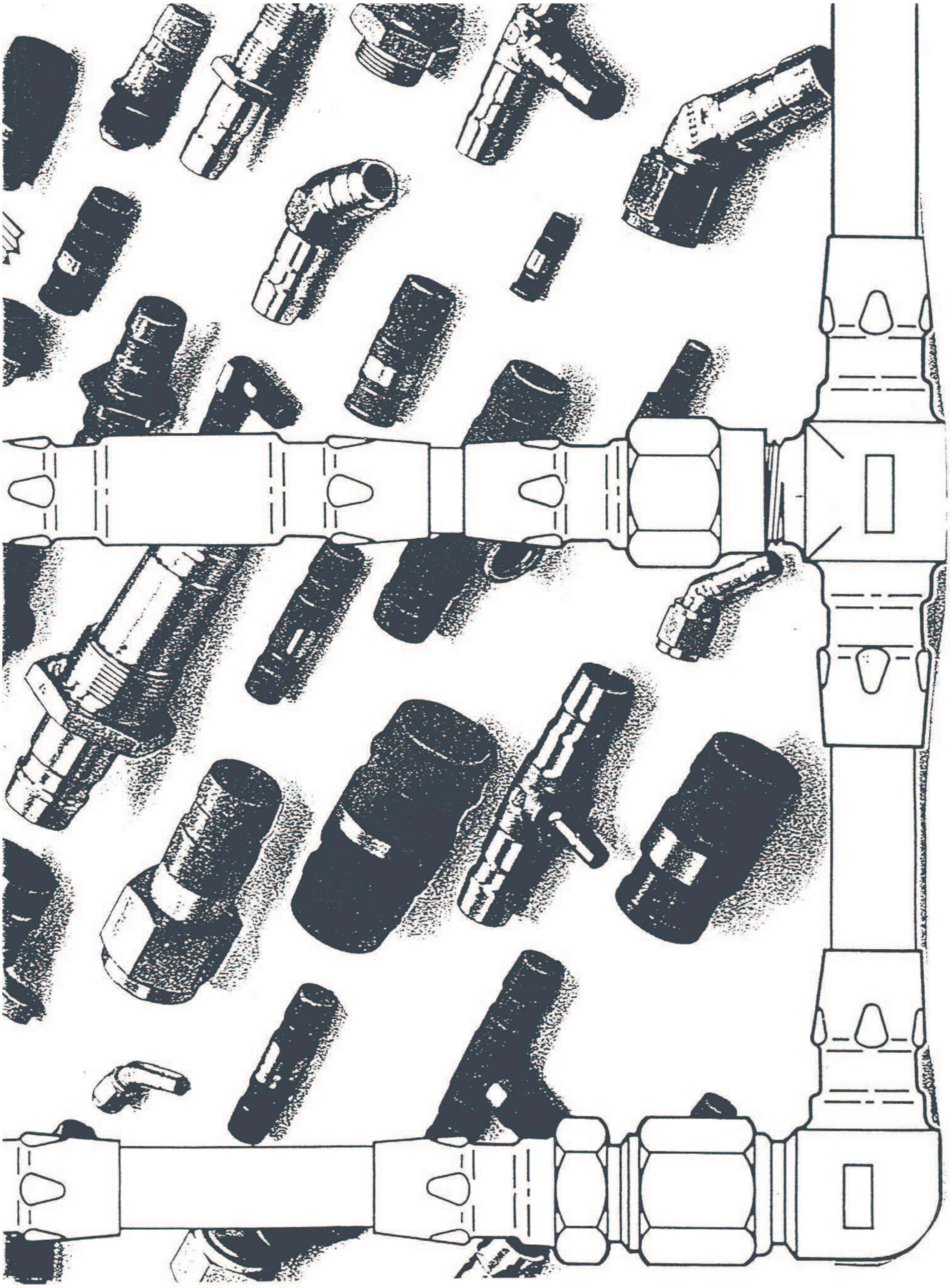
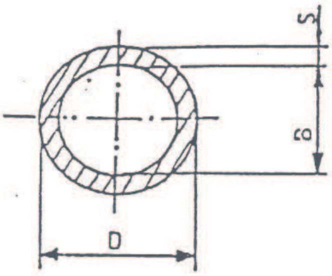


Fig. 16 - Permanent fittings for titanium tubing



MARKING PER
SPEC. DAN436

TABLE 1

S			NOM.	.016 (0,41)		.019 (0,48)		.026 (0,66)		.032 (0,81)		.039 (0,99)		.051 (1,30)	
			MIN.	.0152 (0,386)		.0181 (0,458)		.0247 (0,627)		.0306 (0,772)		.0371 (0,941)		.0485 (1,231)	
DIA DASH NO. (a)	D (b)			INTERNAL DIAMETER B IN inch (mm)											
	NOM.	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.
4	1/4 (6,35)	.250 (6,35)	.253 (6,43)	.2165 (5,499)	.2195 (5,575)										
6	3/8 (9,53)	.375 (9,53)	.378 (9,60)			.3355 (8,522)	.3385 (8,598)								
8	1/2 (12,70)	.500 (12,70)	.504 (12,80)					.446 (11,33)	.450 (11,43)						
10	5/8 (15,88)	.625 (15,88)	.629 (15,98)							.5585 (14,185)	.5635 (14,313)				
12	3/4 (19,05)	.749 (19,025)	.754 (19,15)									.6695 (17,004)	.6745 (17,132)		
16	1 (25,40)	.998 (25,35)	1.004 (25,50)											.895 (22,73)	.901 (22,89)

(a) DASH NUMBER INDICATES NOM. DIA IN 1/16 inch INCREMENTS

(b) TOLERANCES FOR NOM. OUTSIDE DIAMETER INCLUDES OVALITY TOLERANCES

② COMPLETELY REVISED

PAGE	01	02	03	04
ISS./REV.	②	①	②	①

Form: AIF 8001

Approved	Title	Classification
AIRBUS-INDUSTRIE	TITANIUM ALLOY TUBING COLD WORKED AND STRESS RELIEVED FOR HYDRAULIC- AND FLUID SYSTEMS	ABS5004
	Issue: 11/84 Revision: ② 12/85	Page 01 of 04

Published and distributed by: AIRBUS-INDUSTRIE
31700 BLAGNAC
FRANCE

133203

Fig. 17 - Airbus Industrie specification for titanium tubing

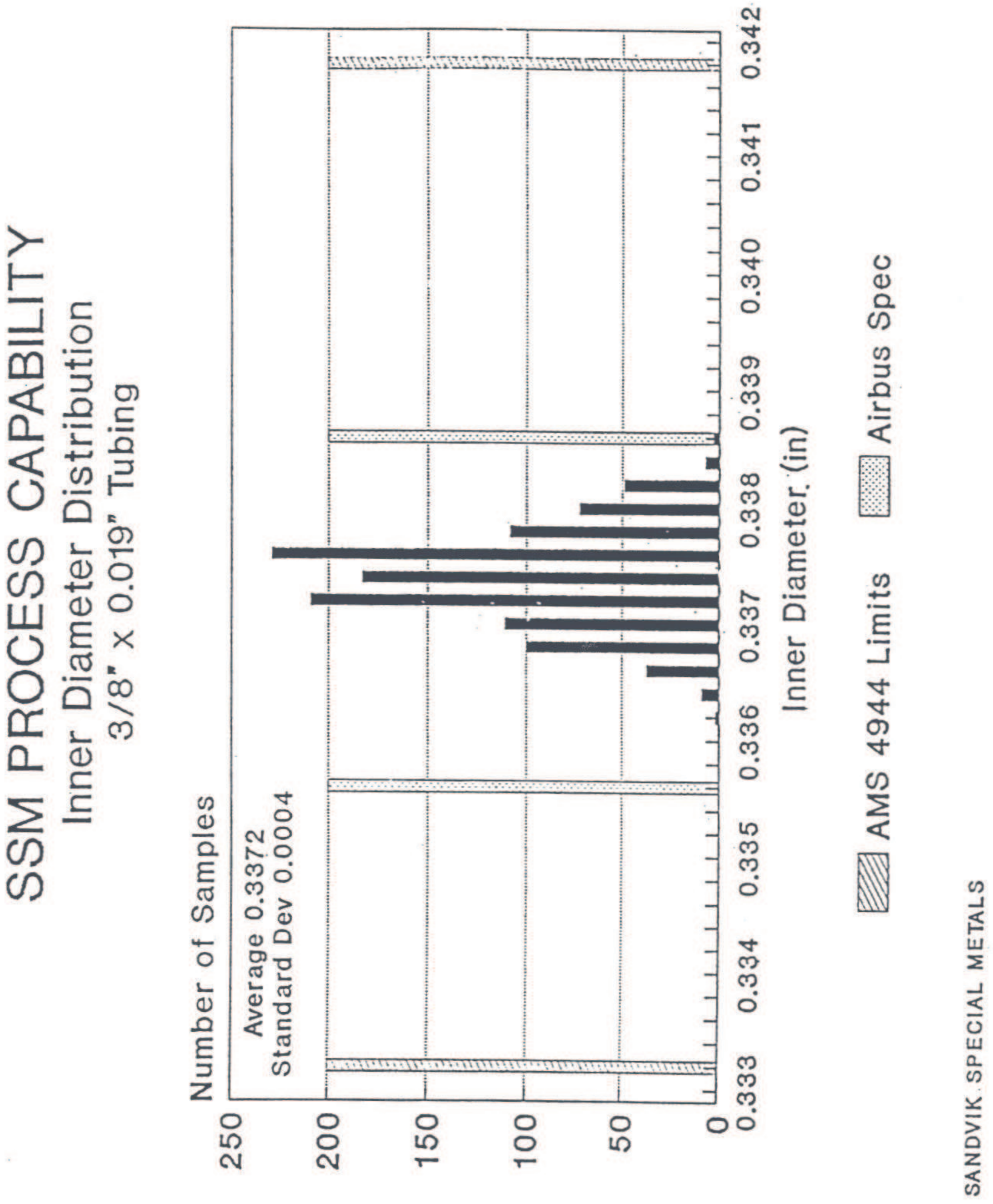
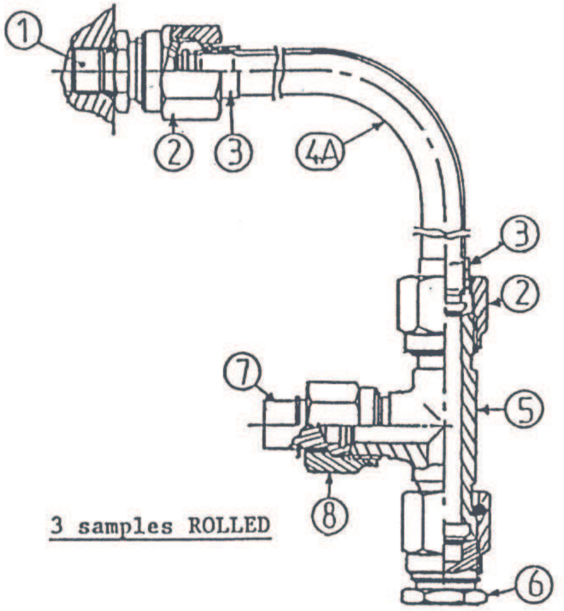
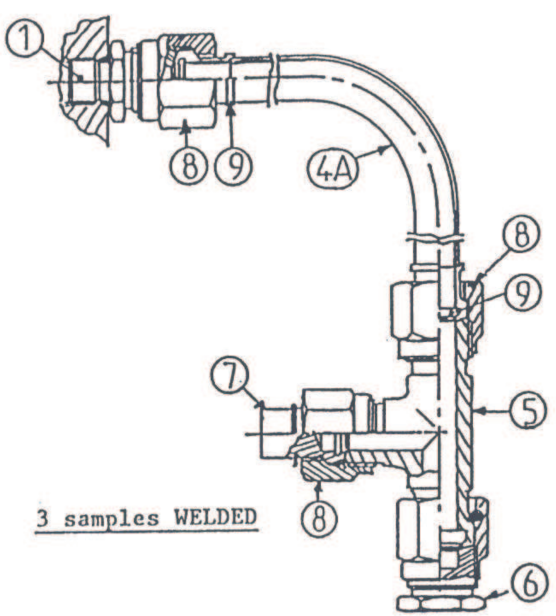


Fig. 18 - Comparison between AMS 4944 limits, Airbus specification and SSM process capability

HARDWARE FO EN 3275 TESTING - (SIZES 6mm to 28 r – ① IMPULSE



3 samples ROLLED



3 samples WELDED

Componants Qty Size	① Adaptor MS/MLS	② Nut	③ Sleeve	4A ti-tubing 90° bent	⑤ Tee EN3261	⑥ Plug EN3268	⑦ Ferrule EN3269	⑧ Nut EN3265	⑨ Slee EN32
06mm	6	6	6	6	6	6	6	12	6
08mm	6	EN 3265 6	38536T 6	6	6	6	6	12	6
10mm	6	6	6	6	6	6	6	12	6
12mm	6	6	6	6	6	6	6	12	6
14mm	6			6	6	6	6	18	12
16mm	6	6	6	6	6	6	6	12	6
20mm	6	38543T	38535T	6	6	6	6	18	12
22mm	6			6	6	6	6	18	12
28mm	6			6	6	6	6	18	12

Fig. 19 - Hardware for Ti-3Al-2.5V tubing testing

Ti-Shaft —
the Ti-3-2.5
Golf Shaft

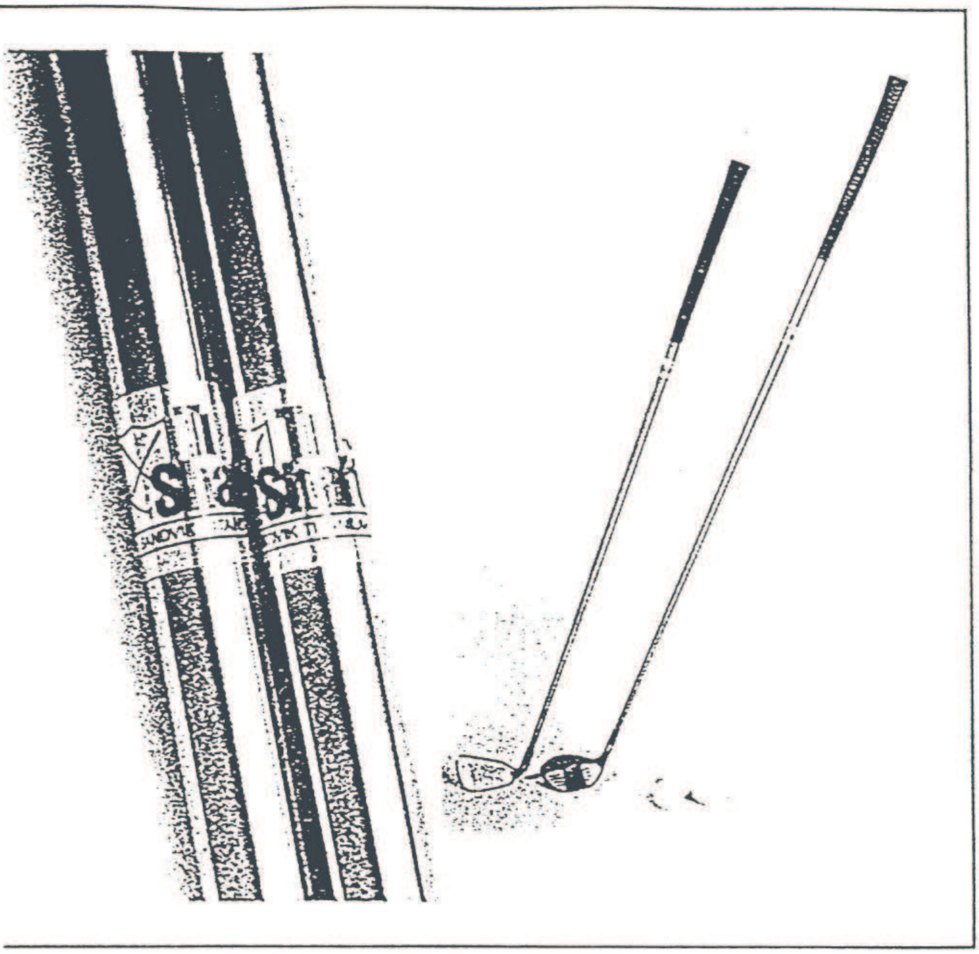


Figure 14-2

Elastic
Modulus
to Weight
Ratio
Comparison
of Different
Materials

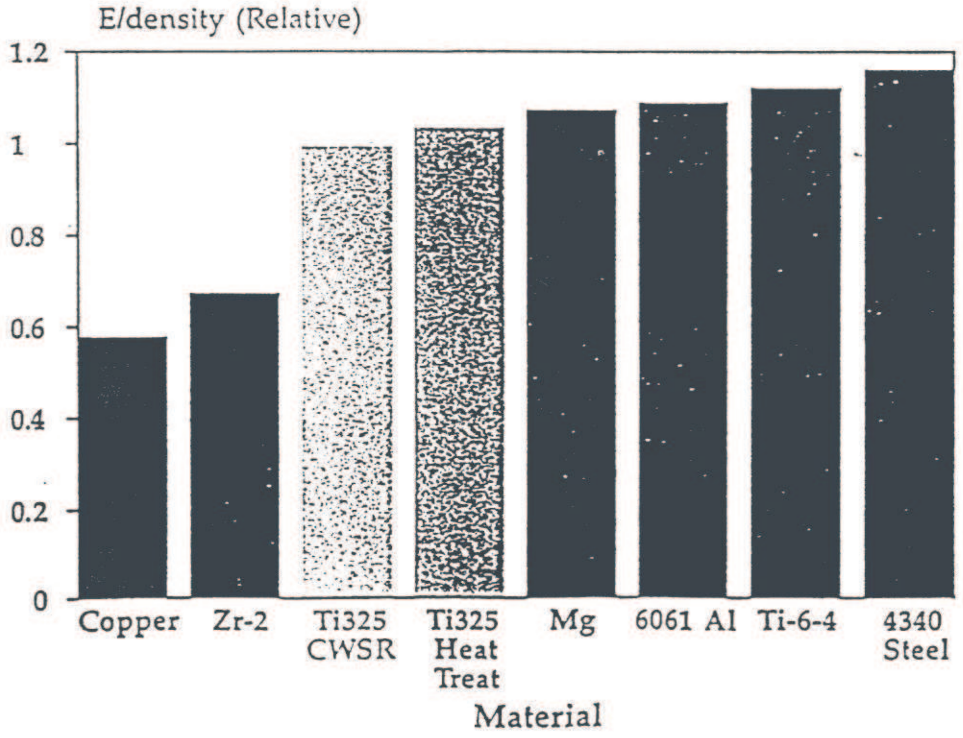


Fig. 20 - Ti-3AL-2.5V golf shaft and comparison of elastic modulus in different materials

Figure 14-4

Ti-3-2.5
Rackets

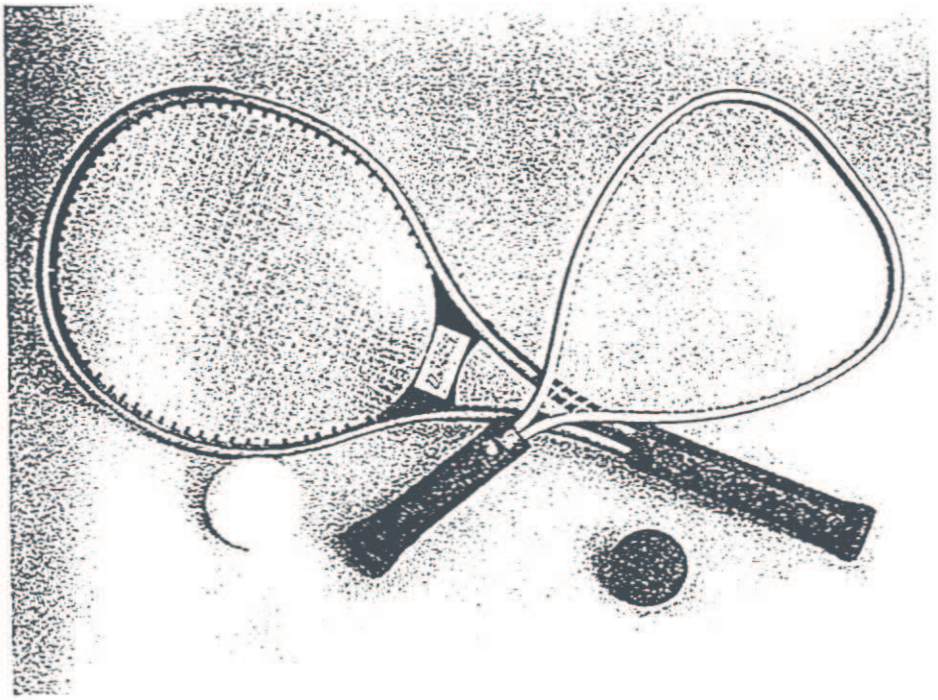


Figure 14-5

Ti-3-2.5
Mountain
Bike Frame

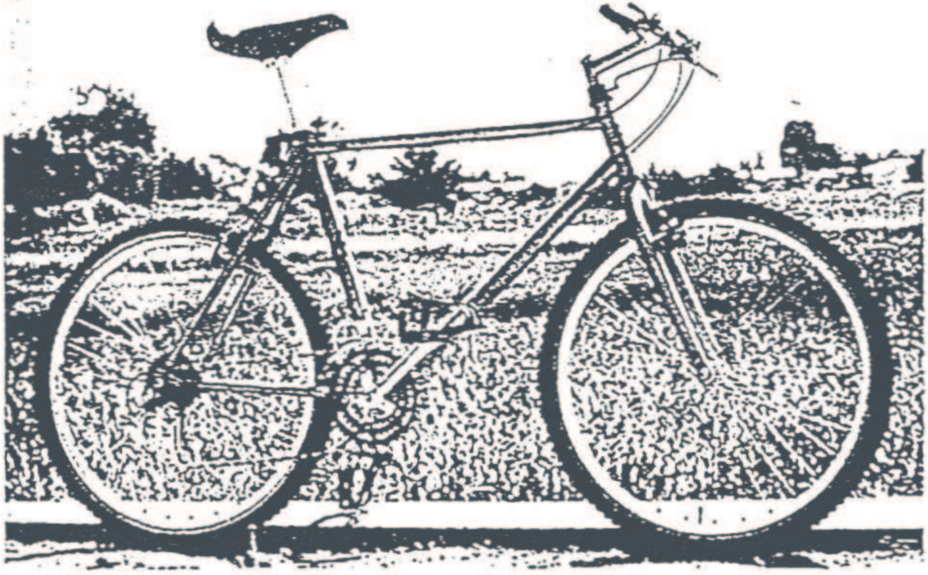


Fig. 21 - Ti-3Al-2.5V tennis rackets and mountain bike frame

Fig. 22 - Ti-3Al-2.5V tooth drill structure, superplasticity formed

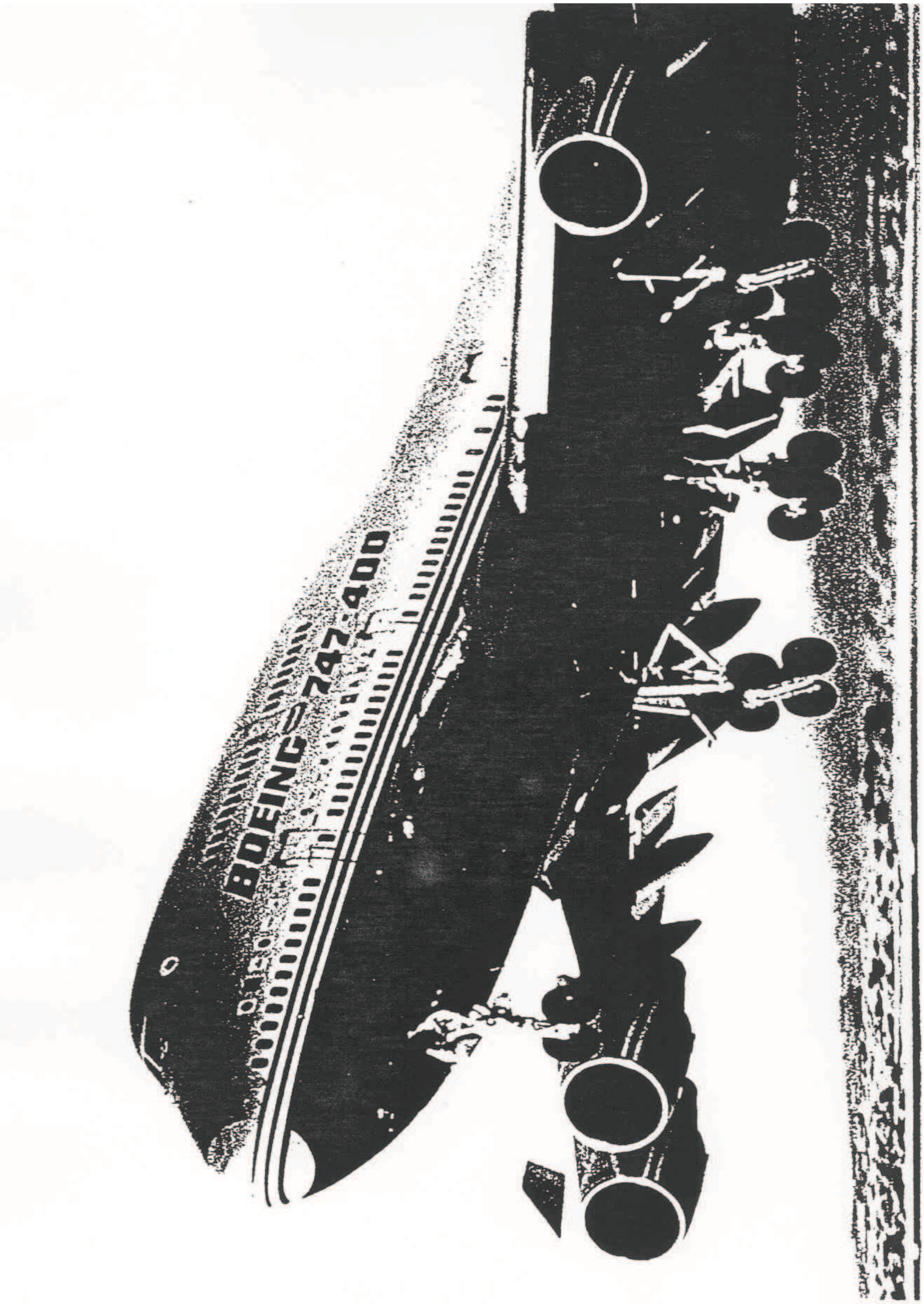


Fig. 23 - The Boeing 747-400 aircraft with Ti-3Al-2.5V hydraulic tubing

VI Meeting Internazionale sul Titanio
Torino, 23 Novembre 1990

"IDEE NUOVE NELLA CRESCITA ECONOMICO-INDUSTRIALE DEL TITANIO"

Monica Cariola - Gian Maria Gros-Pietro
Ceris - C.N.R.

E' la prima volta che in questo meeting internazionale sul Titanio, giunto ormai alla sua sesta edizione, il settore del Titanio viene esaminato anche dal punto di vista dell'economia industriale.
La platea qui presente non è probabilmente molto interessata a modelli economici complessi, tuttavia, anche ai fini di una trattazione tecnica, può essere utile cercare di interpretare alcune situazioni e circostanze particolari che abbiamo avuto modo di rilevare analizzando il settore industriale del Titanio.

E' noto che il Titanio è il quarto metallo strutturale per abbondanza sulla crosta terrestre (0,63%, dopo Alluminio, Ferro e Magnesio) nei giacimenti minerali industriali e che, per di più, tali giacimenti godono di una buona distribuzione geografica che li tutela da problemi di ordine politico-economico, che si riscontrano invece spesso per altre tipologie di industrie

estrattive.
E' altresì noto a Voi tutti che il Titanio ha delle caratteristiche strutturali e funzionali eccellenti, tali da poter essere impiegato nelle applicazioni più varie e severe.

Fatte queste premesse l'economista si chiede allora quale sia il motivo per cui, in presenza di una capacità di offerta potenziale così abbondante e di prestazioni di così primaria importanza, vi sia una notevole resistenza alla piena realizzazione, al pieno sviluppo dimensionale del settore del Titanio, che dovrebbe invece collocarsi, per capacità produttiva, consumi e applicazioni, fra quello degli acciai e quello delle leghe di Alluminio.

Le cause di questa situazione purtroppo sono molte e, spesso, strettamente correlate fra loro: tutte insieme hanno determinato la creazione di barriere talvolta reali, più frequentemente "formali", o meglio "artificiali", che hanno ostacolato l'ingresso nel settore del Titanio di nuovi soggetti economici, disincentivando anche gli investimenti di quelli già presenti e quindi limitando pesantemente lo sviluppo del settore secondo quelle che avrebbero potuto essere invece le sue reali potenzialità.

Se non si temesse di essere troppo tecnici, ma forse non è una parola così desueta, si potrebbe dire che siamo in presenza di una delle più classiche forme previste dalla teoria economica e cioè la restrizione della produzione e il freno allo sviluppo che sono tipica conseguenza di un mercato oligopolistico.

Torneremo in seguito su questo modello per vedere quali possono essere le frequenti vie di ulteriore sviluppo che si hanno in presenza di un mercato oligopolistico con potenzialità tecnologiche non sfruttate.
Si cercherà in questa sede di evidenziare alcune delle cause di questo status quo con le loro maggiori implicazioni (schematizzate nella Fig. 1) e di giungere implicitamente a suggerire nuove idee per il loro superamento.

Come possiamo notare nella parte alta della Fig. 1, lo scenario che riscontriamo nel settore del Titanio da circa 40 anni è caratterizzato da tre fattori chiave dai quali ne discendono poi altri a cascata.

1) Un primo fattore è la politica seguita dai produttori primari del Titanio, cioè i produttori di spugna, i quali, insieme ai produttori di semilavorati, hanno sinora privilegiato la fornitura di utilizzazioni ad alto prezzo, quindi si sono specializzati in business ad alto valore aggiunto, ad alto margine, caratterizzati da una bassa quantità: questa è quella che i managers e businessmen chiamano una politica di nicchia e che noi economisti chiamiamo una politica di restrizione della quantità.

2) Il secondo fattore chiave, coerente con il primo, è lo strettissimo legame tra l'industria del Titanio e l'industria aerospaziale. Ovviamente l'industria aerospaziale è caratterizzata da consumi relativamente bassi, rispetto al resto delle industrie manifatturiere, ma anche dalla capacità di pagare alti prezzi in funzione delle

prestazioni eccezionali che il Titanio può garantire rispetto ad altri materiali.

3) Il terzo aspetto, terzo fattore chiave, è la mancanza di una quotazione ufficiale del prezzo del Titanio (Borsa metalli o altro). E' un fattore che può sembrare un po' diverso dai primi due ma che è determinante nel produrre un mercato poco trasparente e poco efficiente nella allocazione delle risorse.

Se andiamo ad analizzare il 1° fattore, salta subito all'occhio (Vedi TAB. 1) che ci troviamo di fronte ad un mercato dominato da pochi produttori, di cui solo sei con produzioni significative (Timet, RMI, OREMET in USA, Osaka e Toho in Giappone, Deeside in Europa) che tutti insieme coprono circa la metà della capacità produttiva mondiale dichiarata, è bene sottolineare dichiarata perché poi vedremo che tale dato è da discutere, mentre la restante parte è ad appannaggio dell'URSS e, in misura molto minore, della Cina; tuttavia, relativamente a queste ultime due, poco viene ancora reso pubblico.

Si nota subito che stiamo parlando di un mercato molto piccolo (circa 85.000 ton di Titanio prodotte nell'88 contro le 17.000.000 ton, ad esempio, dell'Alluminio).
Quindi un mercato, come si diceva, di circa 200 volte inferiore a quello dell'Alluminio.
Inoltre, sebbene la concentrazione sia abbastanza elevata perché abbiamo sei produttori che coprono la metà della capacità, non abbiamo un grande leader, come per esempio Alcoa nell'Alluminio, che possa rendersi protagonista di investimenti di sviluppo, che

trascinino sia la tecnologia del settore, sia la promozione dell'impiego nei settori di sbocco.

Quindi abbiamo un oligopolio senza leadership. La teoria economica ci dice che l'oligopolio arriva normalmente a condizioni di equilibrio simile a quello del monopolio, in termini di restrizione della quantità, di prezzi più alti, di margini più confortevoli.

Ma, a differenza del monopolio, l'oligopolio può non avere le stesse capacità di gestione della tecnologia.

E questo succede quando non c'è la possibilità di una leadership.

In questo caso si possono perdere delle opportunità tecnologiche, cioè delle frontiere che potrebbero essere rotte non vengono aggredite e si accumula una differenza sempre più rilevante tra il livello di efficienza effettivamente raggiunto dall'industria e quello che potenzialmente la tecnologia renderebbe attuabile in un determinato momento.

Qui si apre il capitolo degli sviluppi possibili di un mercato di oligopolio con queste caratteristiche.

Siamo in quello che noi economisti chiamiamo un mercato contendibile, cioè un mercato che apparentemente è assestato con delle strutture di controllo in mano a pochi produttori ma che è facilmente, almeno in linea teorica, contendibile da parte di outsiders i quali abbiano le dimensioni ed intravedano la possibilità di rompere quei muri che gli attuali operatori non rompono.

Attualmente tale potenzialità potrebbe divenire attuale quando si congiungano due condizioni favorevoli. Da un lato un ampio mercato potenziale che potrebbe esistere già oggi per le considerazioni fatte prima, cioè abbondanza di offerta, minerale distribuito in tutti i Paesi, quindi non sottoposto a rischi politici, eccezionalità delle prestazioni del metallo.

Dall'altro, quando nuovi processi produttivi, come per esempio quello elettrolitico che è stato precedentemente illustrato dall'Ing. Orsello della GTT, consentano di cambiare sensibilmente la struttura di costo della produzione primaria. Allora, con la concomitanza di queste due condizioni, ci può essere il rischio o l'opportunità, a seconda di come la si giudichi, di un ingresso esterno.

In effetti questo rischio, analizzandolo da un punto di vista economico, sembra in questo momento profilarsi in modo concreto: infatti, uno dei principali ostacoli allo sviluppo del mercato del Titanio è costituito dal prezzo, più elevato rispetto a quello degli altri materiali strutturali; ciò è determinato in notevole parte dai costi di produzione della spugna, ancora molto alti a causa dei processi tradizionali impiegati, poco automatizzati, discontinui, ad elevati consumi elettrici e quindi ad alto costo della capacità produttiva per tonnellata. Infatti le lavorazioni metallurgiche successive del Titanio grezzo, dei semilavorati e dei lavorati sono analoghe a quelle degli acciai inossidabili e quindi non esiste una giustificazione economica per cui i costi di trasformazione debbano incidere sul prezzo finale del Titanio, rendendolo più elevato di quello degli acciai.

Non solo, ma il Titanio ha il vantaggio intrinseco di pesare la metà degli acciai inossidabili: quindi, per unità di lunghezza o di volume del prodotto, può costare la metà.

Tutto ciò ci conferma che il reale capitolo su cui lavorare per ottenere un allineamento del prezzo del Titanio con gli altri metalli strutturali e la metallurgia di produzione della spugna di Titanio.

La strategia di alto valore aggiunto e di basse quantità e l'esistenza di un vincolo tecnologico che porta all'uso di tecnologie obsolete possono non essere troppo penalizzanti quando le quantità sono piccole, appunto 1/200 per esempio di quelle dell'Alluminio, ma sicuramente sarebbero giudicate anti-economiche quando i volumi fossero più grandi.

Altro fattore sempre collegato al primo è <u>la carenza di fonti di dati e di statistiche veramente affidabili</u> relativamente al Titanio; in particolare, mentre sono più facilmente ottenibili dati sulle capacità produttive mondiali, altre grandezze (ad esempio produzioni effettive, consumi ecc.) sono di più difficile reperibilità, specie con riferimento ad URSS, Europa e Cina. Le uniche fonti ufficiali sono lo U.S. Bureau of Mines, i cui dati vengono raccolti in modo "acritico" dall'Associazione Americana per lo Sviluppo del Titanio (T.D.A.), e l'Istituto Giapponese per il Titanio; in Europa non esiste alcun organo che curi le statistiche e lo sviluppo del Titanio e, parimenti, non giungono ancora informazioni dai Paesi dell'Est, nonostante l'URSS sia il maggior produttore mondiale. Periodicamente vengono eseguiti studi di mercato, ma si tratta di solito anche in questo caso di elaborazioni acritiche, riscritture di medesime documentazioni che si originano dalle statistiche pubblicate dal Bureau of Mines.

Dalla scarsezza di fonti sulla produzione di Titanio ne deriva un'informazione carente ed inadeguata sulla situazione dell'industria che a sua volta, tuttavia, è la base di tutti gli studi che vengono eseguiti.
In particolare i dati sull'industria del Titanio raccolti all'inizio degli anni '80, in un periodo di mercato cedente e quindi poco dinamici, sono stati utilizzati per formulare delle previsioni che poi non sono state sufficientemente oggetto di revisione e di correzione. Tant'è vero che si è verificato in più di un anno che i consuntivi siano stati superiori alle previsioni, ma l'esistenza di proiezioni e di dati di stima del volume del mercato carenti per difetto rispetto all'effettiva entità del mercato, ha prodotto una di quelle previsioni che si autoadempiono. In altri termini, coloro che hanno esaminato l'opportunità di effettuare investimenti nel Titanio, sia già presenti nell'industria, sia potenziali entranti nella industria, hanno dovuto fare i conti con un quadro di dati statistici carente ed errato per difetto, il che ha portato a deprimere gli investimenti nel settore del Titanio.
Si è quindi creato un circolo vizioso di basse previsioni, basso investimento e quindi basso sviluppo dell'industria, alimentato per di più dagli alti costi che permangono poiché gli investimenti sono scarsi.

Un quadro informativo così carente fa parte delle caratteristiche che denotano un mercato imperfetto, un mercato quindi poco trasparente, poco efficiente nella allocazione delle risorse.

Affermare che il mercato è poco trasparente significa avere

la certezza o la sensazione che si 'hanno 'degli errori di percezione.
Questa certezza o sensazione deriva dal fatto che vi sono delle discrepanze tra la capacità produttiva denunciata e le produzioni reali dell'industria.

In effetti le capacità produttive che emergono dai dati lasciano seri dubbi circa la loro attendibilità, stante la fortissima distanza che in alcuni anni si è constatata tra capacità denunciata e produzione effettiva.
Nel 1983 il grado di sfruttamento della capacità produttiva ha toccato in U.S.A. un minimo del 43% (Fonte: T.D.A.) che è una condizione assai poco comune in qualunque industria dei materiali e che fa pensare che non tutte le capacità che vengono denunciate come esistenti siano in realtà funzionanti.
E in effetti tale situazione di forte eccedenza della capacità produttiva sulla produzione reale è smentita dai tempi di consegna dell'industria del Titanio. Sono normali, per le industrie di materiali quali l'acciaio inossidabile e l'alluminio, tempi di consegna pronta o al massimo di uno - due mesi. Nel caso del Titanio si è arrivati a punte di ottanta settimane, che non è certo una situazione che ci si può aspettare di riscontrare laddove la capacità produttiva è largamente eccedente la produzione.

Ciò porta a concludere, almeno chi è esterno al settore, che probabilmente le capacità produttive denunciate vengono sopravvalutate e che anche questo "errore statistico" contribuisce a quella scarsa trasparenza del mercato a cui si accennava, affinché gli investitori siano scoraggiati dall'investire nel settore ritenendo che esista già un eccesso di capacità produttiva, cosa che invece viene smentita dai tempi di consegna.

Naturalmente ci sono delle considerazioni tecniche, operative che possono in parte spiegare tali tempi di consegna: principalmente il fatto che l'industria del Titanio lavora per il settore aerospaziale la cui domanda è fortemente variabile; questo può portare all'inoccupazione temporanea della capacità o, in certi casi, ad una carenza di capacità.

Qui si innesta il secondo fattore chiave che avevamo enunciato all'inizio: il fortissimo legame col mercato aerospaziale.

Ci si chiede perché l'industria non esca dal mercato essenzialmente limitato all'aerospaziale e non affronti il mercato molto più vasto degli impieghi manifatturieri, degli impieghi terrestri (diciamo così) che potrebbero far fare un salto di almeno un ordine di grandezza se non di due a questo settore dei materiali.
Evidentemente una delle ragioni, forse quella principale, sta proprio nella politica di alti margini, di alto valore aggiunto che i grandi produttori di Titanio hanno continuato a seguire negli ultimi 40 anni. Una politica caratteristica di altri settori industriali, come per esempio quelli delle produzioni militari e belliche, che vede a fianco della connotazione dell'alto prezzo, quella della bassa quantità e quella dell'assenza o dell'estrema limitatezza dello sforzo di marketing.

Diciamo quindi che una competizione orientata a questi sbocchi comporta lo stabilimento di tecniche manageriali e di organizzazioni oltre che di culture aziendali assai poco adatte, almeno in una prima fase, ad affrontare un mercato diverso da quello originale.

Oggi con la distensione che ha steso le sue ali sullo scenario internazionale, si parla spesso di riconversione delle industrie belliche. Ovunque la riconversione di un'attività di tipo militare venga affrontata ci si trova sempre di fronte allo stesso problema: le imprese che producono per il militare sono prive di esperienza, di competenza e di volontà di affrontare una seria politica di marketing.

La sensazione che si ha dall'esterno è che anche l'industria del Titanio primario sia sostanzialmente in questa situazione.
Non volontà, forse, non convenienza di affrontare una politica che richiederebbe nuovi atteggiamenti e quindi abilità finora non possedute dalle imprese.
Il rischio naturalmente è che imprese ben più grandi, abituate ad operare su volumi dieci, cento volte superiori, abituate a fare marketing molto competitivo, intravedano la possibilità di operare anche in questo settore che ha così ampie potenzialità inespresse.

Ne viene fuori uno scenario che negli ultimi decenni è stato costellato da politiche aziendali scarsamente rivolte allo sviluppo di nuovi settori ed al marketing e che ha contribuito a fare del Titanio una specie di metallo prezioso, considerato

prezioso non solo dal consumatore finale, ma persino da alcuni produttori intermedi.
Questa situazione è confermata o aiutata nella sua stabilizzazione, dal fatto che i produttori di beni intermedi, per esempio i produttori meccanici, mentre sono di continuo visitati dai produttori di acciaio inossidabile, di leghe di alluminio, che propongono i loro materiali per le diverse produzioni meccaniche, non sono mai contattati da quelli del Titanio.

Probabilmente, anche l'apporto dei Mass-Media potrebbe aiutare la creazione di un clima propizio presso produttori ed utilizzatori e, indirettamente, favorire flussi finanziari verso tale settore.
E' mancato inoltre, fino ad oggi, un tipo o alcuni tipi di oggetti di largo uso che, venduti in gran numero, abbiano potuto far decollare anche nella mente del consumatore finale l'idea del Titanio come materiale di largo impiego strutturale. si ricorda a questo proposito il caso dell'Alluminio, il cui decollo presso i consumatori finali fu aiutato, negli anni '30, dalla diffusione del bollitore per il tè; un equivalente per il Titanio non si è ancora trovato. ci è pervenuta notizia di alcuni tentativi sporadici, ma non è facile trovare il canale giusto, molti fattori esterni intervengono: ad es. sono state sperimentate mazze da golf in Ti, un campione di tale sport ha vinto utilizzandole, come conseguenza ne sono state vendute molte; lo stesso si è tentato con le racchette da tennis, il campione che le ha impiegate non ha vinto, l'azienda americana che le produceva ha chiuso.

Questi due episodi dimostrano che il Titanio di per sé non è stato protagonista né dell'uno né dell'altro caso, protagonista è stato il campione.

L'importanza degli impieghi del Titanio nel settore aero-spaziale è stata certamente determinante in passato e lo sarà ancora in futuro, ma questo tipo di utilizzo ha ormai raggiunto lo stadio di maturità del suo ciclo di vita, potrà mantenersi su posizioni alte ancora per molti anni ma non ci si devono attendere per esso grossi incrementi nelle quantità richieste, almeno non tali da innescare quel decollo necessario a raggiungere il livello di produzione degli altri metalli suoi concorrenti.

Tale opportunità va ricercata potenziando i consumi dell'industria terrestre in genere, che si trovano ancora allo stadio iniziale del loro ciclo di vita e che promettono perciò ampi margini di incremento.

Nel contempo, in questi ultimi mesi, alcuni produttori di Titanio americani si sono resi conto per la prima volta di un fenomeno che era passato inosservato per circa trent'anni: tutti erano convinti che il settore aero-spaziale fosse per essi il più importante mercato, in quanto assorbiva le maggiori quantità di materiale, (vedi TAB. 2), ma ci si è accorti che di tali quantità, il 74% si trasformava in sfridi di lavorazione, reimmessi poi sul mercato sotto forma di rottame che, rifuso, andava a far concorrenza al titanio grezzo primario.

Seguendo quest'ottica i consumi effettivi finali U.S.A. di

Titanio nell'industria aero-spaziale sono stati in realtà nel 1989 circa del 30%, contro il 61% che sarebbero risultati essere se non si fossero considerati gli sfridi di lavorazione; al contrario gli altri tipi di impieghi del Titanio originano quantità di sfridi ben inferiori, 25% in media per le varie applicazioni industriali, nulla nel caso di aggiunta di Titanio ad altre leghe, per cui i loro consumi reali risultano essere, come percentuale sul totale, ben superiori a quelli riportati dalle statistiche.

In altri termini, la quota che l'industria aerospaziale rappresenta del totale del consumo effettivo di Titanio è ormai inferiore ad 1/3. E ciò pone in ulteriore evidenza la non appropriatezza, o addirittura la rischiosità per l'insieme del settore del Titanio, verticalmente considerato, del rimanere ancorato ad una politica di produzione della spugna che fa essenzialmente riferimento ad un'industria che non solo rappresenta il 30% dei consumi, ma che ha dei parametri di quantità e di costo molto diversi da quelli dei potenziali più grandi consumatori.

Se si considera infine il <u>terzo e l'ultimo fattore chiave</u> individuato all'inizio nello scenario del settore del Titanio (Fig. 1), cioè la <u>mancanza di una quotazione ufficiale dei prezzi del Titanio</u> (Borsa metalli od altro), ci accorgiamo subito che anch'esso non risulta avulso dal contesto che abbiamo fino ad ora delineato.

Questa caratteristica è infatti legata alle altre due: politica di nicchia e basse quantità; legame con un settore aero-

spaziale che spesso ha caratteristiche militari che portano allo stabilimento di prezzi diretti fra produttori ed utilizzatori, senza che si senta la necessità di un riferimento ufficiale.
E naturalmente questo è uno degli elementi che, insieme alla mancanza di dati, maggiormente contribuisce alla creazione di un mercato non trasparente e poco efficiente dal punto di vista economico.

I produttori non hanno mai favorito la fissazione di un prezzo ufficiale del Titanio. Ora, la mancanza di una quotazione, il fatto di avere una domanda erratica da parte del settore aerospaziale, il fatto di avere consegne molto lunghe e comunque con tempi variabili da parte dell'industria e, infine, la speculazione che in queste situazioni viene ovviamente resa possibile da parte dei commercianti, hanno portato il prezzo del Titanio ad essere fortemente oscillante. Questa è una delle condizioni che, caratteristicamente, pongono un materiale ai margini della grande struttura industriale manifatturiera. Essa determina sconcerto da parte degli utilizzatori e scoraggiamento da parte degli investitori, perché l'investitore non è tanto attirato dal prezzo alto dei periodi favorevoli che sa non essere una condizione permanente, quanto dalla possibilità dei prezzi bassi nei periodi sfavorevoli. In sostanza, si paga un prezzo dell'incertezza sotto forma di riduzione degli investimenti.

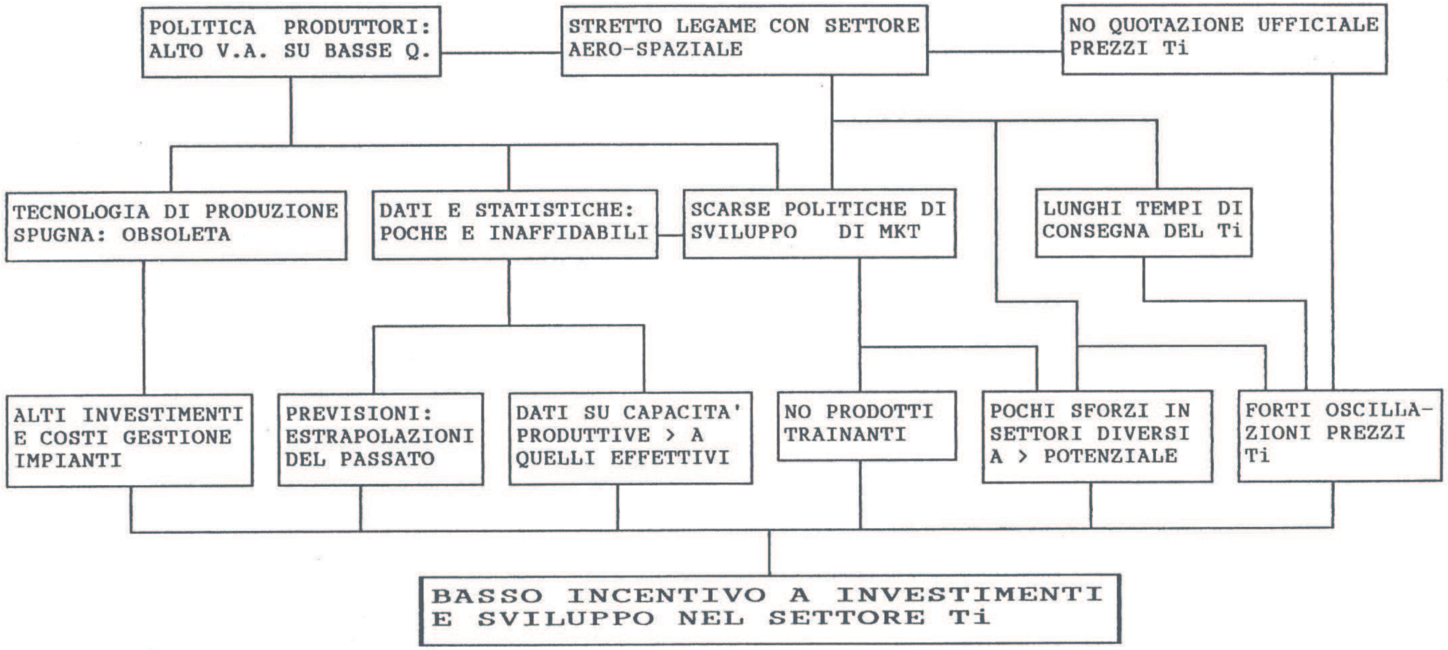
In conclusione quindi, l'insieme di questi elementi ha portato sino ad oggi l'industria del Titanio ad essere fortemente al di sotto delle sue potenzialità.
Non si vuol dare però l'impressione, con questo, di avere un opinione pessimistica sul futuro del Titanio. Noi stiamo vivendo

un periodo di evoluzione economica in cui i mercati contendibili vengono gradualmente, effettivamente contesi. L'ingresso di grandi gruppi nei mercati a basse quantità, ad alti margini e con potenziali di espansione, è ormai diventato un fatto all'ordine del giorno, che spesso si realizza attraverso operazioni di acquisizione.
Gli outsiders entrano in settori di questo tipo acquisendo uno degli operatori. E questo di solito è reso più facile proprio dalla politica di basse quantità, quindi bassa dimensione delle imprese da acquisire. Tale facilità di acquisizione e di alti margini rendono possibile per l'acquirente ripagare l'impresa acquistata con gli utili da essa derivanti in un giro molto breve di anni.

In futuro, quindi, queste possibilità potrebbero diventare reali, soprattutto in considerazione delle nuove opportunità tecnologiche che si stanno delineando nel settore e che rendono possibile aggredire, con un successo abbastanza facilmente prevedibile, segmenti molto più ampi di domanda.

FIG. N. 1

SCENARIO SETTORE Ti
NEGLI ULTIMI 40 ANNI



TAB. 1

CAPACITA' PRODUTTIVA MONDIALE DI SPUGNA DI TITANIO; 1980 - 1989

FONTE: U.S. Bureau of Mines - Japan Titanium Society

PRINCIPALI PRODUTTORI DI SPUGNA (Suddivisi per zona di appartenenza)	CAPACITA' PRODUTTIVA IN TONNELLATE EVOLUZIONE TEMPORALE									
	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
U.S.A										
TIMET	12.700	13.600	13.600	13.600	13.600	12.700	12.700	12.700	12.700	12.700
RMI Company	8.600	8.600	8.600	8.600	8.600	8.600	8.600	8.600	9.100	10.900
Oremet Titanium	2.700	4.100	4.100	4.100	4.100	4.100	4.100	4.100	4.500	5.500
Teledyne Wah Chang	1.400	1.400	1.400	1.400	1.400	1.400	-	-	-	-
International Titanium Inc.	-	-	2.300	2.300	2.300	2.300	2.300	-	-	-
Western Zirconium	-	-	500	500	500	500	-	-	-	-
TOTALE	25.400	27.700	30.500	30.500	30.500	29.600	27.700	25.400	26.300	29.100
GIAPPONE										
Osaka Titanium	11.800	13.200	18.200	18.200	18.200	15.400	18.200	11.800	11.800	13.200
Toho Titanium	9.100	11.800	11.800	11.800	11.800	11.800	11.800	9.500	9.500	10.800
New Metal Industries	2.300	2.300	2.300	2.300	2.300	2.300	2.300	-	-	-
Showa Denko	-	-	-	1.800	1.800	1.800	1.800	1.800	1.800	3.000
TOTALE	23.200	27.300	32.300	34.100	34.100	31.300	34.100	23.100	23.100	27.000
GRAN BRETAGNA										
Deeside Titanium	-	-	3.200	5.000	5.000	5.000	5.000	5.000	5.000	5.000
ICI	3.600	3.600	1.800	-	-	-	-	-	-	-
TOTALE	3.600	3.600	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
TOTALE MONDO OCCIDENTALE	52.200	58.600	67.800	69.600	69.600	65.900	66.800	53.500	54.400	61.100
ALTRI										
U.R.S.S.	34.900	41.700	45.400	45.400	47.200	48.100	48.100	49.900	49.900	52.200
Cina	1.800	2.700	2.700	2.700	2.700	2.700	2.700	2.700	2.700	2.700
TOTALE MONDIALE	88.900	103.000	115.900	117.700	119.500	116.700	117.600	106.100	107.000	116.000

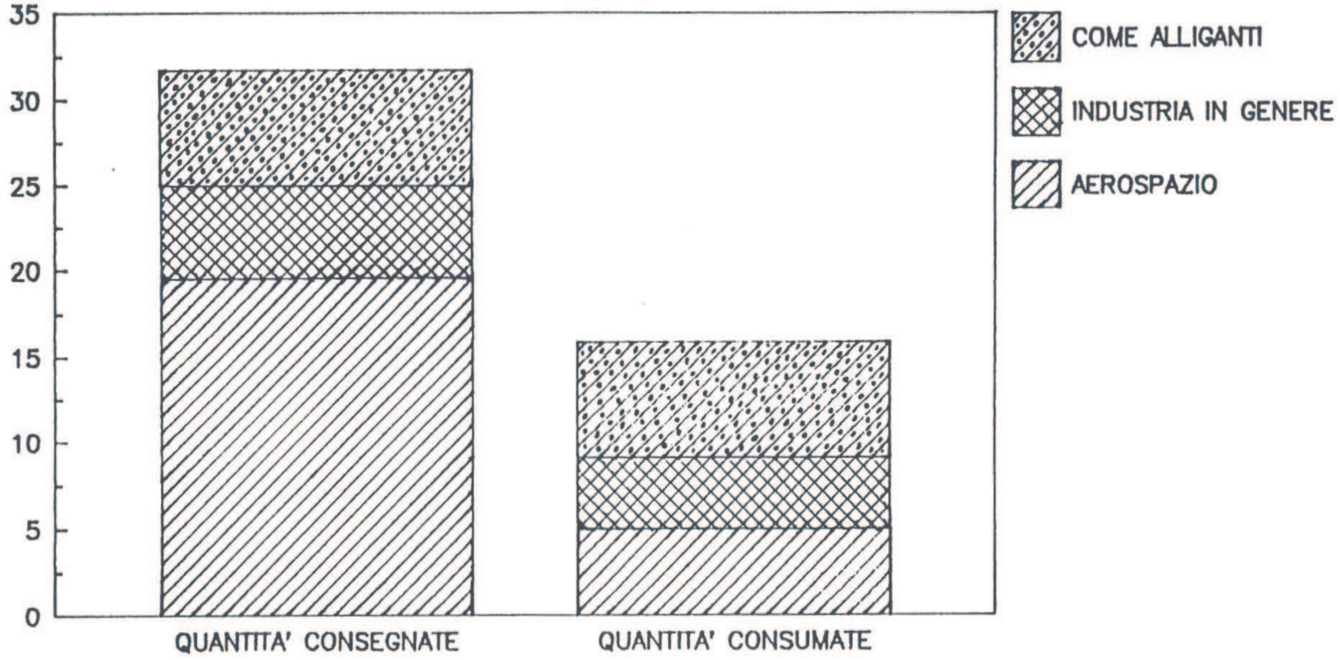
TAB. 2: STIMA DEI CONSUMI di Ti – 1989, U.S.A.

Fonte: elaborazione da dati RMI Company

SETTORI DI IMPIEGO	QUANTITA' CONSEGNATE A		QUANTITA' CONSUMATE B		QUANTITA' DI SFRIDI 1-B/A
	000 t	%	000 t	%	%
Aerospazio	19,5	61,4	5,0	31,0	74%
Industria in genere	5,5	17,2	4,1	25,7	25%
Aggiunta ad altre leghe	6,8	21,4	6,8	42,8	0%
	31,8	100,0	15,9	100,0	

FIG. 2

STIMA DEI CONSUMI Ti – 1989, U.S.A.



Fonte: elaborazione da dati RMI Company

VI International Meeting on Titanium
Turin, 23 November 1990

"NEW IDEAS IN THE ECONOMIC-INDUSTRIAL GROWTH OF TITANIUM"

Monica Cariola - Gian Maria Gros-Pietro
Ceris - C.N.R. (National Council of Researches), Italy

This is the first time that, in this international meeting on Titanium, the sixth one, the titanium industry is analyzed from an industrial economic point of view.
This is a kind of audience which is probably not very interested in complex economic models. However, even if the treatment is technical, it could be useful to try to interpret some particular situations and circumstances that have been identified analyzing titanium industry.

It is known that titanium is the fourth structural metal in the earth's crust in order of abundance (0.63% , after aluminum, iron and magnesium) in the industrial ore deposits and that, in addition, these deposits have a good geographic distribution, that sets them free from the political-economic problems often found in other kinds of extractive industries. We also know that titanium has excellent structural and functional characteristics, that make it suitable for use in many different applications.

After making these premises the economist wonders why, with such a huge potential supply capacity and so many important applications, there is such a substantial resistance to a full growth, and a full dimensional development of the titanium industry, which should place itself, for production capacity, consumption and applications, between steels and aluminum alloys.

Unfortunately the causes of this situation are numerous, and often closely linked to one another: all them have contributed to the creation of sometimes real and more often "formal" or "artificial" barriers, that have hindered the entry of new economic subjects into the titanium sector, thus discouraging also the investments of already existing companies and therefore strongly limiting the development of the sector compared with what its actual potential could have been.

At the risk of sounding rather technical, but perhaps the word is not too outdated, we could say that we are in the presence of one of the most classical forms covered by economic theory, that is, the restriction of production and disincentive to development which are a typical consequence of an <u>oligopolistic market</u>.

Later on we shall come back to this model to see which are the possible ways of further development in the presence of an oligopolistic market with unexploited potential.
Now it can be useful to point out some of the causes of this status quo and their main implications (schematized in Fig. 1), and to come to implicitly suggest new ideas to overcome them.

As we can see in the top part of Figure 1, the <u>scenario</u> of the <u>titanium sector</u> over the last 40 years is characterized by <u>three key factors</u>, from which others are derived.

1) A first factor is the policy followed by the primary titanium producers, that is sponge producers, who together with semi-finished products producers have until now elected the supply of high-cost applications, therefore they have specialized in high-value added business activities, characterized by high profit margins and small quantities of metal: this is what managers and businessmen call a niche policy and economists call a quantity restriction policy.

2) The second key factor, which is coherent with the first one, is the very close link between the titanium industry and the aerospace industry. Obviously the aerospace industry is characterized by relatively low consumption, compared with the manufacturing industries, but it is also characterized by the capacity to pay high prices for the unique performance that titanium can ensure compared with other materials.

3) The third key factor is the lack of an official quotation of titanium prices (Metal Exchange or others). This factor may seem to be somewhat different from the first two ones, but it is a determining factor in producing a market which is little transparent and scarcely efficient in allocation of resources.

When analyzing the first factor it can be easily noted (see Table 1) that we are dealing with a marked dominated by few producers, of which only six have significant output (Timet, RMI, OREMET in the USA, Osaka and Toho in Japan, Deeside in Europe), which cover about half of the reported world production capacity, and it is important to underline reported, because we will see later that this statistic is questionable, while the remaining part is covered by the USSR, and, to a much legger extent, by China; however, little information regarding these two countries is publicly available.

It can be observed that we are talking about a very small market (about 85,000 t of titanium produced in 1988 against 17,000,000 t of aluminum, for example).
Moreover, although the concentration of the production is substantially high because we have six producers that cover half of the production capacity, we do not have a great leader, such as Alcoa for Aluminum, with the capacity to perform development investments that can both promote technological advancement and applications in the user's sectors.

Therefore, we have an <u>oligopoly without leadership</u>. The economic theory says that oligopoly reaches equilibrium conditions similar to monopoly, in terms of restriction of the quantity, higher prices and more comfortable profit margins.
But, unlike monopoly, oligopoly cannot have the same technology management capacity.
This happens where the possibility of a leadership does not exist. In this case it is possible to miss technological opportunities, that is, new frontiers that could be broken are not attacked; and an ever increasing difference accumulates between the level of efficiency actually reached by the industry, and the one that technology would make feasible at a given moment.
Now we come on to the possible developments of an oligopolistic

market having these features.

We are in what economists call a contendible market, that is, a market which is apparently stable, with control structures in the hands of few producers, but that could be easily contended, at least in theory, by outsiders having the power to remove the constrictions that the present operators do not move. Currently such a potentiality could happen if two favourable conditions concur. On the one hand, a large potential market that could already exist because of considerations made above, that is extensive supply, ore distributed in all Countries, and hence not subject to political risks, unique characteristics of the metal.

On the other hand, when new production processes, such as the electrolytic one illustrated by Mr. Orsello of GTT, allow to substantially change the primary production cost structure. Then, the concurrence of these two conditions may create the risk or the opportunity, depending on the point of view, for an outsider to enter.

Indeed, for an economist this risk seems to outline itself concretely: actually, one of the main obstacles to the development of the titanium market is price, which is higher than that of other structural metals; this is mainly due to sponge production costs, which are still high because of the traditional processes used, that are scarcely automatized, discontinuous, and with high power consumption, and thus with high unitary production capacity costs.

In fact, the subsequent metallurgical treatments of raw titanium,

from semi-finished to finished products, are similar to those of stainless steel, and therefore there is no economic reason why the processing costs should have repercussions on the final price of titanium, making it higher than that of stainless steel.
Moreover, titanium has the intrinsic advantage of having half the weight of stainless steel. Therefore, the unit cost size or volume may be half as much.
All this confirms that titanium sponge production metallurgy is the field where the largest work has to be done in order to attain the lining up of titanium prices with those of the other structural metals.

The high value added and low quantity strategy, and the existence of a technological restraint that involves the use of obsolete technologies may not be too detrimental in the case of small quantities, e.g. 0.5 pct of those represented by Aluminum, but they would certainly be judged uneconomic in case of larger quantities.

Another factor still connected to the first one is the lack of reliable data and statistics concerning titanium; in particular, while it is quite easy to obtain data about world production capacity, other figures (e.g. actual production, consumption, etc.) are hard to obtain, especially for the USSR, Europe and China. The only official sources are the U.S. Bureau of Mines, whose data are collected in an "uncritical" way by the Titanium Development Association (T.D.A.), and the Japan Titanium Institute. In Europe there is no institution that organizes statistics and the development of titanium and, similarly, no information comes from the Eastern Block countries, although the

USSR is the main world producer. Periodically market research surveys are carried out, but also in this case they are usually uncritical formulations, rewritings of documents that originate from the statistics published by the Bureau of Mines.

As a consequence of the scarcity of sources on titanium production, data on the industry is lacking and inadequate, and this information is the basis of all the studies that are carried out. In particular, the data about the titanium industry collected in the early 1980's, in a falling market period, and hence depressed, were used to make forecasts that were not subsequently revised or corrected. As a consequence, in several instancies the actual figures have been higher than the forecasts, but the existence of projections and estimated data about market volume below the true figure, produced self-fulfilling forecasts.

In other words, those who have looked at possible investments in titanium, both operators already belonging to the industry and potential new ones, have had to face an inadequate statistical data framework, which has discouraged investments in the titanium sector.

Thus, a vicious circle of low forecasts, low investment and hence low industry development has been created, which is also worsened by costs which remain high because of the scarcity of investments.

Such a poor information framework is one of the features of an imperfect market, that is, a scarcely transparent market not very efficient in the allocation of the resources.

Stating that the market is scarcely transparent means that we are sure or we feel that it is wrongly perceived. This certainty or feeling is a consequence of the discrepancies between the stated production capacity and the actual production of the industry.

In fact, production capacity data are scarcely reliable because of the variance observed for several years between declared capacity and actual production.

In 1983 the degree of production capacity utilization reached a minimum of 43% in the U.S.A. (Source: T.D.A.), which is a very unusual situation for any primary materials industry and leads us to believe that not all of the declared capacity corresponds to actual production. In fact, this situation of large excess of production capacity over actual production is disproved by the delivery terms of the titanium industry. As far as the stainless steel and aluminum industries are concerned, prompt delivery to a maximum of one to two months are normal terms. In the case of titanium, peaks of up to 80 weeks have been recorded, which is not at all the situation that one would expect where production capacity substantially exceeds production.

This leads to the conclusion, at least to those who do not belong to the field, that the declared production capacities are overstated, and that this "statistical error" contributes to the scarce transparency of the market mentioned before, so that investors are discouraged to make investments in the sector, thinking that there is already an excess of production capacity, an assumption which is disproved by the delivery times.

Of course, there are technical and operating considerations that may partly explain these delivery times; mainly the fact that the titanium industry works for the aerospace sector, whose demand is strongly variable. This can lead to the temporary underutilization of capacity or, in certain cases, to a lack of capacity.

Here comes in the <u>second key factor</u> mentioned at the beginning: <u>the very close link with the aerospace market</u>.

We wonder why the industry does not leave the essentially limited aerospace market to enter the wider manufacturing applications market, or "terrestrial" applications (so to say), which could make it grow by of one to two orders of magnitude.

Obviously one of the reasons, perhaps the main one, is the high profit margin, high value added policy that titanium producers have had during the last 40 years. A policy which characterizes other industrial sectors, such as the defence, which, besides the high cost, shows low amounts and no or extremely limited marketing efforts.

Therefore it can be said that competition directed towards these markets involves the creation of management techniques and structures, in addition to corporate cultures that are unprepared, at least in the first stage, to face a market different from the original one.

Now that political détente has spread its wings over the international scene, and the reorganization of the arms industry is a frequently discussed topic. Wherever the reorganization of a military activity is carried out, the same problem is faced: the companies that produce for the military sector have no experience, competence or desire to face a serious marketing policy.

The feeling one has from the outside is that this is basically the situation of the primary titanium industry.
No desire, perhaps no convenience in facing policies that would require new attitudes, and thus skills that the companies have not had up until now.

Of course, the risk is that larger companies, accustomed to operate with ten to one hundred times larger volumes, and accustomed to carry out a highly competitive marketing effort, foresee the possibility to operate also in this field, that has such a strong potential.

The outcome is a scenario that in the last decades has been characterized by corporate policies scarcely aimed at the development of new sectors and at marketing policies and has contributed to turn titanium into some sort of a precious metal, not only from the end-user's point of view, but also from that of some intermediate manufacturers.
The stabilization of this situation is helped by the fact that the intermediate manufacturers, such as mechanical parts manufacturers, while being continuously visited by stainless steel and aluminum producers, who propose their materials for different mechanical applications, are never contacted by titanium producers.

The contribution of the media could probably also help to create a favourable environment both with manufacturers and users and, indirectly, favour financial flows towards the sector.
In addition, until now there has not been a type of large consumer goods that, sold in large quantities, could have brought in to the mind of the end-user the idea of titanium as a widely-used structural material.
We recall the case of Aluminum, which take off among end-users in the thirties was aided by the spread of the tea kettle; an equivalent for titanium has not been found yet. There have been some sporadic attempts, but it is not easy to find the right channel, since many external factors also play a role: for instance, titanium golf clubs were manufactured, a golf champion won using them, and as a consequence many of them were sold. The same attempt was made with tennis rackets. The champion using them did not win, and the American company that produced them had to shut down.

These two events show that in both cases, the protagonist, was not titanium but the champion.

The importance of titanium applications in the aerospace sector was decisive in the past, and it will be so in the future, but this type of use has already reached the stage of maturity in its life cycle; it is possible that it will keep high positions still for many years, but no large growth in the demand should be expected, at least in quantities able to cause the take off necessary to reach the production level of other competitor metals.

The only way to do this is by increasing the consumption of non aerospace industry in general, which is still at the initial stage of its life cycle, and therefore has greater growth prospects.

Meanwhile, over the last few months some American titanium manufacturers have become aware for the first time of a phenomenon that went unnoticed for about thirty years: everybody was sure that the aerospace market was the most important one, because it absorbed the largest quantity of material, (see Table 2), but it was realized that 74% of the materials was turned into scrap, which was then melted down and sold again on the market, in competition with primary titanium.

Based on this, actual U.S.A titanium consumption in the aerospace industry (1989) amounted to about 30%, as opposed to 61% if scrap is not taken into account; in contrast other titanium applications produce much less scrap: an average of 25% for the different industrial applications, none in the case of titanium added to other alloys. As a consequence their actual consumption as a percentage of the total, is much higher than that reported by the statistics.

In other words, the share of the aerospace industry in total actual titanium consumption is currently lower than 1/3. This shows how inappropriate or even risky it is for the titanium industry as a whole to stick to a sponge production policy that takes as its basic reference an industry which not only represents 30% of the market, but has also quantity and quality parameters that are substantially different from those of potential large consumers.

Finally, if we consider the third and last key factor identified at the beginning, in the titanium scenario (Fig. 1), that is, the lack of an official quotation of titanium prices (Metal Exchange or others), we realize that this factor is not detached from the framework we have outlined till now.

Actually, this characteristic is linked to the other two: niche policy and small quantities; link to an aerospace sector that often has military characteristics that lead to the establishment of direct prices between producers and end-users, without the need of an official reference.
Of course, this is one of the elements that, together with the lack of data, substantially contributes to the creation of a market that is non-transparent and scarcely efficient from an economic point of view.

Manufacturers have never favoured the fixing of an official price for titanium. Now, the lack of a quotation, the fact of having erratic demand from the aerospace sector, the fact that the industry has long and variable delivery terms, and, finally, the speculation that in such situations is obviously made possible by the dealers, have caused the titanium price to be highly fluctuating. This is one of the conditions that, typically, set a material on the fringe of the large manufacturing industry structure. This causes disconcert among users and discouragement among investors, because investors are not so attracted by the high prices of good periods, being conscious that this is not a steady condition, but by the possibility of low prices in bad periods. In conclusion, the price of uncertainty is paid for in the form of reduced investments.

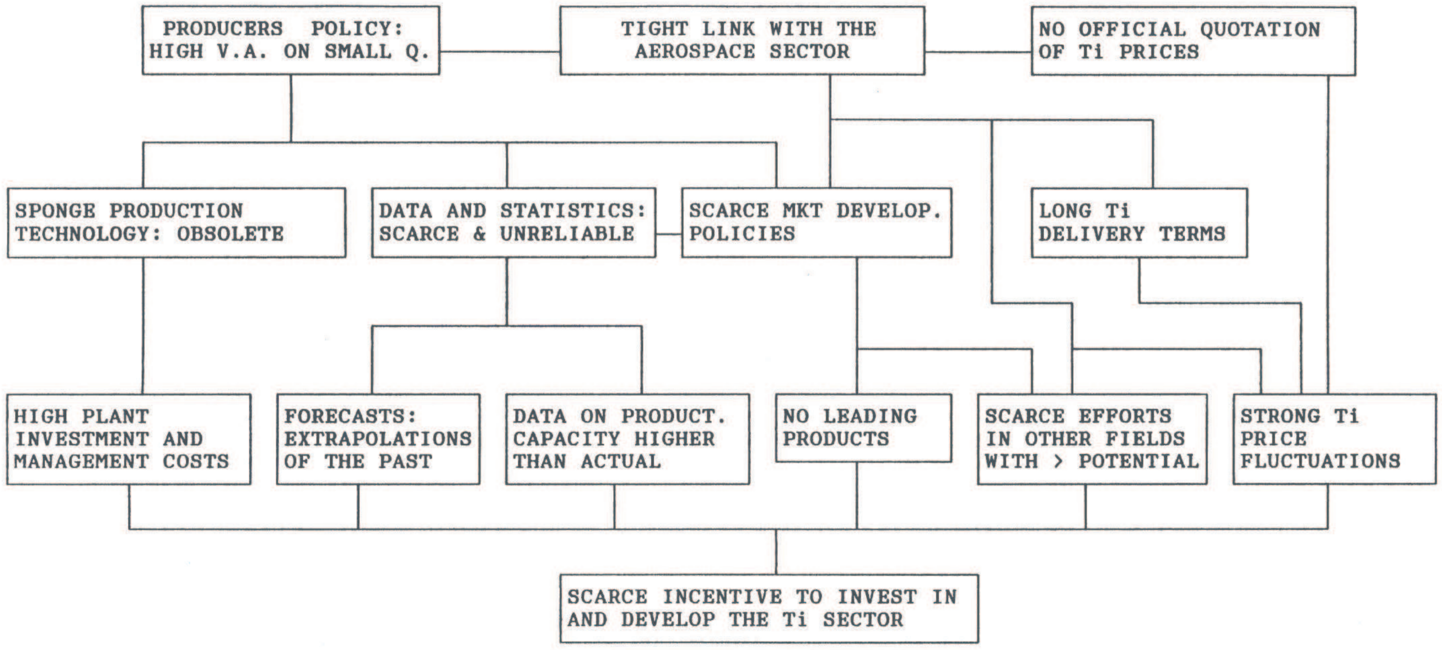
The conclusion is that these elements as a whole have until now caused the titanium industry to perform for below its potential.
However, with this we don't want to give a pessimistic impression of the future of titanium. We are experiencing a period of economic evolution, in which contendable markets are gradually and effectively being contended. The entry of large groups into low-volume high margin markets with expansion potential is common and often takes place through takeover operations.

Outsiders enter the sectors by buying-out one of the operators. This is generally made easier by the low-quantity policy, which involves a small size of the target companies. This ease of acquisition and high margins make it possible for the buyer to pay it back with the acquired company's profits in a few years.

Therefore, these possibilities are quite likely in the future, mainly because of the new technological opportunities that are taking shape in the industry and that make it possible to cover, with an easily foreseeable success, much wider demand portions.

FIG. 1

TITANIUM SECTOR SCENARIO IN THE LAST 40 YEARS



TAB. 1

TITANIUM SPONGE WORLD PRODUCTION
CAPACITY: 1980 - 1989
SOURCE: U.S. Bureau of Mines - Japan Titanium Society

MAIN SPONGE PRODUCERS (Divided by areas)	PRODUCTION CAPACITY (in tons)									
	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
U.S.A										
TIMET	12.000	13.600	13.600	13.600	13.600	12.700	12.700	12.700	12.700	12.700
RMI Company	8.600	8.600	8.600	8.600	8.600	8.600	8.600	8.600	9.100	10.900
Oremet Titanium	2.700	4.100	4.100	4.100	4.100	4.100	4.100	4.100	4.500	5.500
Teledyne Wah Chang	1.400	1.400	1.400	1.400	1.400	1.400	-	-	-	-
International Titanium Inc.	-	-	2.300	2.300	2.300	2.300	2.300	-	-	-
Western Zirconium	-	-	500	500	500	500	-	-	-	-
TOTAL	25.400	27.700	30.500	30.500	30.500	29.600	27.700	25.400	26.300	29.100
JAPAN										
Osaka Titanium	11.800	13.200	18.200	18.200	18.200	15.400	18.200	11.800	11.800	13.200
Toho Titanium	9.100	11.800	11.800	11.800	11.800	11.800	11.800	9.500	9.500	10.800
New Metal Industries	2.300	2.300	2.300	2.300	2.300	2.300	2.300	-	-	-
Showa Denko	-	-	-	1.800	1.800	1.800	1.800	1.800	1.800	3.000
TOTAL	23.200	27.300	32.300	34.100	34.100	31.300	34.100	23.100	23.100	27.000
GREAT BRITAIN										
Deeside Titanium	-	-	3.200	5.000	5.000	5.000	5.000	5.000	5.000	5.000
ICI	3.600	3.600	1.800	-		-	-	-	-	-
TOTAL	3.600	3.600	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
WESTERN WORLD TOTAL	52.200	58.600	67.800	69.600	69.600	65.900	66.800	53.500	54.400	61.100
OTHER										
U.S.S.R.	34.900	41.700	45.400	45.400	47.200	48.100	48.100	49.900	49.900	52.200
CHINA	1.800	2.700	2.700	2.700	2.700	2.700	2.700	2.700	2.700	2.700
WORLD TOTAL	88.900	103.000	115.900	117.700	119.500	116.700	117.700	106.100	107.000	116.000

TAB. 2

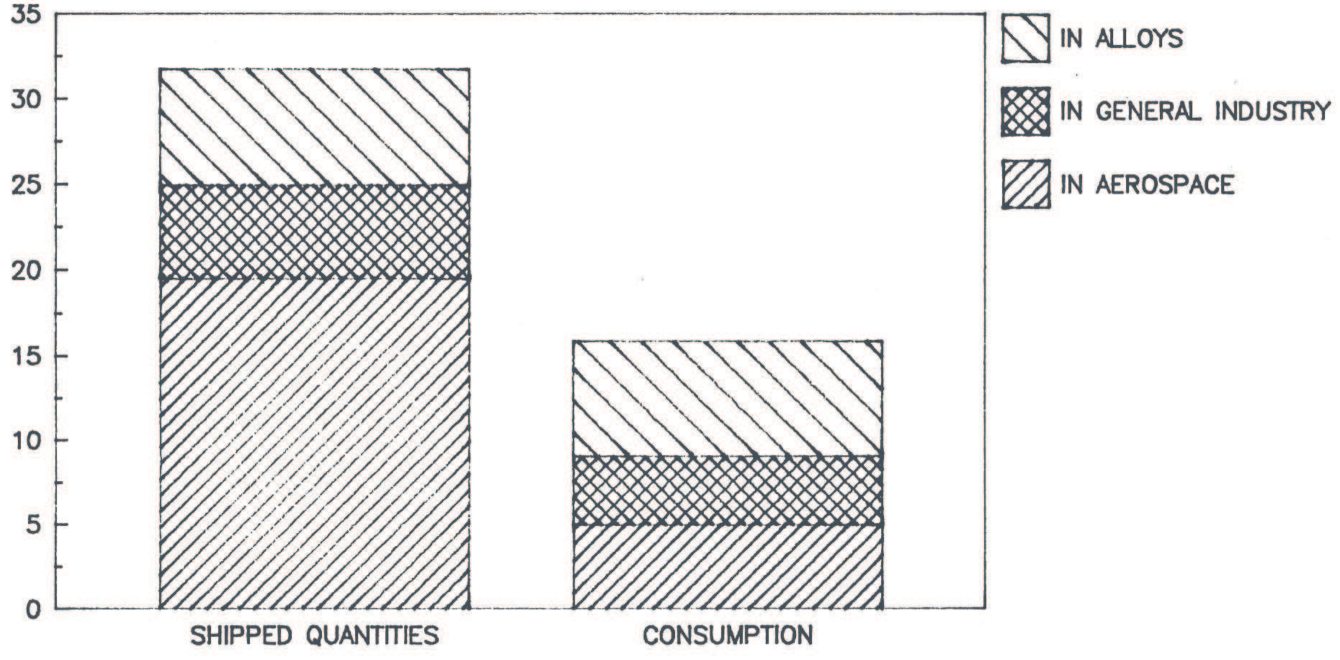
ESTIMATE OF Ti CONSUMPTION - 1989, U.S.A.

Source: RMI Company's processed data

DELIVERED SECTORS OF APPLICATION A	CONSUMED QUANTITIES B		SCRAP QUANTITIES 1-B/A		PORTION
	000 t	%	000 t	%	%
Aerospace	19.5	61.4	5.0	31.0	74%
Industry in general	5.5	17.2	4.1	25.7	25%
Addition to other alloys	6.8	21.4	6.8	42.8	0%
	31.8	100.0	15.9	100.0	

FIG. 2

ESTIMATE OF TITANIUM CONSUMPTIONS – 1989, U.S.A.



Source: Elaboration from RMI Company data

GINATTA TORINO TITANIUM
NOVEMBER 23, 1990

NEW ADVANCES IN ELECTRON-BEAM REFINING

THOMAS H. HARRINGTON
Consultant

D. MICHAEL FERRIS
General Manager
Consarc Corporation
Development Center
Albany, Oregon, USA

The electron beam cold hearth refining and casting process uses a water cooled copper trough or "cold hearth" placed between the melting station and the casting station. Thus separating the melting and refining steps from the solidification operations.

The water cooled copper trough or cold hearth is so configured as to provide an extended surface area in a high vacuum, where the residency time of the metal can be controlled.

The electron beam energy applied to the molten metal provides a stirring action to the shallow metal bath resulting from the intense heating of a localized area and the immediate temperature balancing by the surrounding, relatively cooler metal. This stirring results in the liberation of low density particles (such as oxides) tram the bath and allows them to float to the top where they are retained by the surface tension of the metal pool.

These oxides tend to volatilize during refining.

The stirring action on the cold hearth resulting from the temperature gradients surrounding the beam impact areas liberates carbides, oxy and carbo-nitrides which dissolve and resolidify as a fine, two phase liquid-solid mixture of fine micro-segregates suspended in a highly fluid metal, containing an estimated 30%-40%

solids of small dendritic crystallites with a secondary arm spacing of about 50 microns.

The solidification of the metal is accomplished under carefully controlled heat transfer conditions. By maintaining these heat flux patterns, the solidified metal maintains the very small scale dendritic micro-structure uniformly throughout the resulting cast product.

High Density Inclusions in titanium alloys. A program has been carried out where titanium alloy was purposely seeded with broken tungsten carbide pieces, molybdenum and tantalum wires and titanium nitride seeds simulating hard alpha particles, these were added to a hearth during the melt. The skull was later X-rayed and chemically analyzed. All of hearth skulls examined exhibited a similar pattern, the seeded HDIs has dissolved within a short distance from the entry location on the hearth, none had reached the exit zone of the hearths.

EB refining also benefits in the removal of the volatile

[Missing Text]

Torr should be maintained. While the Electron-Beam can be maintained at higher operating pressures of 50 to 100 microns these pressure are too high to facilitate the necessary thermochemical reactions.

Vaporization losses during electron-beam refining has become a very misunderstood matter. For the moment let us separate the EB cold hearth refining conditions for titanium and its alloys from superalloy refining and casting because they are the same process practiced in two different modes.

The superalloys are introduced to the hearth as a previously consolidated and homogenized VIM ingot. In order to affect the refining on the hearth as described earlier in this paper, care is taken to add heat to the hearth to allow only clean metal to flow to the solidification station. The liberated non-metallics present on the surface, luminesce and are obvious to the E.B. furnace operator. A repeatable, programmed sweep beam pattern with a beam power density of 35 to 60kW is sufficient for refining a full hearth of metal of approximately 18 to 20 inch wide by 30-36 inches long with metal inventory of about 1/2 inch depth. A hearth of this general configuration is capable of refining 350 to 450 pounds of

VIM input quality, nickel base alloy, per hour, using a total of 120 to 150 kW for melting, refining (including surface sweeping) opening the pour lips and hot topping the inqots. This estimate is based on a dual strand caster.

Larger furnaces for superalloy forging ingots may require larger hearths, ingot molds and higher power EB guns, but mega watt power is not part of the future of superalloy refining. At the power levels described above the chromium losses for IN-718 are typically 2% to 3% during EB refining that equates to change from 19.5% input to 19.0% output. Hf, Al, Ti, Zr, B, Cb, Y and V are unchanged during EB processing.

The E.B. melting of titanium and titanium alloys is carried out at pressures of 50 to 100 microns, this is due to the higher levels of contained gases and water vapors from sponge and cleaned machine chips added to the melt. These are low density materials which are fed into the melt. The combined problems of low density, poor coupling, high surface area, feed stocks require large amounts of electric power to melt.

Ingot production rates in the mega watt range EB titanium furnaces are in the 1100 to 1500 pound per hour range depending upon ingot size, shape and alloy grade. Aluminum and Chromium are preferentially evaporated, rather unevenly from the titanium alloys in which they are contained because of the high beam power densities used.

The plasma arc melting (PAM) and electron-beam melting (EBM) are both cold hearth processes are currently being studied.

Titanium alloys produced by Electron Beam Melting (EBM) (EBCHR) and Plasma Arc Melting (PAM), (PACHR) is underway by several aircraft engine builders funded in part by the USAF.

These two processes obviously compliment one and other and their greatest value will be realized when the are joined. The capacity of the plasma torch to operate at 1 atmosphere and pour an unrelenting blast of heat, on to the melt stock, when molten allow the metal to pass to a vacuum chamber for EB refining and on to an ingot casting/solidification station with continuous electron-beam hot topping.

There is much design and equipment building work to be done to satisfy these growing markets, each with specific production/application needs.

We would like to share with you, some ideas we have for specific furnace designs.

AGGIORNAMENTO SULLE ATTIVITA' INDUSTRIALI DELLA GTT NEL TITANIO

Gianmichele Orsello - Ezio Debernardi
G.T.T. S.p.A.

Gentili Signore e Signori,
come di consueto la GTT ritaglia per sé un piccolo spazio per illustrare nell'ambito di questo convegno i progressi effettuati nel corso di questo anno.

Il convegno è arrivato alla sesta edizione e anche quest'anno raccoglie specialisti tecnici e operatori commerciali.

Ritengo che vi sia vivo interesse da parte di tutti ad ascoltare le memorie che vengono presentate, ma anche ad incontrarsi, al di fuori di questa sala, tra operatori.

Il Meeting GTT infatti rappresenta l'unico appuntamento europeo annuale che accoglie: produttori, utilizzatori, commercianti e ricercatori. Nel 1989 l'adesione fu di 402 persone di cui oltre 50 provenienti dall'estero. Quest'anno tale cifra sarà ampiamente superata: con le ultime iscrizioni si arriva a 425 persone.

La GTT lavora da oltre 10 anni per sviluppare il metodo produttivo elettrolitico, la metallurgia e le applicazioni del titanio. In questo biennio la GTT ha conseguito significativi risultati, quali la vendita di licenze per il proprio processo alla società leader americana RMI, alla società australiana Minproc che l'anno scorso ha partecipato al convegno presentando una memoria, alla società Titania, 100% del gruppo ILVA e di cui l'anno scorso è stato illustrato il lay-out dell'impianto.

Desidero sintetizzare la storia di oltre 10 anni di sviluppo (Fig. l), dalle celle di laboratorio alla cella industriale installata presso la RMI.

La capacità è stata sviluppata da pochi kg fino alla produttività industriale di 400-500 kg/giorno (Fig. 2).

La qualità del prodotto è stata confermata essere significativamente più alta di quella del miglior titanio prodotto col processo Kroll tradizionale (Fig. 3) in particolare per quanto riguarda i cloruri e le impurezze metalliche.

Diamo una rapida occhiata alla cella installata a Santena (Modex 3) (Fig. 4) realizzata dalla GTT, e alla fase di estrazione e strippaggio di un catodo (Fig. 5) osservate i cristalli di titanio elettrodepositato sulla superficie.

La cella Modex 4 (Fig. 6) progettata e costruita dalla GTT e installata alla RMI è di dimensioni industriali. Osserviamo da questo lato della cella (Fig. 7) il cono della macchina dalla quale viene estratto il titanio, che viene prodotto in continuo con un processo ad alta efficienza energetica e ad un costo di produzione significativamente più basso dei processi tradizionali.

Vediamo la parte alta della cella (Fig. 8) e guardiamo l'interno della cella (Fig. 9) tramite gli oblò che consentono l'osservazione del processo, pur essendo l'impianto completamente automatizzato.

Questo è il modo in cui un impianto costituito da più celle viene costruito (Fig. 10) accostando 4 celle in un modulo e accoppiando i moduli a due a due in modo da ottimizzare i servizi per otto celle.

La GTT ha iniziato la costruzione dell'impianto e la fornitura delle apparecchiature per la società Titania; questa diapositiva (Fig. 11) è una vista prospettica dell' impianto. Osserviamo qui la precamera centrale con lo stripper, che è la macchina che stacca il titanio dai catodi (Fig. 12) e in questo spaccato di modello (Fig. 13) i vari elettrodi, anodi e catodi, immersi nel bagno fuso.

Operatori specializzati dell' industria del titanio hanno riconosciuto che il concetto base di questo impianto è intrinsecamente sicuro da un punto di vista degli operatori e della sicurezza ambientale ed è possibile raggiungere una operatività con nessuno scarto di lavorazione, di cui dover preoccuparsi per lo smaltimento.

L'interesse per questa tecnologia in tutto il mondo è molto grande, particolarmente in quei paesi che possiedono giacimenti di minerale, non soltanto rutilo, ma anche ilmenite, in quanto oggi sono disponibili processi industriali di basso costo e su larga scala per la produzione del cosiddetto rutilo sintetico dall'ilmenite.

Rutilo naturale e rutilo sintetico sono la materia prima per il processo di carboclorurazione mediante il quale viene prodotto tetracloruro di titanio che è l'intermedio utilizzato come materia prima nell'elettrolisi. L'installazione di altre capacità produttive nel mondo, porterà sempre maggiore disponibilità di metallo e non si verificheranno più casi come quelli che stiamo vivendo oggi di tempi di consegna dell'ordine di svariati mesi o di un anno per i semilavorati in titanio e leghe, da parte degli attuali produttori esteri.

La società Titania sta effettuando una attività importante per la produzione e la commercializzazione di semilavorati in titanio, acquistando lingotti e bramme dai produttori esteri, e sottoponendoli a cicli di lavorazione e laminazione negli stabilimenti ILVA che producono normalmente semilavorati in acciai inox e sui quali, con opportune messe a punto, si effettua la trasformazione anche dei semilavorati in titanio.

La GTT collabora con Titania S.p.A. sia nella parte commerciale, sia nel marketing, come nel recente 30° Salone Nautico Internazionale di Genova che ha destato un vastissimo interesse tra pubblico e operatori.

Un'altra attività che effettua la GTT è lo sviluppo delle applicazioni del titanio e delle sue leghe in prototipi non convenzionali, ossia non utilizzati nelle tradizionali industrie aerospaziali o chimiche in cui il titanio è noto ed applicato da qualche decennio.

A nome del mio collega Dr. Debernardi, responsabile del dipartimento di Metallurgia della GTT, sintetizzo le principali applicazioni studiate e realizzate dalla GTT in questo periodo. Le applicazioni più importanti sono nel settore dell'ingegneria civile, delle quali parlerà diffusamente l'architetto Pession: nello stand avete visto una porzione di tetto.

Sono attualmente allo studio prototipi di molle e di frizioni per le applicazioni dell'industria automobilistica.

Una applicazione realizzata in collaborazione con la Selcom è la bussola per il metal detector per i controlli di sicurezza di banche, casse di risparmio, aeroporti, ecc, che potete vedere nel nostro stand.

La taratura del metal detector è resa più semplice dalla realizzazione della bussola in titanio per le sue caratteristiche di totale amagneticità.

Un'altra applicazione, questa in collaborazione con l'ENEA è la realizzazione di biciclette in titanio, in particolare mountain bike (Fig. 14), (anche questa nello stand) e che è importante non solamente per il significato tecnico della applicazione ma anche per l'impatto che questa applicazione può avere sul grande pubblico.

Un'altra applicazione significativa è la sedia a rotelle per portatori di handicap. (Fig. 15)

Sono state anche realizzate slitte sia per il trasporto, sia per la competizione sulla neve (Fig. 16).

Tra le applicazioni che sono state sviluppate nel corso degli ultimi anni, e in parte già presentate a questo convegno, voglio rapidamente ricordare: reattori per lo sviluppo delle pellicole fotografiche, bracci di robot, barre di torsione per le sospensioni degli autocarri, vari particolari per industria chimica (parti di valvole e di pompe), cilindri oleodinamici, particolari meccanici per macchine impacchettatrici, cilindri per impianti di elettrozincatura, coltelli per taglio ad ultrasuoni di prodotti alimentari.

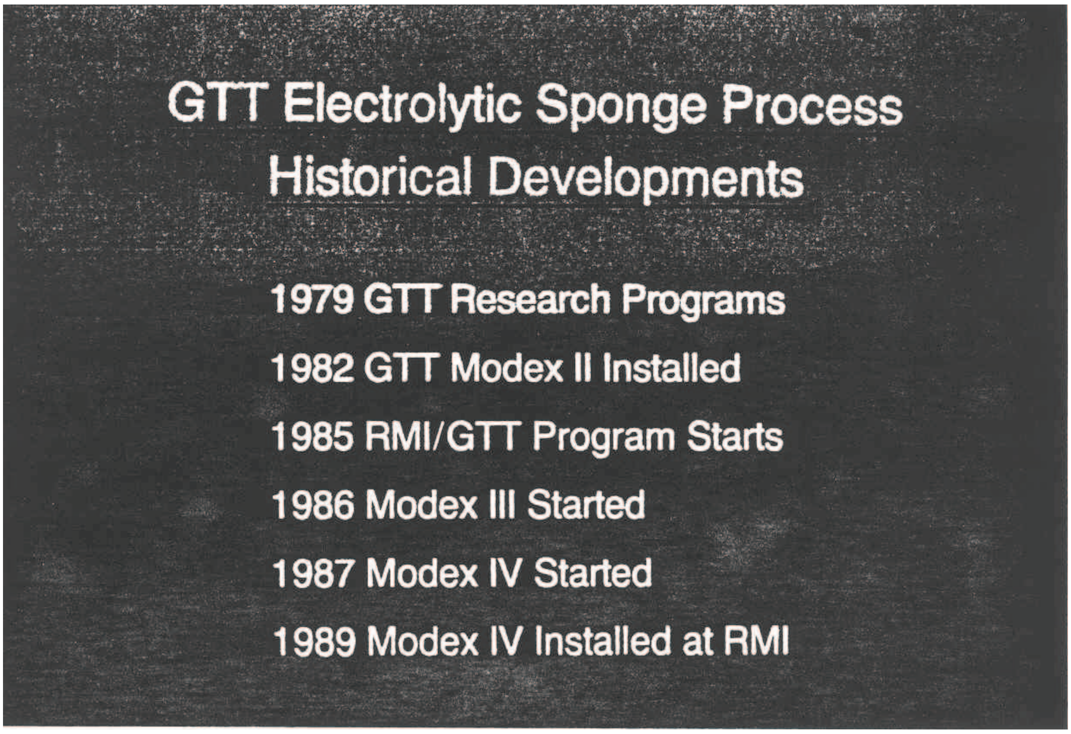
Un breve cenno alle attività della metallurgia: sono stati prodotti dalla GTT lingotti prototipali di leghe di titanio quali la Nb-Ti, gli alluminiuri di titanio e altre leghe, che sono state sottoposte successivamente a cicli completi di lavorazione a caldo e a freddo fino all' ottenimento del prodotto finito (Fig 17 - 18 - 19 - 20).

E' in corso di acquisizione e prevediamo il completamento dell'installazione per la fine del prossimo anno, di un nuovo forno VAR, capace di fondere lingotti di peso fino a due t.

L'attività di promozione continua con la preparazione di documentazione tecnico-scientifica e le illustrazioni delle proprietà, delle caratteristiche, delle applicazioni del titanio in vari convegni. Il Dr. Debernardi della GTT presiede il comitato UNI per il titanio che è stato recentemente costituito per la preparazione della normativa italiana sui semilavorati di titanio e sue leghe. Il comitato raccoglie un buon numero di aziende qualificate che si sono impegnate nello sviluppo e nella stesura delle Norme UNI entro il 1992.

Noi GTT ci rivolgiamo a tutti gli operatori tecnico-commerciali dell'industria italiana in particolare per ricordare che siamo a disposizione per studiare le applicazioni del titanio e realizzare prototipi in tempi brevi, grazie al titanio che teniamo a stock (pronto a magazzino) con l'obiettivo di facilitare la realizzazione di nuove idee e quindi allargare sempre più il campo di applicazione di questo metallo moderno in impieghi che vadano oltre quelli tradizionali.

Quantitativi più importanti e significativi per la gamma completa dei semilavorati (piani, tubi, lunghi) sono reperibili in tempi brevi presso il produttore nazionale Titania S.p.A.. Nel chiudere il mio intervento, colgo l'occasione per ringraziare tutti i colleghi del gruppo Ginatta per l'impegno profuso in questi anni nell'ottenimento di questi significativi risultati, inclusa l'organizzazione di questo convegno.



GTT Electrolytic Sponge Process
Historical Developments

1979 GTT Research Programs

1982 GTT Modex II Installed

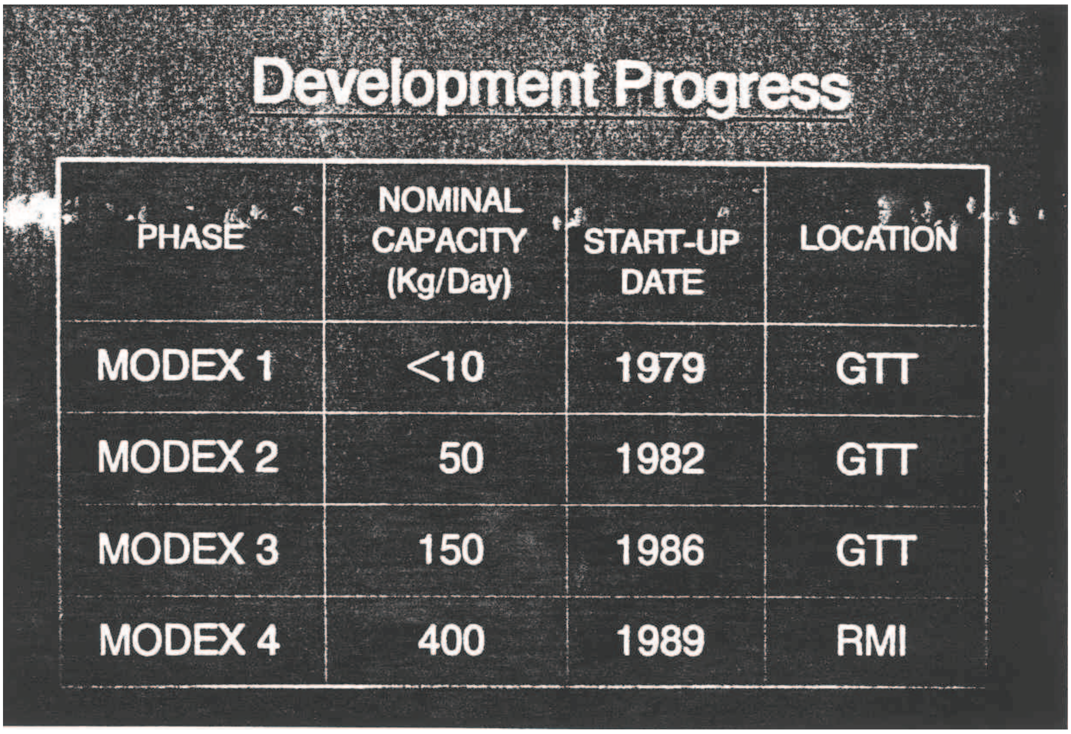
1985 RMI/GTT Program Starts

1986 Modex III Started

1987 Modex IV Started

1989 Modex IV Installed at RMI

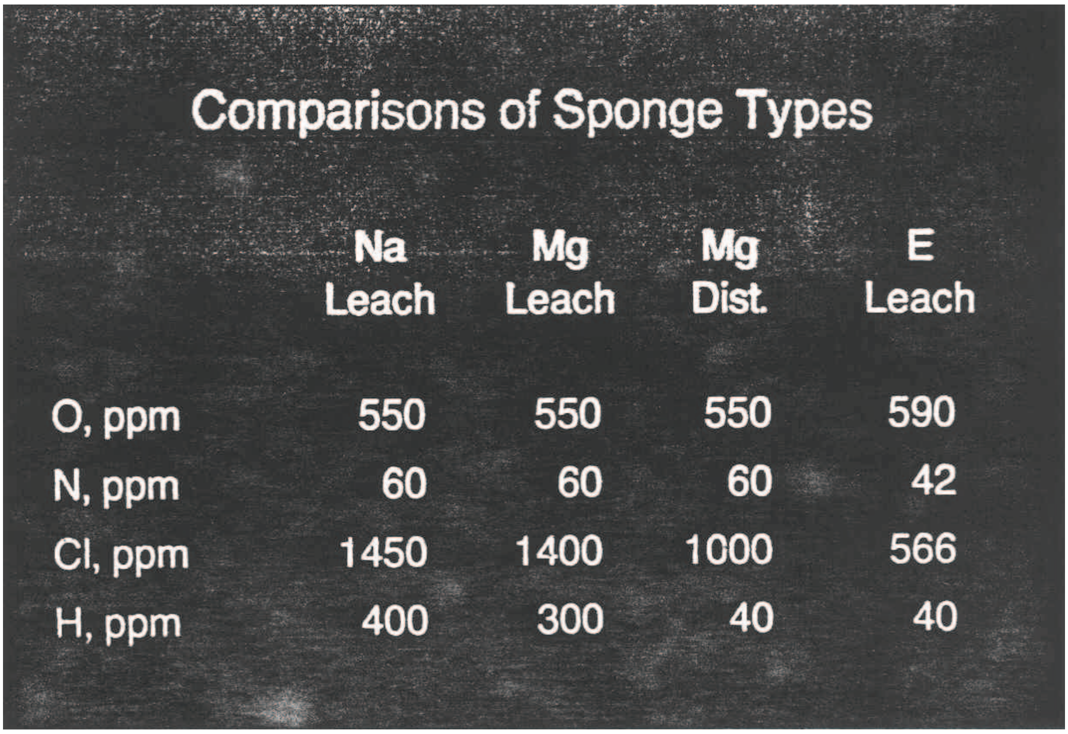
Fig. 1



Development Progress

PHASE	NOMINAL CAPACITY (Kg/Day)	START-UP DATE	LOCATION
MODEX 1	<10	1979	GTT
MODEX 2	50	1982	GTT
MODEX 3	150	1986	GTT
MODEX 4	400	1989	RMI

Fig. 2



Comparisons of Sponge Types

	Na Leach	Mg Leach	Mg Dist.	E Leach
O, ppm	550	550	550	590
N, ppm	60	60	60	42
Cl, ppm	1450	1400	1000	566
H, ppm	400	300	40	40

Fig. 3

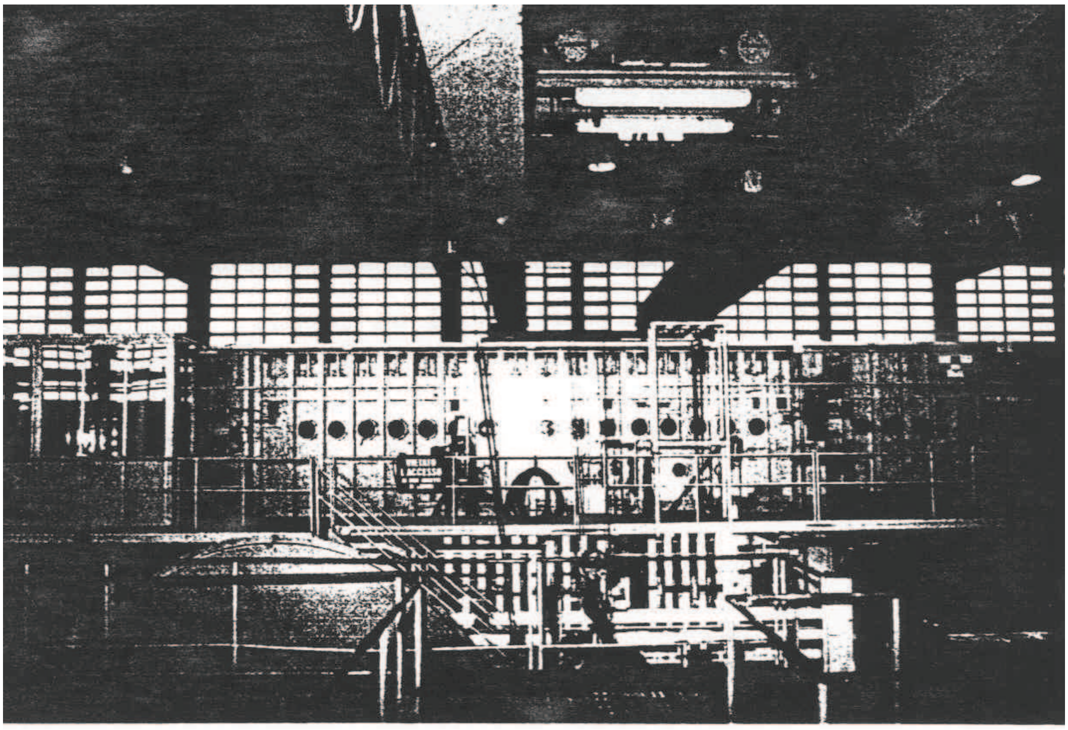


Fig. 4 - GTT - Modex 3

Fig. 5 - GTT - Modex 3: estrazione di un catodo

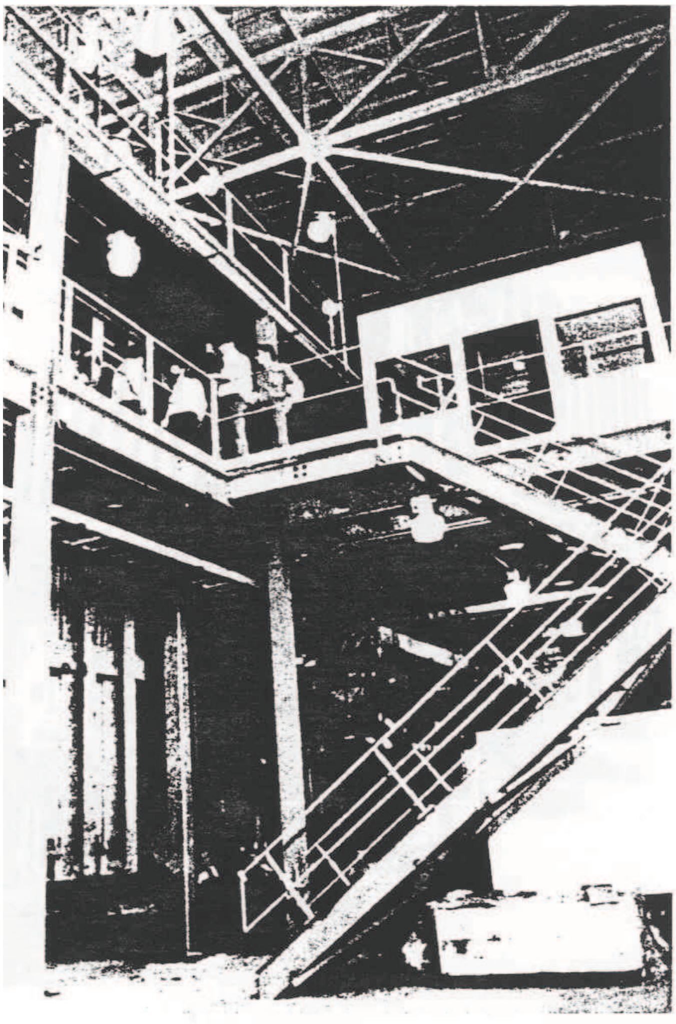


Fig. 6 – RMI – Modex 4, costruito da GTT

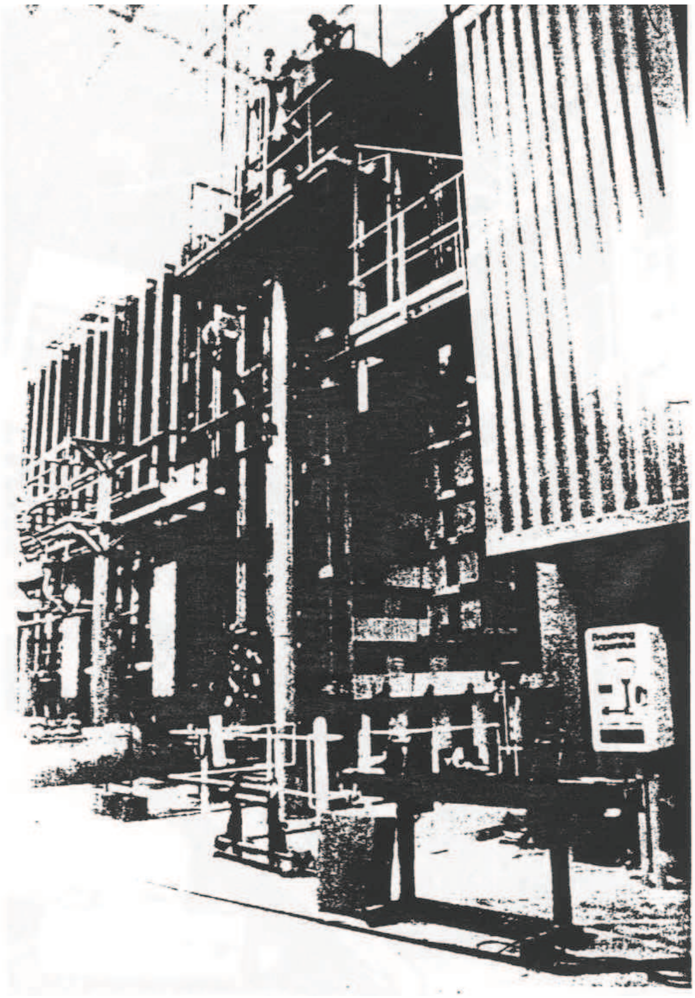


Fig. 7 - RMI - Modex 4 GTT: area estrazione titanio

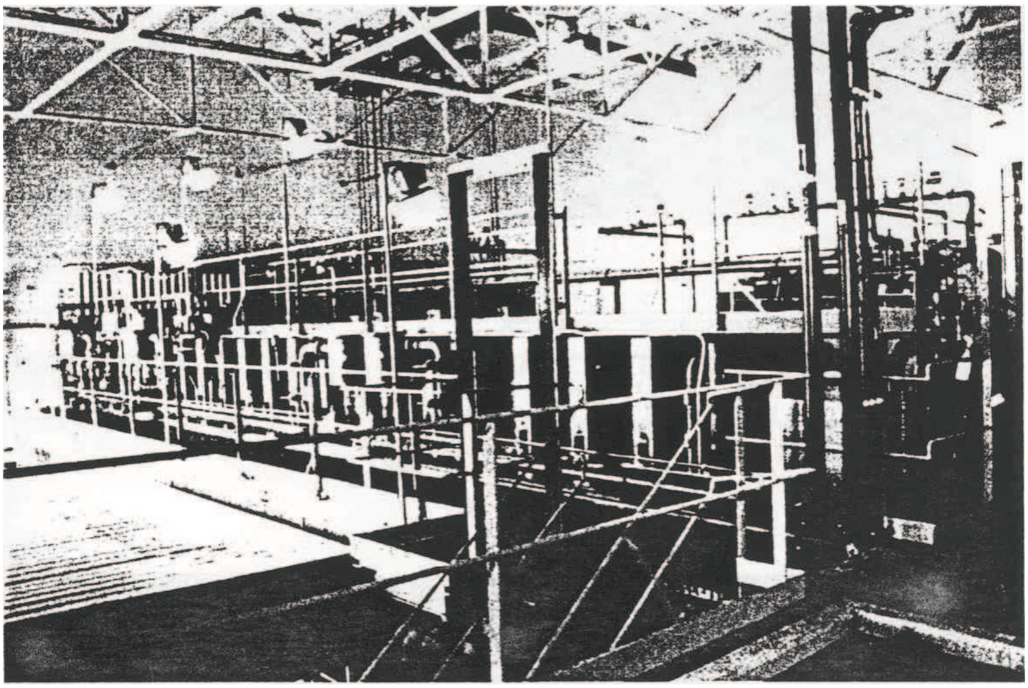


Fig. 8 - RMI - Modex 4 GTT: parte alta della cella

Fig. 9 - RMI - Modex 4 GTT: parte interna della cella

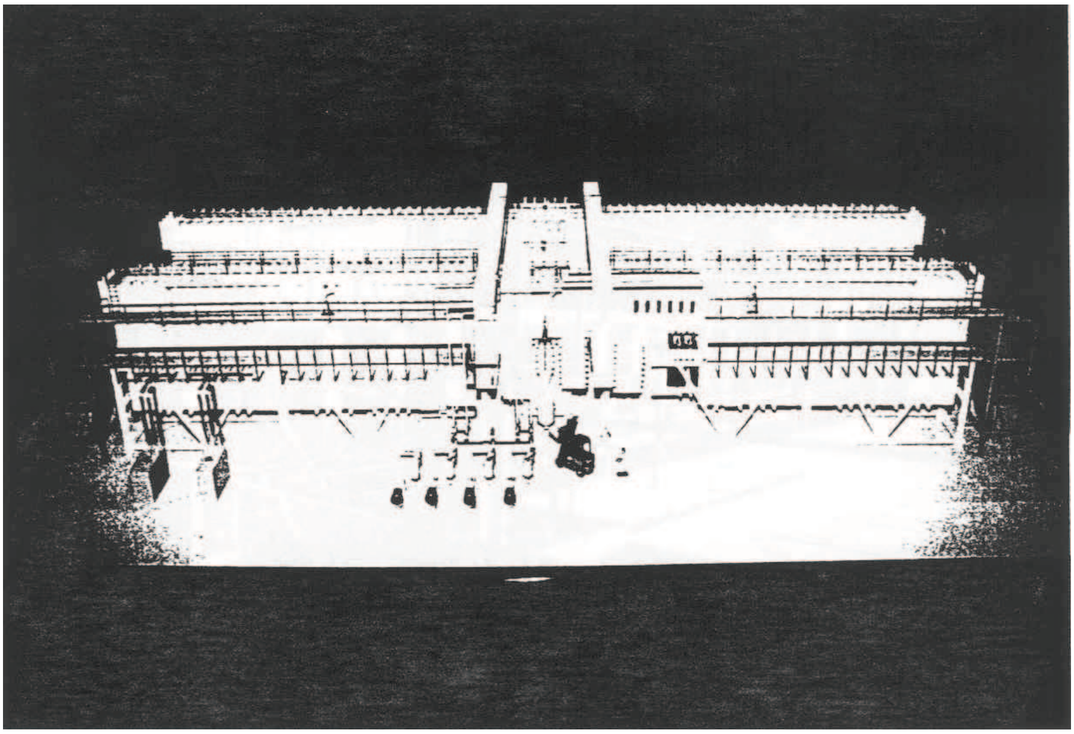


Fig. 10 - GTT - Modello di due moduli di impianto industriale (8 celle)

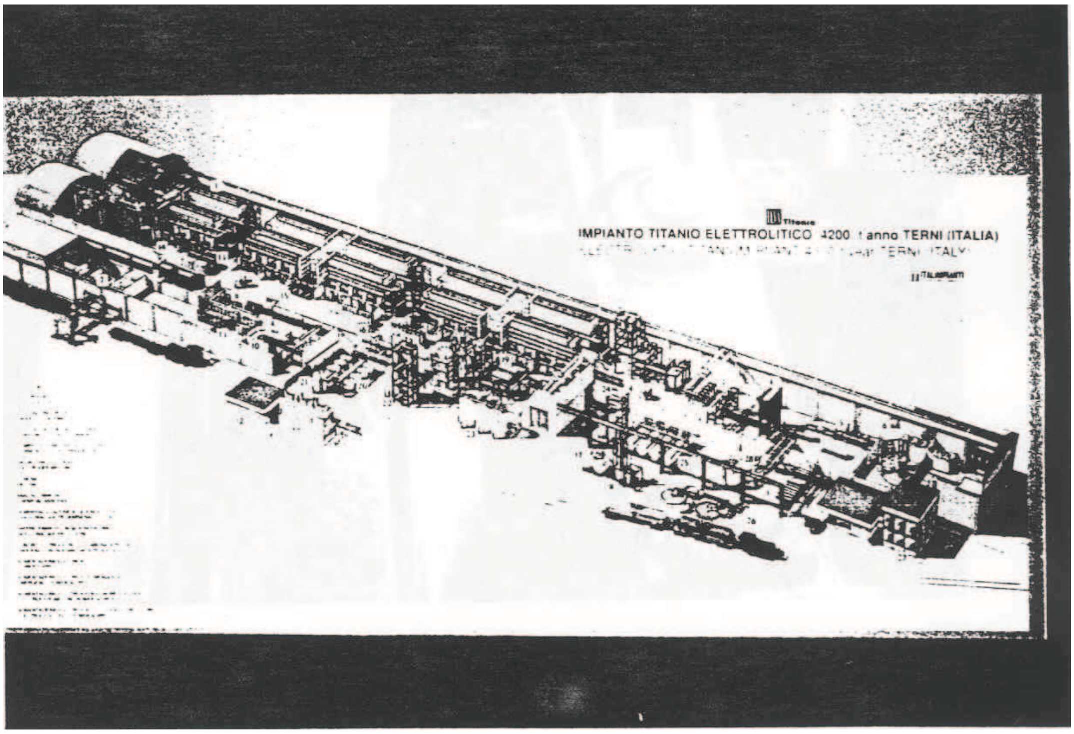


Fig.11

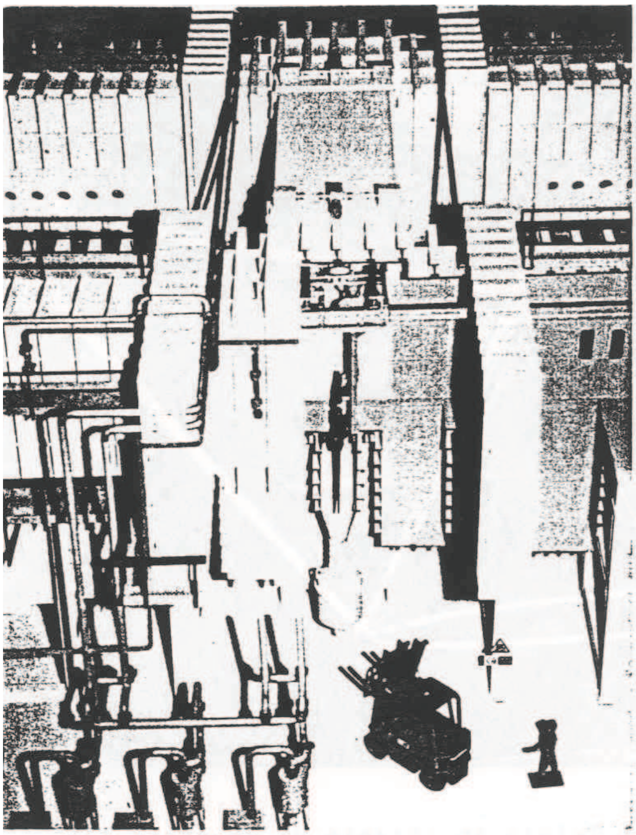


Fig. 12 - GTT - Modello di impianto industriale:
area estrazione titanio

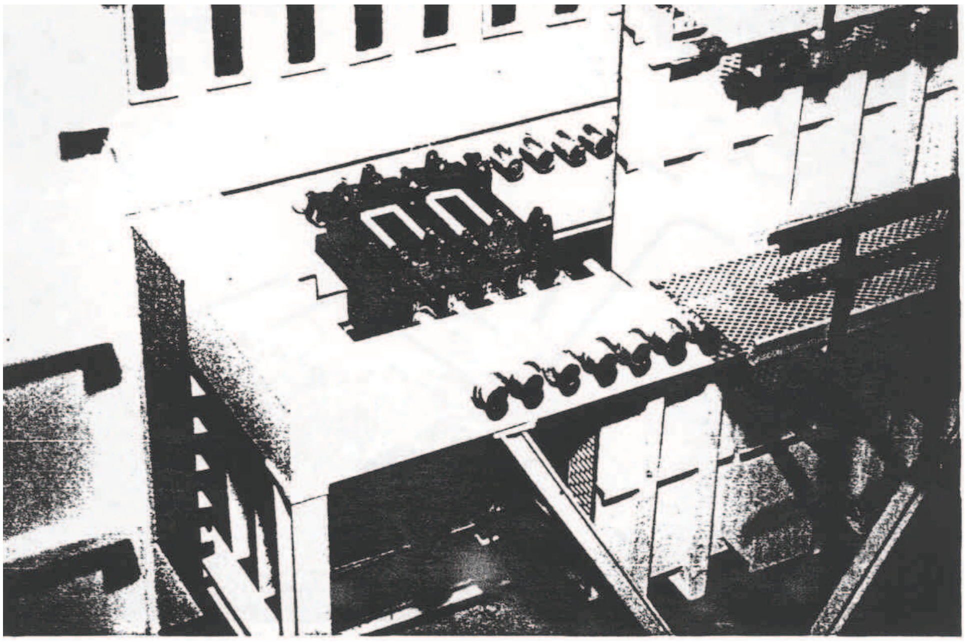


Fig. 13 - GTT - Modello di impianto industriale:
vista delle celle con elettrodi

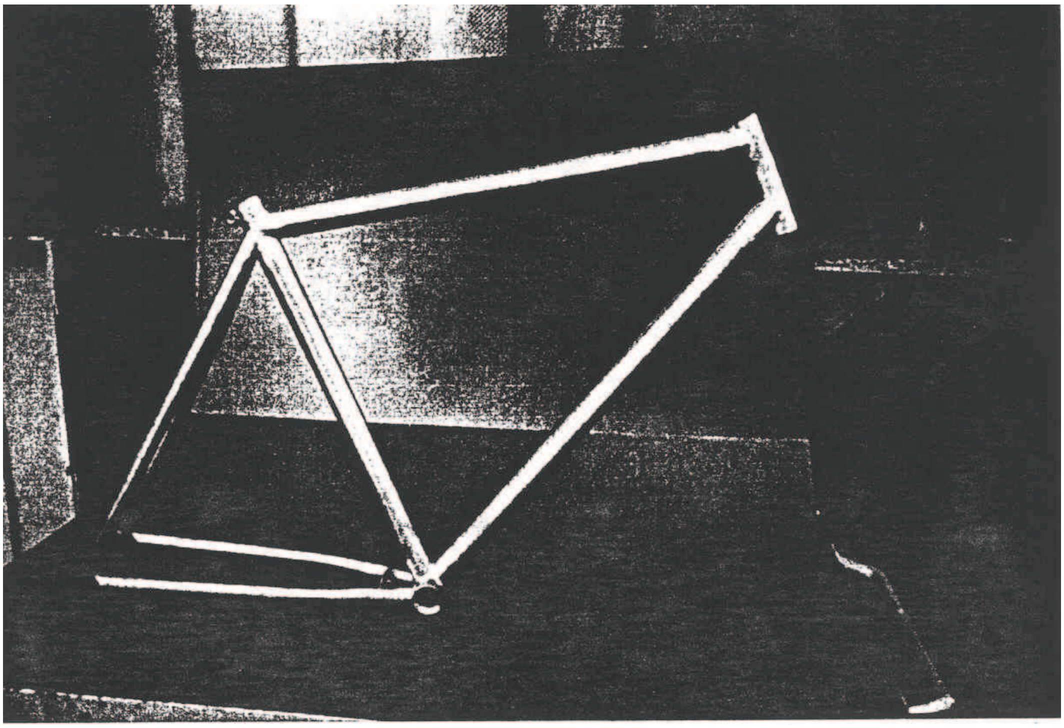


Fig. 14 - Telaio in titanio di mountain bike

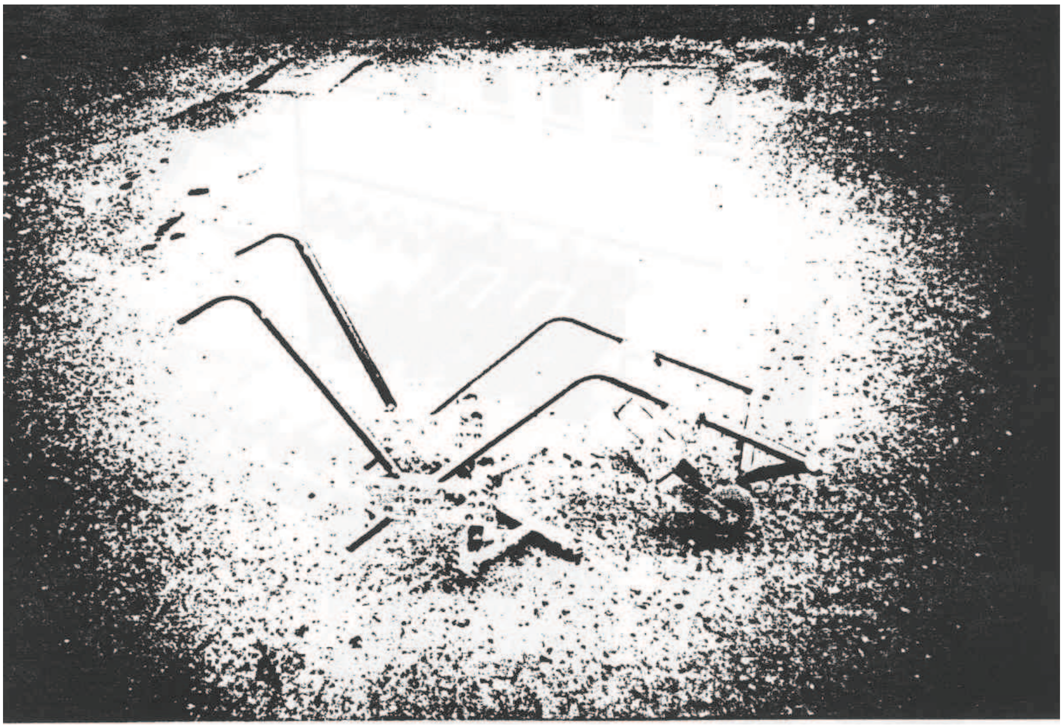


Fig. 15 - Telaio in titanio di sedia a rotelle per portatori di handicap

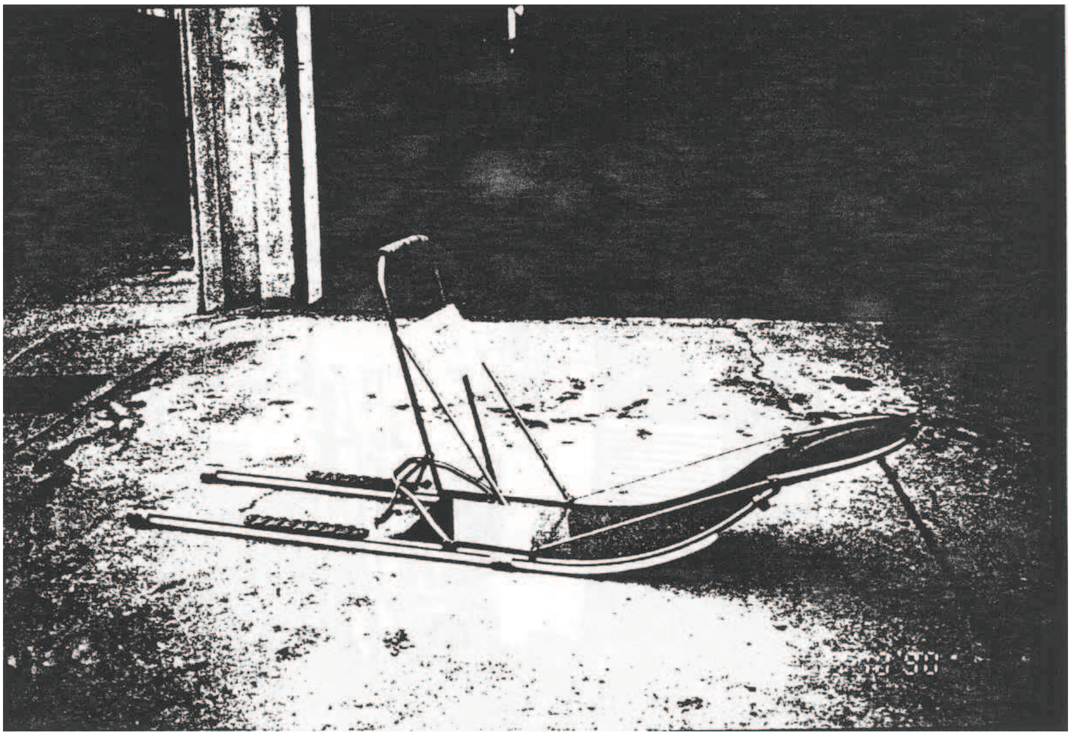


Fig. 16 - Slitta in titanio per competizioni sulla neve

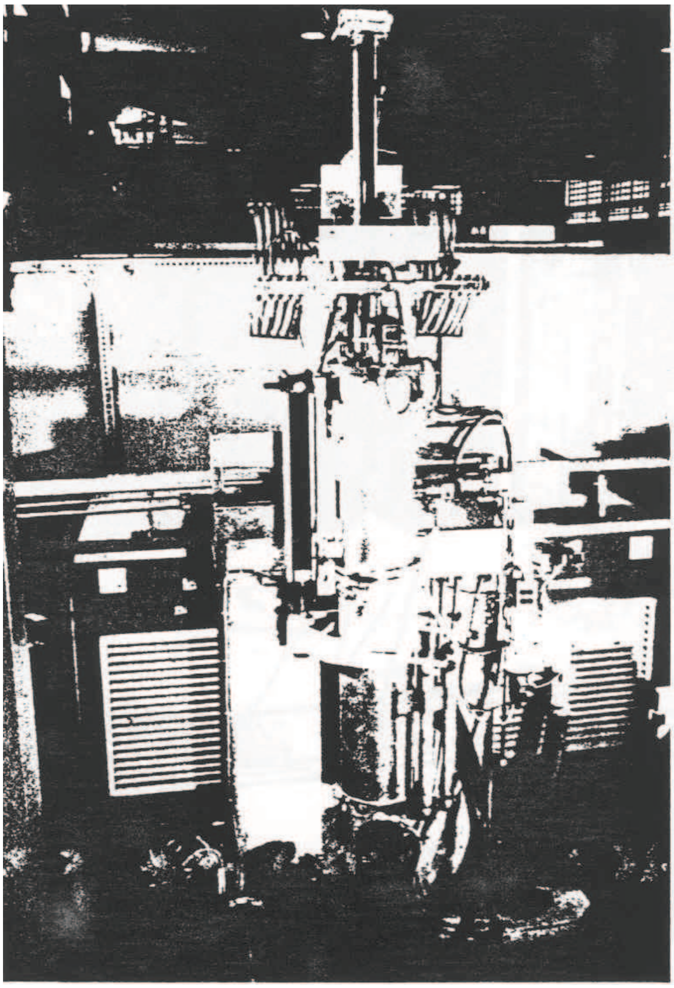


Fig. 17 - GTT - Forno pilota per fusione del titanio e leghe

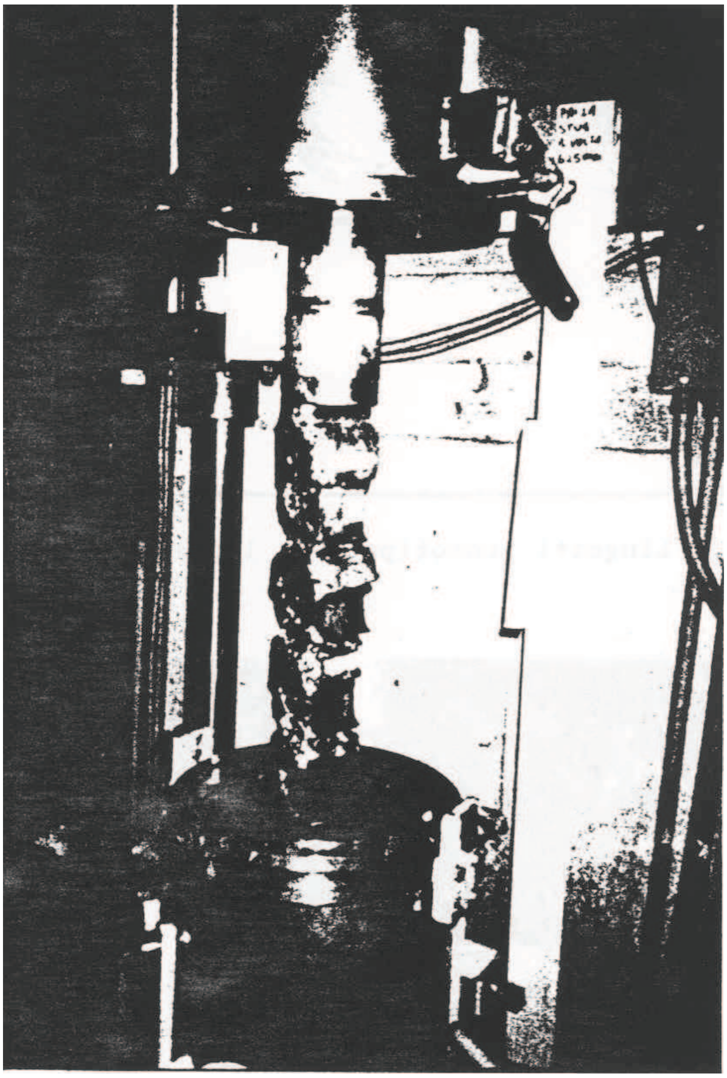


Fig. 18 - Fusione di leghe di titanio

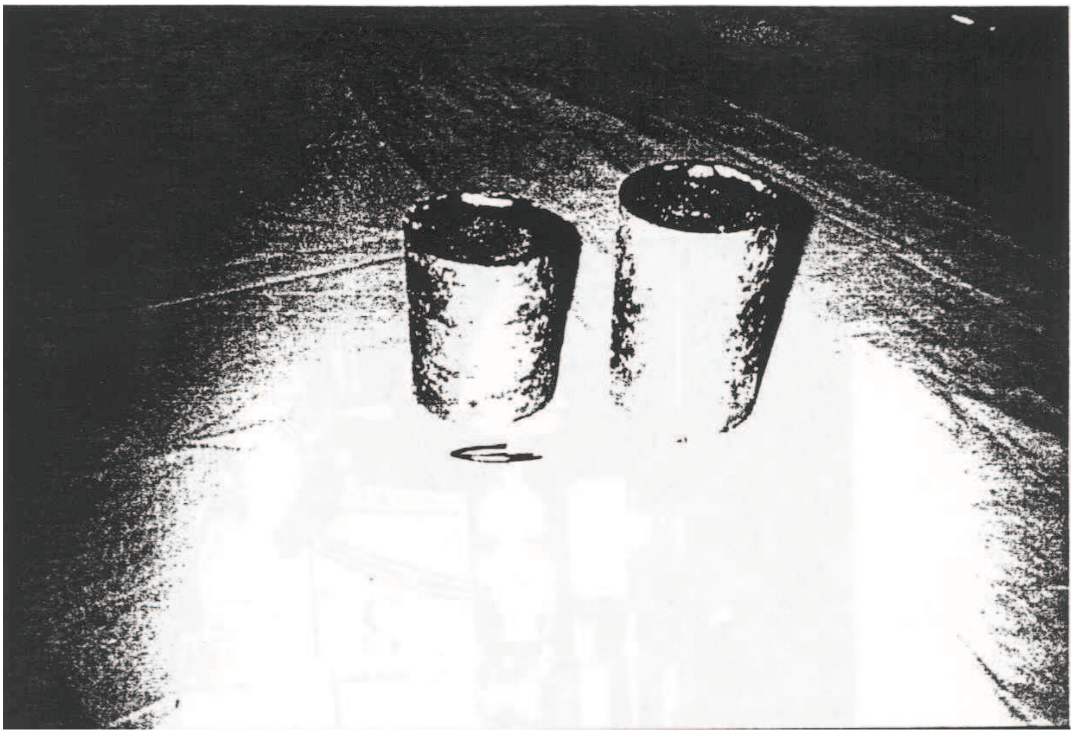


Fig. 19 - Lingotti prototipali di leghe di titanio

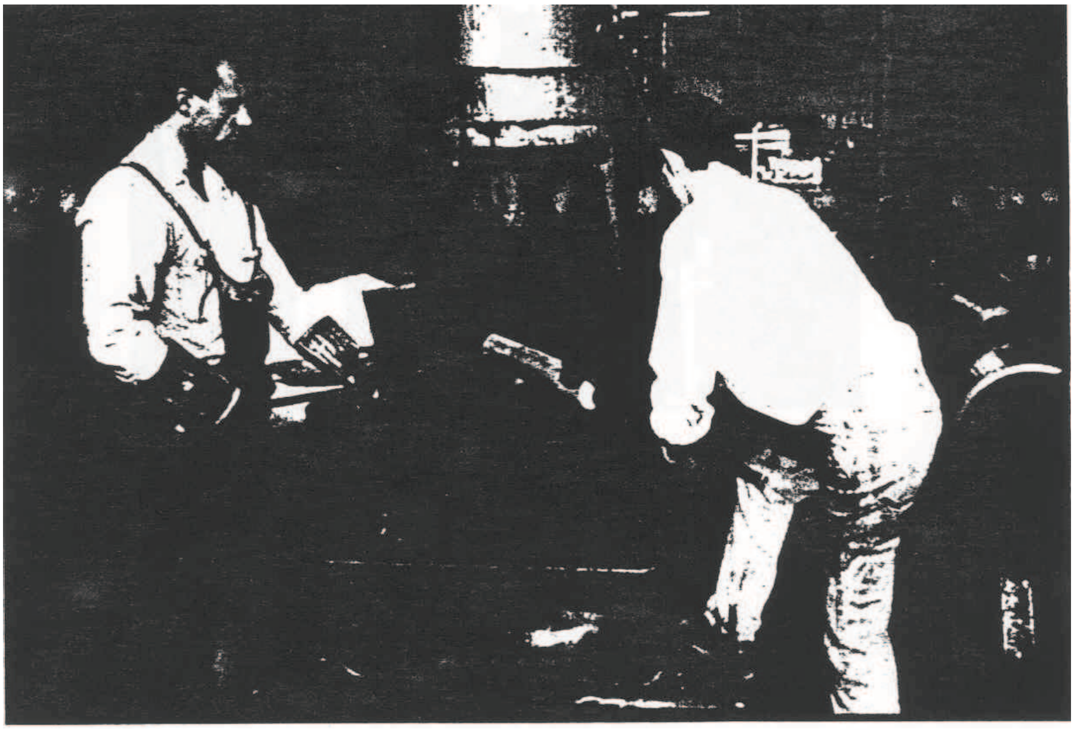


Fig. 20 - Forgiatura di leghe di titanio

PLASMA COLD HEARTH MELTING OF TITANIUM IN A PRODUCTION FURNACE

William R. Chinnis
Teledyne Allvac, 2020 Ashcraft Ave.
Monroe, N.C. 28110

In response to increasing demand from the aerospace industry for defect-free titanium, Teledyne Allvac completed installation of a plasma cold hearth furnace in late 1989. This equipment was designed to remove high density inclusions by entrapment in the skull and Type I alpha defects by dissolution in the molten metal or by entrapment in the skull.

That this concept works has been demonstrated in cold hearth furnaces with electron beam but not plasma as the heat source. Several plasma heats were seeded with thousands of defects including titanium nitrides, tungsten carbide, tungsten, tantalum, and molybdenum. These ingots were then converted directly (no VAR) to bar, immersion ultrasonic and x-ray inspected to confirm defect removal.

INTRODUCTION

A significant problem of titanium alloys used in critical applications is the occasional occurrence of high density and hard alpha inclusions. Catastrophic jet engine failures, some resulting in loss of life, have been directly attributed to the undetected presence of such defects in titanium components.

Cold hearth melting is a technique designed to produce the highest quality titanium alloys completely free of these inclusions. This capability has already been demonstrated in a production cold hearth furnace using electron beam as the heat source and in pilot scale plasma cold hearth furnaces.

In mid-1986, Teledyne Allvac decided to add cold hearth melting to its existing titanium melting capabilities. This decision was primarily driven by the aerospace industry's need for defect-free titanium, and also reflected Teledyne's desire for additional melting capacity. A plasma cold hearth furnace was installed in late 1989 and production began in February of 1990.

This report describes the furnace design and capabilities, melting experience gained to date, and evaluation of the material produced in the furnace.

DEFECTS AND COLD HEARTH MELTING

Two types of inclusions occur in titanium alloys: high density inclusions (HDIs) and Type I hard alpha defects. HDIs are particles of significantly higher density than titanium and are introduced through contamination of raw materials used for ingot production. These defects are commonly molybdenum, tantalum, tungsten, and tungsten carbide. Hard alpha defects are titanium particles or regions with high concentrations of the interstitial alpha stabilizers nitrogen, oxygen, or carbon. The most troublesome defects are high in nitrogen and typically result from titanium burning in air during raw material manufacture, handling, or melting. Due to the nature of conventional melting processes and limitations in inspection techniques, both types of defects can find their way into finished titanium components.

Cold hearth melting offers the ability to eliminate these inclusions. In this method, the raw materials are fed into one end of a water cooled copper hearth where they are melted. The molten metal is heated further as it flows across the hearth and is deposited in an ingot mold at the other end. A solid titanium skull forms between the liquid pool and the copper hearth. Any HDI fed in with the raw materials will sink to the bottom of the pool and become trapped in the skull. If a Type I alpha defect fed in is denser than the liquid, it will be removed in a similar manner. If the defect is less dense, it will be carried along with the flow and must be dissolved before reaching the ingot. Pool superheat, pool volume, and melt rate are critical, therefore, as they directly affect this dissolution.

TELEDYNE ALLVAC'S PLASMA COLD HEARTH FURNACE

One of the first design decisions made was to use plasma rather than electron beam as the heat source. A fair comparison of the two methods is complex and not within the scope of this report. The major factor influencing the choice of plasma, however, was the high vacuum conditions required for electron beam melting. The significant evaporation of alloying elements that occurs under these conditions makes ingot chemistry control very difficult and also results in a significant yield loss. Both of these concerns are eliminated with plasma.

Teledyne Allvac's plasma furnace, supplied by Retech Inc, uses four 750 kilowatt transferred arc plasma torches. One torch heats each of three hearth pools and the fourth heats the ingot top (Fig. 1). Metal flow from the melting area is carried through two right angles and three shallow lips before reaching the ingot. A steel wall provides a barrier between the initial melting pool and the ingot mold. This turning of the flow through a 180 degree angle with an intervening barrier wall is an important feature as it prevents unmelted material from moving directly into the ingot and short circuiting the defect removal process. Plasma torch movement is controlled through easily programmed patterns. The same microcomputer that controls torch movement also provides ingot withdrawal control.

Ingots from 14 inches to 30 inches in diameter can be cast in lengths up to 250 inches. Two rotary drum feeders can deliver raw materials with maximum dimensions of six inches. A bulk feeder is also installed which can feed pieces up to 24 inches in diameter and 15 feet long. The melt chamber and withdrawal chamber are equipped with isolation valves so that multiple ingots can be cast and removed without opening the furnace.

The plasma furnace is operated with an inert gas atmosphere at a one to 3 psi positive pressure. Argon, helium, or a mixture can be used. Typically, a 100 percent helium atmosphere ia used which gives the highest energy efficiency. Each of the plasma torches uses up to 110 standard cubic feet per minute of helium. Economics require, therefore, an efficient gas recycling system. Such a system, provided by Air products and Chemicals, is utilized with the Teledyne Allvac furnace.
This system provides particulate separation, compression, and removal of hydrocarbons, hydrogen, and moisture. Oxygen and moisture are typically maintained at less than 10 ppm.

MELTING EXPERIENCE

Between February and July of 1990, 32 ingots totaling approximately 250,000 lbs. were produced in the furnace. The majority of the ingots were Ti-6Al-4V. Melt rates and yields anticipated for the furnace have been achieved. Raw materials ranging from 100 percent revert to 100 percent virgin were melted with no problems. Both vacuum distilled and acid leached sponge were used. Melting acid leached sponge in large percentages presented no problems except for some difficulty viewing through the clouds of dust generated. No significant difference in yield is noted with raw material types.

During the initial melting, standard practices were developed and a number of operational problems were solved. Raw material feeding was one of the most difficult tasks tackled. Several generations of hydraulic pushers and feed chutes for the rotary feeders were tried before the present arrangement was assembled. The bulk feeder has not been used extensively due to time constraints. Feeding and melting large revert is difficult because of arc length limitations. Routine use of this type of material should be possible, however, with further process development.

Plasma torch water leaks were common before enough experience was gained to avoid damage. The primary danger is what is referred to as a double arc. Normally, the arc is transferred from an internal electrode past an electrically isolated nozzle to the titanium at ground potential. If the nozzle comes close to or touches ground, the arc immediately transfers to the nozzle and water soon appears. The best way to avoid damage is to monitor for low nozzle voltage. With sufficient automation, a number of actions can be taken in response to this signal.

Automatic ingot withdrawal control has been incorporated. The electrode voltage from the ingot plasma torch is used to indicate arc length. With appropriate mathematical processing of this signal, regulating withdrawal to maintain a constant pool level ia relatively simple.

PRODUCT EVALUATION

Chemical Uniformity

The chemical uniformity of the plasma cold hearth melted ingots is of great interest because this property should be one of the major advantages over electron beam melting. The chemistry of five typical plasma plus VAR ingots is given in Table 1. These ingots, approximately 10,000 pounds each, were converted to billet and sampled at surface and center from five equally spaced locations along their length. The average given in the table is that of the ten samples; the variability given ie the difference between the highest and lowest values.

Measurements from a conventionally produced ingot are given for comparison, as well as the specification aims. No measurable evaporation loss is observed, which if present would appear most strongly in lowered and variable aluminum content. Overall chemical uniformity is comparable to that of conventionally produced ingots. Nitrogen and copper analysis showed no significant air or hearth copper contamination.

Billet and Bar Inspection

Twenty-One plasma plus single or double VAR ingots have been processed to four or five inch diameter billet and contact ultrasonic inspected. No inclusions or other defects were found. Billet macrostructure evaluation of these heats yielded results typical of conventionally processed ingots. Several of these heats have been processed to small bar (less than 2 inch diameter) and evaluated for macrostructure and microstructure. Again, results typical of conventional product were obtained.

Average room temperature tensile properties of six plasma heats processed to bar are given in Table 2 and compared to that of conventionally processed material and typical aerospace grade minimums. No significant difference with the standard material is noted. At least six heats have been immersion ultrasonic inspected at bar with no defects found.

SEEDED HEATS

Part of the qualification plan for the plasma cold hearth furnace is an evaluation of its inclusion removal capabilities. This is done by "seeding" various types of inclusion sources into the raw material for one or more heats and inspecting the resulting product for inclusions. Some preliminary evaluations of this type have already been done. A 5,000 pound heat was melted with chips machined with tungsten carbide tools. This type of chip is known to contain as many as one tungsten carbide particle per pound. After melting, the ingot was processed to small bar and ultrasonic and x-ray inspected. No defects were found.
The skull remaining in the hearth was x-rayed and found to contain many defects, obviously removed from the raw material.

Two 3,000 to 4,000 pound heats were made with Type I hard alpha sources added. 300 to 400 artificially nitrided sponge particles were added to virgin compacts to be fed in with the rest of the raw material. After melting, the ingots were processed to small bar and ultrasonic inspected (immersion to a #2 FBH). No defects were found.

Most recently, five 4,000 to 5,000 pound heats were made, the first seeded with HDI and hard alpha sources, the others with hard alpha sources only. The HDI sources consisted of various size pieces of tungsten, tungsten carbide, tantalum, and molybdenum added at a rate of more than one per 10 pounds of ingot. Nitrided sponge of various nitrogen levels, torch cut revert, and enfoliated bar ends were added as hard alpha sources at a rate of almost one per pound of ingot. These defects were put with virgin material carefully compacted to avoid crushing the brittle hard alpha seeds. Ultrasonic and x-ray inspections showed the first heat to be completely free of HDIs. Ultrasonic inspection of all five heats showed less than one percent survival of the hard alpha seeds. It should be noted that this is less than one percent survival of artificially generated seeds added in a worst case method. This is very promising, as it is a significant improvement over triple VAR, the best of the conventional processes. Additional trials are planned to further improve this performance.

SUMMARY

Plasma cold hearth melting promises to produce high quality titanium alloys free of high density and Type I hard alpha inclusions. In early 1990, Teledyne Allvac began operating a production scale furnace of this type. Initial melting has shown the furnace to be reliable and capable of melting a wide variety of raw materials. Good melt rates and high yields have been achieved. Evaluation of billet and bar product has shown good chemical uniformity, mechanical properties, and freedom from defects.

Seeding trials have demonstrated the furnace's ability to remove 100 percent of high density inclusions. The process also removed more than 99 percent of artificial worst case hard alpha seeds, which is a significant improvement over triple VAR.

TABLE 1

PLASMA + VAR CHEMICAL UNIFORMITY

	Al		V		Fe		O	
HEAT	AVG	VAR	AVG	VAR	AVG	VAR	AVG	VAR
AK73	6.26	0.26	4.13	0.24	0.18	0.06	0.16	0.04
AK77	6.20	0.14	3.91	0.17	0.21	0.10	0.16	0.06
AK87	6.19	0.20	3.93	0.22	0.18	0.05	0.15	0.05
AK88	6.33	0.11	4.03	0.17	0.19	0.03	0.17	0.05
Std. Prod.	6.13	0.24	3.92	0.29	0.17	0.11	0.15	0.05
Spec. Aim	6.30		4.20		0.15		0.17	

AVG - Average of ten samples
VAR - Variation, difference between highest and lowest of ten samples

TABLE 2

PLASMA HEAT ROOM TEMPERATURE TENSILE

	UTS (ksi)	0.2% YS (ksi)	RA (%)	EL (%)
Plasma Avg.	144	133	43	17
Typical Std. Grade	148	136	43	17
AMS 4978 Minimums	135	125	25	10

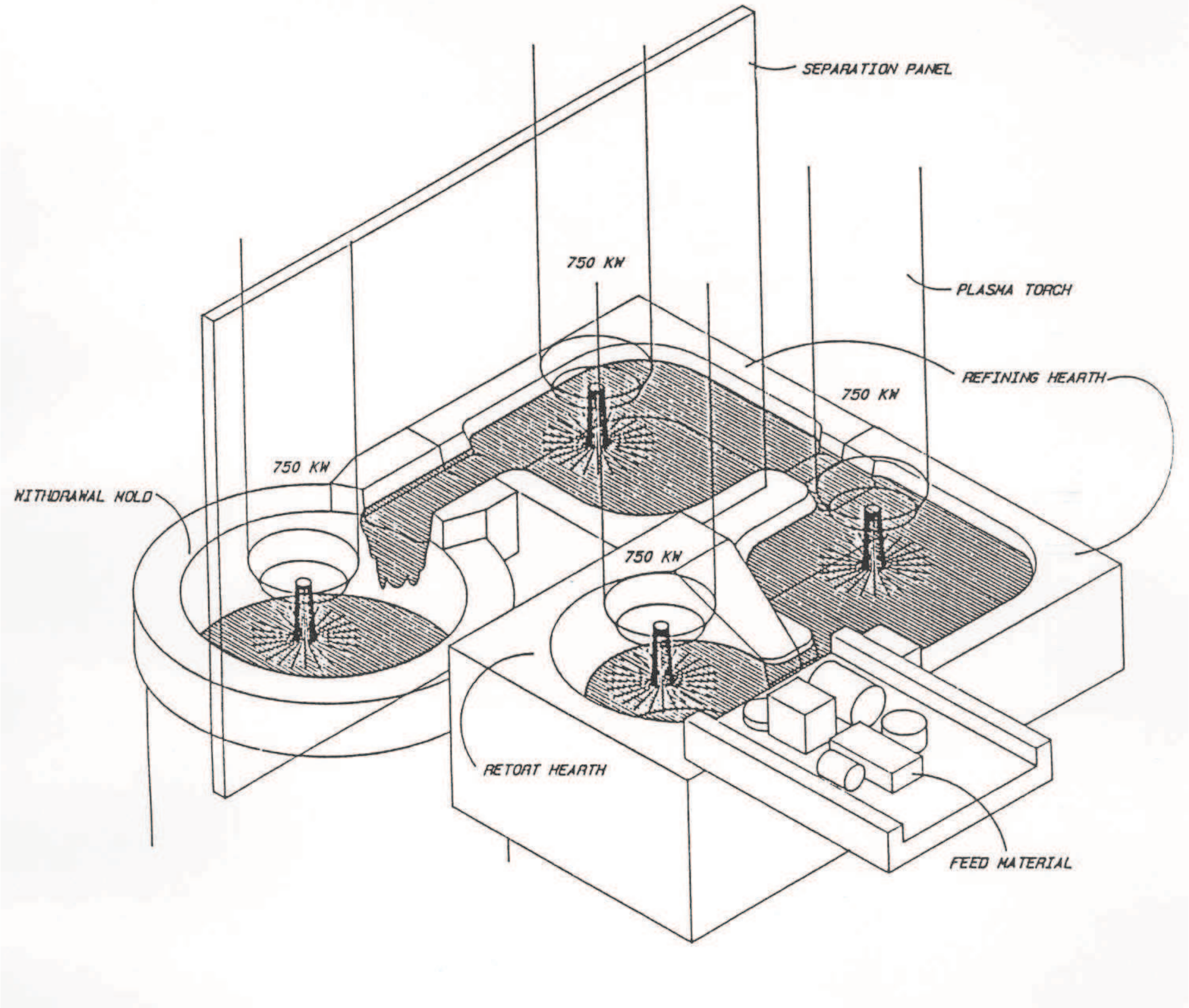


FIG. 1 – TELEDYNE ALLVAC'S PLASMA FURNACE

COMPORTAMENTO MECCANICO DI UNA LEGA BETA-C COMMERCIALE

D.Buttinelli*, F.Felli*, G.B.Festa*, P.Lingua**.

(*) Dipartimento di Ingegneria Chimica, dei Materiali, delle Materie Prime e Metallurgia - Università "La Sapienza", Roma.
(**) GINATTA TORINO TITANIUM.

INTRODUZIONE

Nella prospettiva di una possibile futura produzione di leghe di titanio in ambito nazionale, viene tra le altre proposta la lega BETA-C (Ti-3Al-8V-6Cr-4Mo-4Zr) poiché presenta, oltre alle caratteristiche proprie delle leghe β di titanio, quali ad esempio ottima forgiabilità, elevate caratteristiche meccaniche e buon comportamento a fatica, anche una buona lavorabilità sia a caldo che a freddo, ma soprattutto un'eccellente resistenza alla corrosione (1).

Questa lega viene prodotta, peraltro, anche con specifiche non aeronautiche e può rendersi molto utile per varie applicazioni industriali; per tali motivi il suo potenziale mercato può risultare più ampio (2).

Lavoro svolto con contributo M.U.R.S.T. (fondi 40% - 1989)

In questo lavoro è stato studiato il comportamento meccanico di una lega BETA-C commerciale prodotta dalla soc. RMI (USA), ponendo particolare attenzione al binomio caratteristiche di velocità di propagazione della cricca - resistenza meccanica, in relazione alle possibili tessiture di lavorazione ed in funzione dei diversi trattamenti termici.

Alcuni risultati vengono confrontati con quelli di leghe di Ti ($\alpha+\beta$) con caratteristiche di comportamento a fatica molto buone, quali la lega 6-6-2 e la lega 6-4 (3-4). Questi dati sono ricavati da prove eseguite sulla stessa macchina ed in condizioni operative molto simili a quelle usate per la lega BETA-C.

Al fine di una migliore presentazione riepilogativa dei dati di fatica o meglio degli andamenti di propagazione sub-critica della cricca, nelle varie condizioni di invecchiamento della lega, viene usata la relazione semiempirica di Collipriest (5), che permette di esprimere analiticamente la velocità di avanzamento della cricca di fatica mediante l'uso di un numero assai ridotto di parametri caratteristici sperimentali. L'equazione è del tipo:

EQ

il cui andamento della curva di fatica è fornito dalla funzione arcotangente iperbolica.

MATERIALI E PROCEDURE SPERIMENTALI

La lega studiata è stata fornita allo stato solubilizzato (815°C÷1/2ora; A.C.), laminata in piastre di 20mm di spessore, con la seguente composizione chimica: Al 3,3% - V 8,1% - Cr 5.8% - Mo 3,9% - Zr 3,8% - Fe 0,03% - Nb 0,08% - C 0,02% - N 0,015% - H 80 ppm.

Dalla piastra, tramite taglio alla fresatrice, sono stati ricavati i provini per le prove di invecchiamento, di trazione e di fatica, nelle direzioni L e T.

Le prove di invecchiamento sono state condotte su provini 20x25x4(mm) in forno in atmosfera di argon, in un intervallo di temperatura 450°C÷600°C, per tempi fino a 24 ore, con rilevazione della durezza Vickers (carico 50kg, tempo di azione 15 secondi).

Le prove di trazione sono state eseguite sui provini solubilizzati ed invecchiati a 450°C-475°C-500°C-525°C-550°C-570°C per 20 ore, determinando $\sigma_{y0,2}$ - σ_r e A%.

Sono state eseguite anche prove di invecchiamento in doppio stadio che non hanno dato risultati significativi.

Le prove di fatica sono state condotte seguendo le norme ASTM E647 in condizioni ambientali di laboratorio, con macchine il cui carico viene generato da un elettromagnete ed amplificato meccanicamente con una frequenza di 9,5 Hz. I provini di spessore B=12,5mm e W=40mm del tipo CT (compact tension specimen), prelevati dalla piastra nelle configurazioni LT e TL, sono stati esaminati, in questa prima parte della ricerca, nelle condizioni di solubilizzati e di invecchiati a 450°C, 500°C e 570°C per 20 ore.

Il criterio di scelta per questi tempi e temperature è legato al fatto che si ottengono le caratteristiche meccaniche più elevate compatibilmente con tempi di trattamento adeguati per la pratica industriale.

Temperature più basse portano a caratteristiche meccaniche più elevate, ma solo con tempi di trattamento sensibilmente lunghi.

I carichi applicati sono del tipo sinusoidale, con rapporto R=0,5 (R=Pmin/Pmax). La lettura della lunghezza della cricca è stata eseguita per via ottica con microscopio a 40 ingrandimenti, con verifica dopo rottura del campione.

Da queste misure, con l'impiego del metodo polinomiale, si ricava la velocità di avanzamento della cricca. I risultati sono stati poi elaborati tramite un programma appositamente sviluppato per l'elaborazione delle curve da/dN-ΔK.

I dati sperimentali sono stati poi interpolati con il modello semiempirico di Collipriest (5); questo modello insieme a quelli di Paris e Forman sta alla base della previsione del comportamento a fatica di un componente reale.

Gli esami metallografici [reagente d'attacco: 1 ml HF(40%), 5 ml HNO_3, 94 ml H_2O (distillata)] e quelli delle superfici di frattura sono stati condotti mediante microscopia ottica ed al microscopio elettronico a scansione Hitachi S-2500 dotato di sistema (EDS) Kevex 8000.

TABELLA 1

LEGA	σ_y (MPa)	σ_R (MPa)	A%	HV_{50}	K_{IC} (MPa$\sqrt{m}$)
BETA-C (SOL.)	834	851	17	265	
BETA-C (450°C-20h)	1090	1170	10	360	
BETA-C (475°C-20h)	1184	1266	5	410	
BETA-C (475°C-28h)	1274	1324	4	425	
BETA-C (500°C-20h)	1145	1224	7	390	
BETA-C (525°C-20h)	1102	1182	8	375	
BETA-C (550°C-20h)	923	952	12	325	
BETA-C (570°C-20h)	904	933	12	310	L 90* T 65
6-4 ** (Val. Min. e Max)	883-986	986-1082	10 -14		66-96
6-6-2 ** (Val. Min. e Max)	938-1076	1069-1179	8 -16		45-85

*Rif.(8)

**Rif.(7)

RISULTATI E DISCUSSIONE

In tabella 1 sono riportate le caratteristiche meccaniche ottenute per la lega BETA-C alle varie temperature di invecchiamento dopo 20 ore di trattamento. Premesso c11e non si riscontrano sensibili differenze per i campioni prelevati in senso longitudinale e trasversale, gli incrementi più significativi si ottengono alle temperature nel campo 500°C-450°C dove si hanno i valori massimi di σ_y 1184 MPa e σ_r di 1266 MPa, anche se A% scende sino a valori del 5%. Valori più elevati si ottengono per tempi di trattamento maggiori come mostrato da una prova di trattamento eseguita a 475°C per 28 ore, dove si è ottenuto per σ_y 1274 MPa e σ_r di 1324 MPa. Per questa lega la lettura (6) riporta valori max. raggiungibili fino a σ_r 1654 MPa.

Nel presente lavoro ci si è limitati a durate del trattamento simili a quelle industriali, è tuttavia in corso un'indagine più approfondita nel campo di temperatura 350°C-450°C e ovviamente tempi di trattamento più lunghi, condizioni queste che portano a caratteristiche resistenziali ben più elevate.

Nella medesima tabella vengono riportati per confronto i valori delle due leghe $(\alpha+\beta)$ 6-6-2 e 6-4 (7), da cui si evince che già si raggiungono per la BETA-C caratteristiche sensibilmente superiori.

Per quanto riguarda le indagini metallografiche viene evidenziata per il solubilizzato una struttura con taglia dei grani discretamente grossolana e disomogenea (fig.1). Tuttavia con il trattamento termico di invecchiamento (fig.2a,b) si può riscontrare una precipitazione di α_s (fase scura) perfettamente distribuita nella matrice β (fase chiara) sempre più fine al diminuire della temperatura, essendo le dimensioni dei precipitati

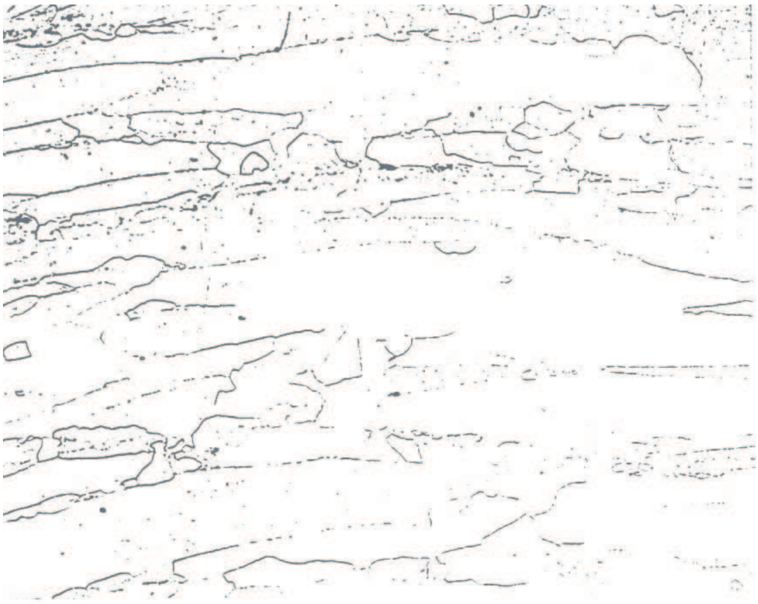


Fig.1 - Micrografia ottica della lega BETA-C solubilizzata (x80)

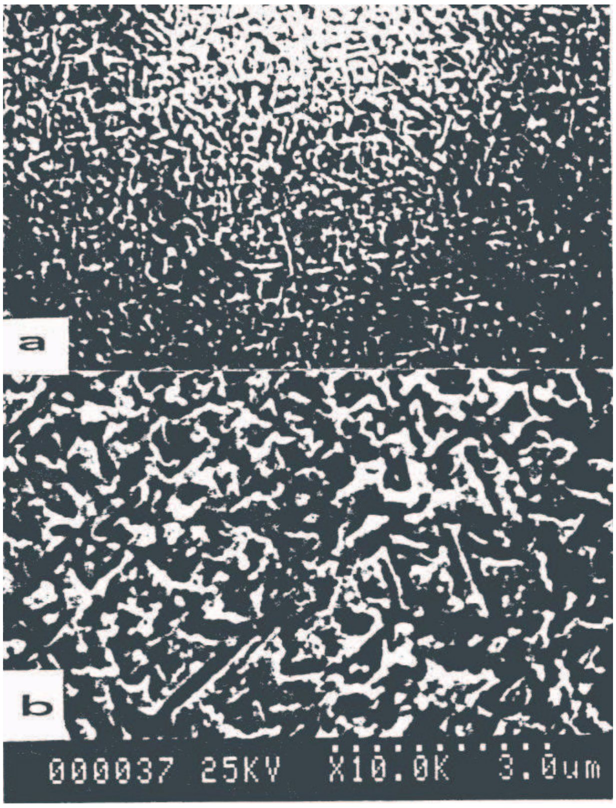


Fig.2 - Micrografia SEM della lega BETA-C per i campioni invecchiati alla temperatura di: a) 475°C; b) 525°C

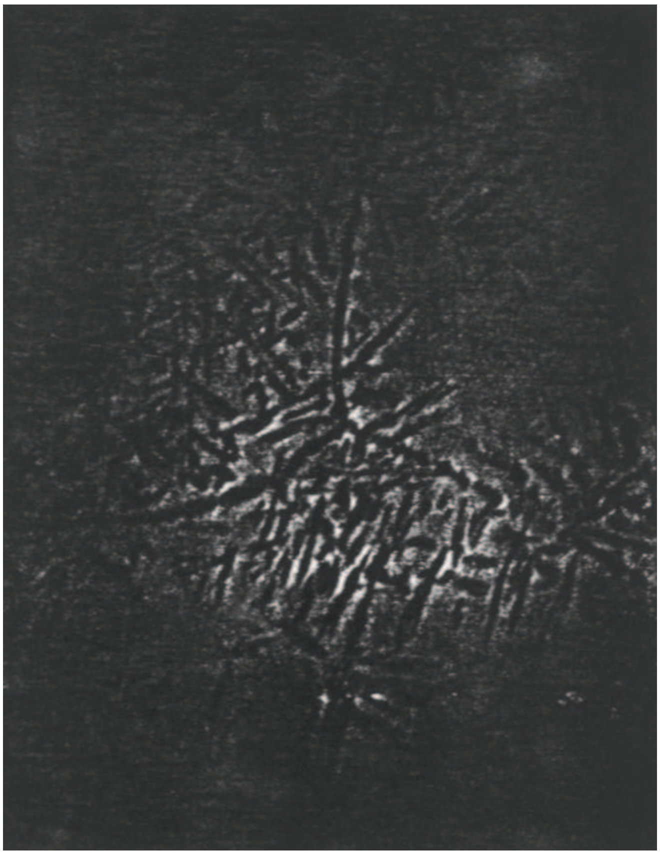


Fig.3 - Micrografia SEM di un campione invecchiato a 570°C (x2000)

dell'ordine di 1,5 μm a 525°C fino a 0,1 μm a 475°C. A temperature superiori la precipitazione di α_s è più grossolana e non più omogenea (fig.3).

Nelle figg. 4 e 5 sono riportati i risultati sperimentali delle prove di fatica eseguiti nelle direzioni LT e TL.

(fig.4 - lega solubilizzata ed invecchiata a 570°C)

(fig.5 - leghe invecchiate a 450°C e 500°C)

Nelle figg. 6 e 7 sono riportate le sole curve di Collipriest relative ai risultati precedenti per i campioni LT (adottando come valore di K_{rc} 65 MPa√m) e TL (K_{rc} 90 MPa√m), (8).

Una prima importante evidenza è data dal fatto che non si ha una marcata differenza tra la velocità di propagazione della cricca tra i campioni TL ed LT, mentre per quanto riguarda i campioni invecchiati questi presentano maggior velocità di propagazione della cricca rispetto ai solubilizzati per i più bassi valori di $\Delta K(<\Delta K_{th})$, ben evidenziato anche dalle difficoltà incontrate nella nucleazione della cricca nei campioni solubilizzati durante l'esecuzione delle prove di fatica.

Per valori più alti di ΔK ($\Delta K>10$ MPa√m) si ha un'inversione di tendenza, si osserva infatti una diminuzione dell'incremento della velocità di propagazione della cricca per i campioni invecchiati tanto maggiore quanto minore è stata la temperatura d'invecchiamento. Questo fenomeno è tuttavia contenuto in differenze di valori non molto sensibili.

L'esame metallografico delle superfici di frattura dei provini rotti per fatica, mostra tuttavia alcune evidenze morfologiche utili ad una prima interpretazione del fenomeno: infatti i campioni evidenziano morfologie delle superfici di frattura fondamentalmente simili nelle fasi iniziali (figg.8,9), con propagazione transgranulare caratterizzata da un aspetto a gradini

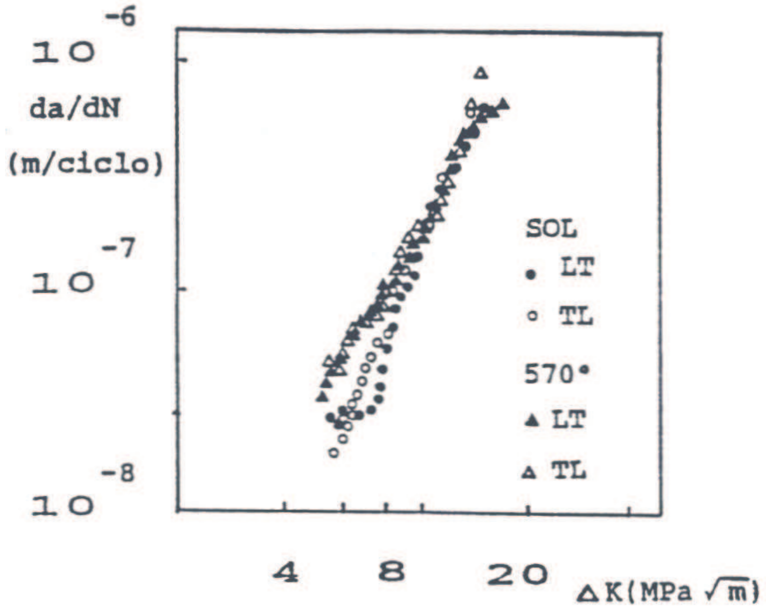


Fig.4 - Risultati sperimentali delle prove di fatica per i campioni nelle direzioni LT e TL allo stato solubilizzato ed invecchiato a 570°C (R=0,5; f=9,5 Hz).

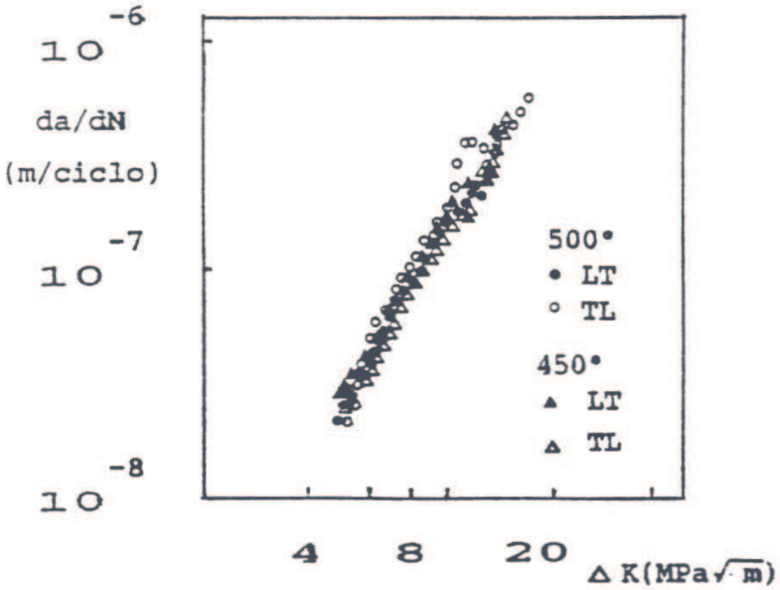
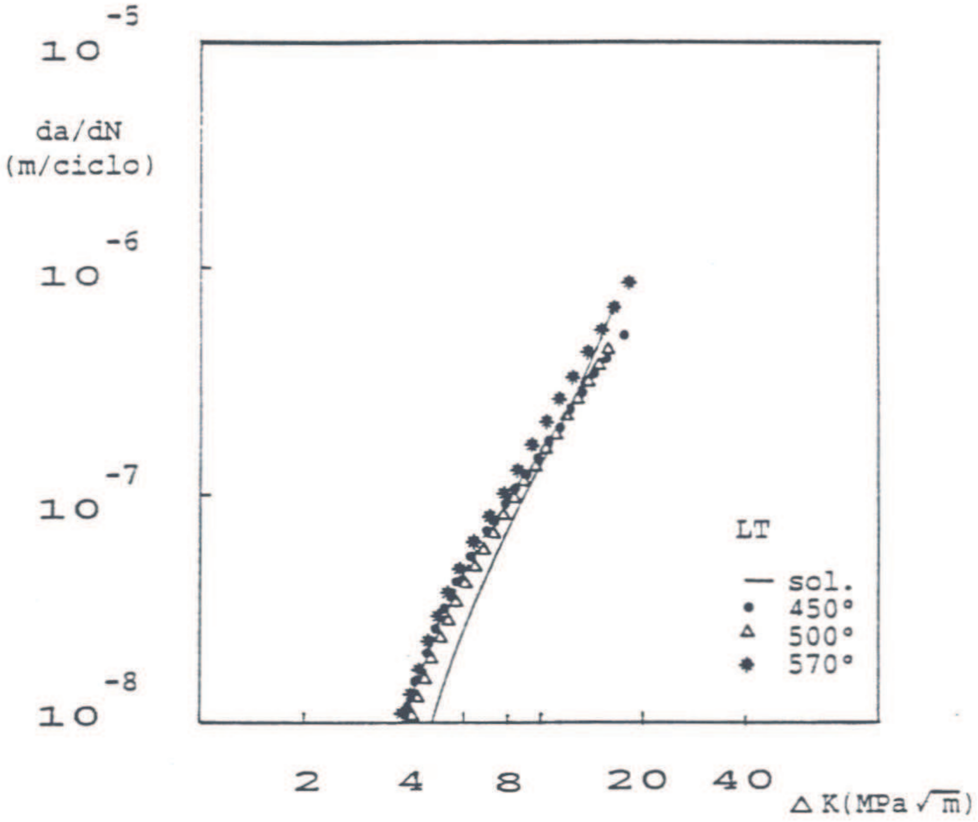
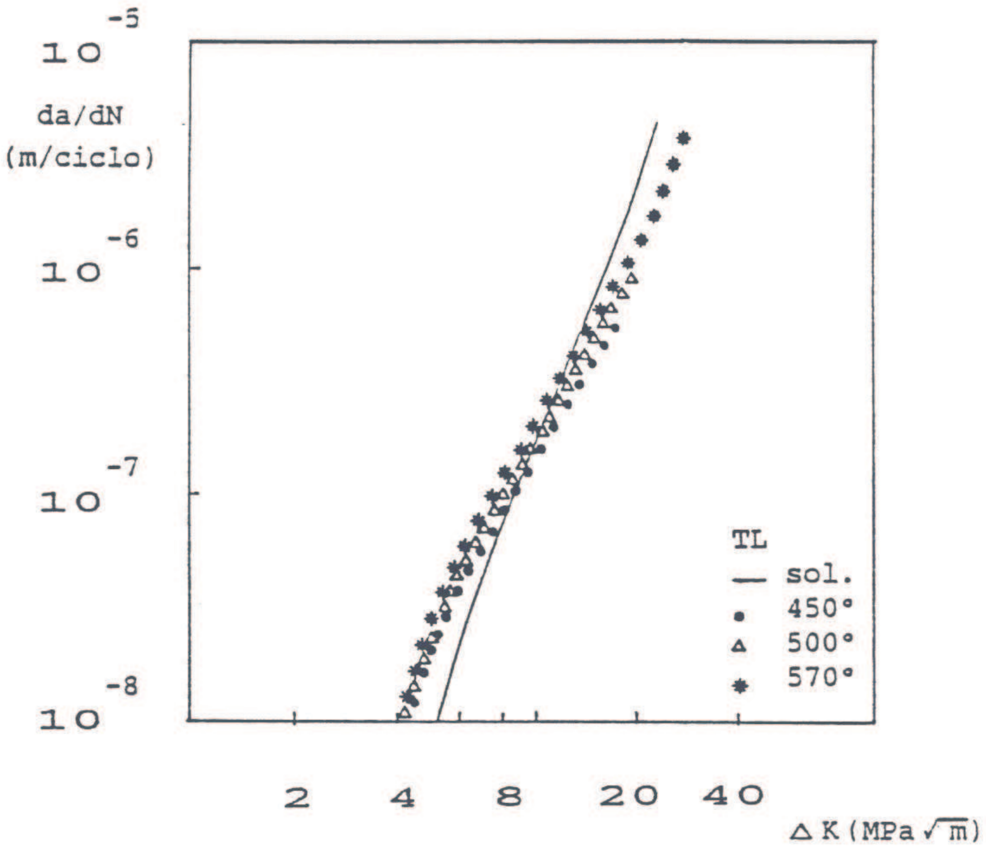


Fig.5 - Risultati sperimentali delle prove di fatica per i campioni nelle direzioni LT e TL allo stato invecchiato a 450°C e 500°C (R=0,5; f=9,5 Hz).



	SOLUBILIZZATO	450°C	500°C	570°C
COLLIPRIEST				
$C(10^{-8})$	0.32	1.95	1.20	1.53
n	2.31	1.66	1.83	1.86

Fig.6 - Velocità di avanzamento della cricca di fatica per la lega BETA-C nella direzione LT, alle varie condizioni di trattamento indicate, dati interpolati con il modello di Collipriest (K_{rc}=65 MPa√m).



	SOLUBILIZZATO	450°C	500°C	570°C
COLLIPRIEST				
C (10^-[illegible])	0.097	1.09	1.25	1.27
n	2.85	1.88	1.9	1.95

Fig.7 -Velocità di avanzamento della cricca di fatica per la lega BETA-C nella direzione TL, alle varie condizioni di trattamento indicate, dati interpolati con il modello di Collipriest (K_{rc}=90 MPa√m).

(cleavage like-steps), tuttavia i campioni solubilizzati si differenziano per un aspetto caratterizzato da maggior rugosità.

A 20 mm circa dall'intaglio (ΔK≈12 MPa√m) la frattura assume un aspetto con le classiche striature di fatica distanziate di circa 1 μm ed in buon accordo con le velocità misurate.

Il fatto che in questa zona i campioni invecchiati presentano velocità di propagazione della cricca minori, pur apparentemente in disaccordo con i limitati dati riportati in letteratura per prove di fatica della lega BETA-C (9-10) e più in generale per le leghe β, potrebbe essere legato a maggiori effetti di chiusura presenti in questa zona (ΔK elevato) evidenziati anche dalla maggior rugosità delle superfici di frattura per i campioni invecchiati (figg.10-11), (11). D'altro canto, si conferma quanto dimostrato da Duerig, Allison e Williams (12) che per una lega β Ti-10-2-3 hanno evidenziato come la velocità di propagazione della cricca è quasi insensibile al tipo di struttura indotta dal trattamento termico ad eccezione per invecchiamenti ω.

In fig. 12 viene riportata la fascia individuata dall'insieme dei dati sperimentali ricavati da tutte le prove eseguite e per confronto le curve di una lega 6-6-2 e 6-4 (3,4).

Le prove sulla lega 6-4 sono state realizzate su provini provenienti da due diversi forgiati, nell'intento di saggiare la sensibilità di questa lega alle variazioni microstrutturali.

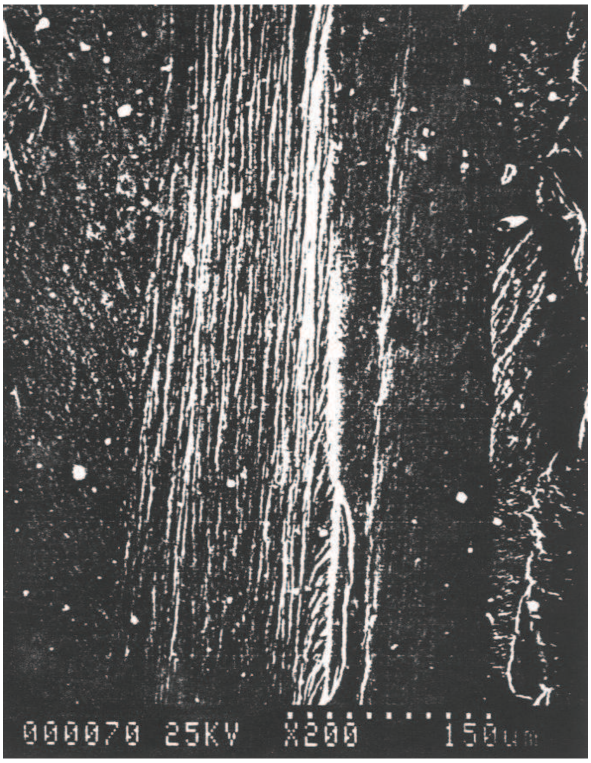
In fig.13 A e 13 B si riportano le microstrutture dei due campioni rispettivamente.

Come si può notare la variazione tra le due microstrutture è estremamente contenuta, presentando entrambe una fase a globulare ed aciculare, immersa in una matrice di fase β trasformata.

Nel campione "A", tuttavia la fase a aciculare è percentualmente maggiore rispetto al campione "B". Le curve per queste leghe sono

Fig. 8 - Micrografia SEM della superficie di frattura di fatica del campione solubilizzato (a circa 4 mm dall'intaglio).

Fig. 9 - Micrografia SEM della superficie di frattura di fatica del campione invecchiato a 500°C (a circa 4 mm dall'intaglio).



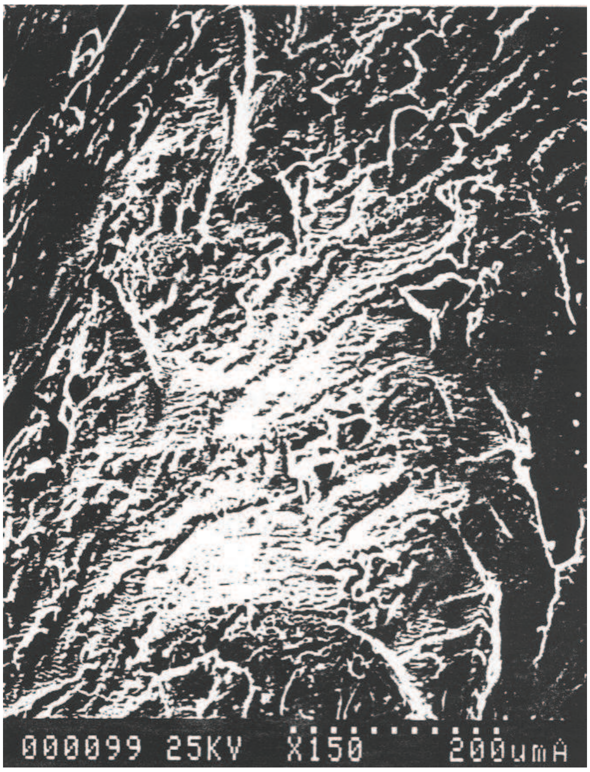


Fig. 10 - Micrografia SEM della superficie di frattura di fatica del campione solubilizzato (a circa 20 mm dall'intaglio).

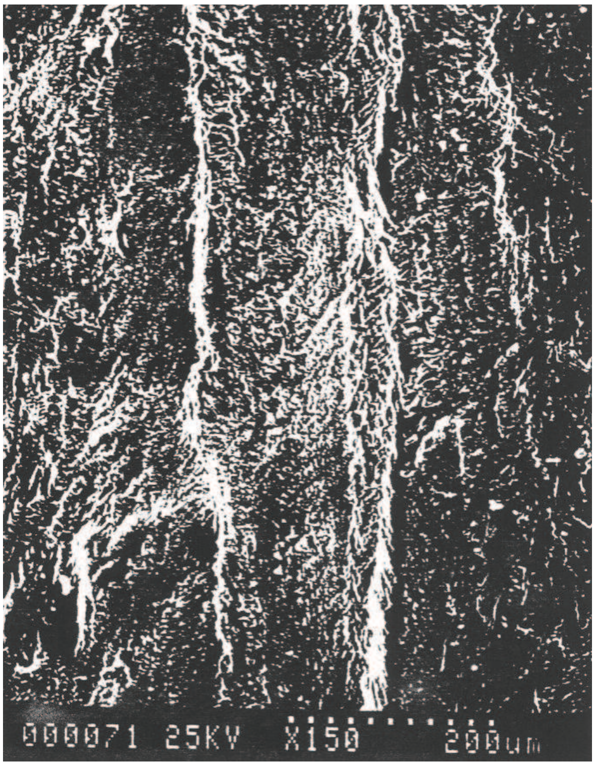


Fig. 11 - Micrografia SEM della superficie di frattura di fatica del campione invecchiato a 500°C (a circa 20 mm dall'intaglio).

state ottenute con la stessa macchina e nelle medesime condizioni operative della lega BETA-C.

Unica differenza nel caso della lega 6-4, il valore di R pari a 0,33.

Bisogna tuttavia rilevare che per valori di R minori, diminuiscono le velocità di propagazione della cricca (3). La lega 6-4(A) con tenore di fase aciculare maggiore presenta un comportamento alla propagazione della cricca tendenzialmente peggiore della 6-4(B).

Da questo quadro emerge che la lega BETA-C si colloca molto vicina in termini di velocità di propagazione della cricca ai valori delle leghe 6-6-2 e 6-4 che, occorre sottolineare, appartengono, tra le leghe di titanio, a quelle che presentano caratteristiche di resistenza a fatica migliori. D'altro canto, anche se le velocità di propagazione della cricca sono leggermente superiori per la lega BETA-C, quest'ultima mostra caratteristiche tensili sensibilmente superiori.

Emerge anche una maggior sensibilità della lega 6-4 alle variazioni strutturali rispetto alla lega BETA-C.

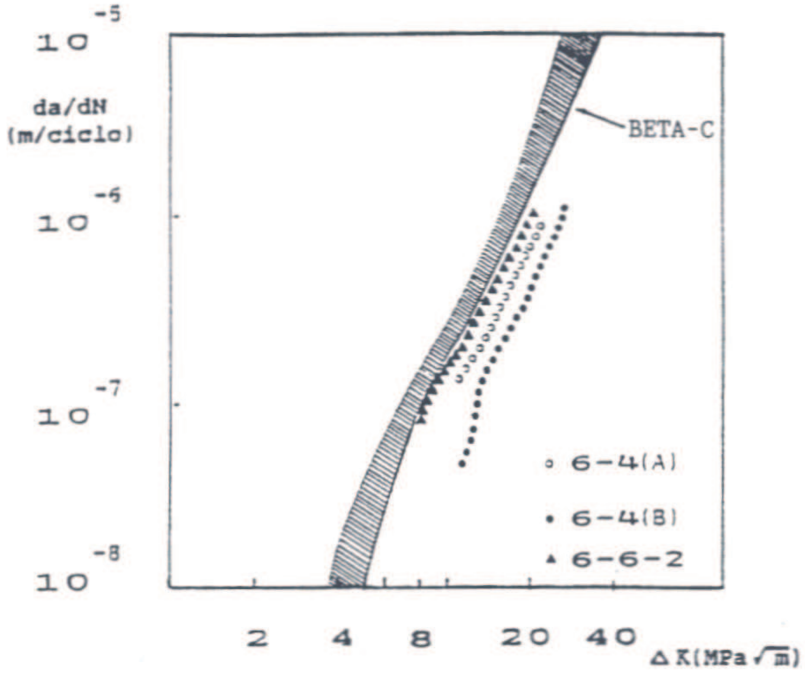


Fig. 12 - Velocità di avanzamento della cricca di fatica. La fascia individua l'insieme dei dati sperimentali ricavati da tutte le prove eseguite sulla lega BETA-C. Per confronto vengono riportate le curve ottenute per una lega 6-6-2 e due leghe 6-4 (per le leghe 6-4, R=0,33), (Rif. 3,4).

Fig. 13 - Microstrutture di due diversi campioni di lega 6-4 contrassegnati "A" e "B" rispettivamente (x500), (Rif. 4).

CONCLUSIONI

Limitatamente ai trattamenti d'invecchiamento più consoni ad un processo tecnologico industriale, la totalità delle prove svolte ha dimostrato che alle temperature di invecchiamento più basse (450°C-500°C) si realizzano le strutture con più elevate caratteristiche meccaniche (durezza e σ). Le indagini metallografiche dimostrano una precipitazione più fine ed omogenea in questo campo di temperature.

Nell'intervallo 475°C-500°C si ha la migliore combinazione di proprietà tensili e resistenza a fatica, con preferenza alla temperatura inferiore se si vogliono elevati carichi di snervamento e doti plastiche accettabili. Il comportamento a fatica è poco influenzato dalle differenti strutture. Dal confronto con leghe di maggior impiego ed ormai affermate quali la 6-6-2 e la 6-4, la lega BETA-C esce abbastanza bene, presentando caratteristiche tensili sensibilme11te superiori e comportamento a fatica abbastanza simile, anche se a livelli leggermente inferiori.

RINGRAZIAMENTI

Gli autori desiderano ringraziare i proff. M.Cavallini e M.Marchetti per le utili discussioni sulle prove di fatica, i tecnici sigg. G.Bacosi e C.Panzironi per la preziosa collaborazione nello svolgimento delle prove meccaniche e degli esami metallografici.

RIFERIMENTI BIBLIOGRAFICI

1) RMI-Titanium Technical Bulletin: "RMI 3Al-8V-6Cr-4Mo-4Zr Titanium Alloy for Deep Hardening Applications", January, (1969).
2) D.E.Thomas, S.Ankem, W.D.Goodin, S.R.Seagle: "Beta-C: An Emerging Titanium Alloy for the Industrial Marketplace", in "Industrial Applications of Titanium and Zirconium", (C.S.Young, J.C.Durham), (1986), pp. 144-163.
3) A.La Barbera, M.Marchetti: "Propagazione di Cricche per Fatica nella Lega Ti-6Al-6V-2Sn: "Modelli di Propagazione ed Analisi Frattografica", V Convegno Nazionale del Gruppo Italiano Frattura (IGF) - [Atti], Trento, Italia, 8-9 Giugno 1989.
4) Tesi di Laurea: "Aspetti Fratturistici ed Analisi a Fatica di Giunzioni Saldate con Tecnica Electron Beam", Cattedra di Tecnologie Aeronautiche (Prof. M.Marchetti), Facoltà di Ingegneria, Università di Roma "La Sapienza" - A.A. 1988-'89.
5) J.E.Collipriest: "An Experimentalist's View of the Surface Flaw Problem", ASME, pp. 43-62.
6) H.J.Rack, T.J.Headly: "Stability of Aged Ti-3Al-3V-6Cr-4Mo-4Zr", Scr.Metall., 14, (1980), pp. 1211-1216.
7) J.C.Chesnutt, C.G.Rhodes, J.C.Williams: "Relationship between Mechanical Properties, Microstructure, and Fracture Topography in $\alpha+\beta$ Titanium Alloys", Fractography-Microscopic Cracking Processes, ASTM STP 600, American Society for Testing and Materials, 1976, pp. 99-138.
8) D.H.Wilson, C.M.Esler: "Properties of Ti-3Al-8V-6Cr-4Mo-4Zr", in "Beta Titanium Alloys in the 1980's, (R.R.Boyer,

H.W.Rosenberg), (1984), pp. 457-482.

9) C.G.Rhodes, N.E.Paton: "The Influence of Microstructure on Mechanical Properties in Ti-3Al-8V-6Cr-4Mo-4Zr (Beta-C)", Metall. Trans.A, 8A, (1977), pp. 1749-1761.

10) G.W.Kuhlman, A.K.Chakrabarti: "Room Temperature Fatigue Crack Propagation in Beta Titanium Alloys", Microstructure Fracture Toughness and Fatigue Crack Growth Rate in Titanium Alloys [Proc. conf.], Denver, Colorado, USA, 24-25 Feb. 1987, pp. 3-15.

11) G.W.Kuhlman, A.K.Chakrabarti, T.L.Yu, R.Pishko, G.Terlinde: "Lcf, Fracture Toughness, and Fatigue/Fatigue Crack Propagation Resistance Optimization in Ti-10V-2Fe-3Al Alloy Through Microstructural Modification", Microstructure Fracture Toughness and Fatigue Crack Growth Rate in Titanium Alloys [Proc. Conf.], Denver, Colorado, USA, 24-25 Feb. '87, pp. 171-191.

12) T.W.Duerig, J.E.Allison, J.C.Williams: "Microstructural Influences on Fatigue Crack Propagation in Ti-10V-2Fe-3Al", Metall.Trans.A, 16A, (1985), pp. 739-751.

SIXTH INTERNATIONAL MEETING ON TITANIUM

MARKETING OF TITANIUM
FOR
ARCHITECTURE APPLICATION
IN JAPAN

Kazuyasu KITAOKA
(Kobe Steel, Ltd.)
Co-Chairman
Application Development Committee
Japan Titanium Society

CONTENTS

1. Brief history
2. Shipments and uses of titanium for architecture application in relation to other materials
3. Characteristics of different roofing materials and their transitions
4. Properties required for roofing materials and sales points in relation with other materials
5. Important Marketing Target
6. Some current issues regarding marketing of titanium for architecture application
7. Future challenges

1. Brief history

Titanium was first used in Japan in 1973 as a building material for the small roof of (50m^2) a Japanese Shinto shrine located at the sea coast.
Subsequently after that, titanium was used for roofs and door plates of small buildings, including the citizen's constitution of Chigasaki City, roofs of Shinto shrines and their arch ways and because its use was on a very small scale and the number of projects was also small. architects' interest, at that time, was minimal.

However, since 1984 when titanium was used for the dome roof of the Electric Power Museum. a new modern building completed in the center of Tokyo. and owned by the Tokyo Electric Power Company. Inc. (TEPCO) , it has been attracting the attention of people engaged in architecture.

It was almost at the same time that the Application Development Committee and the Building Materials Group, a sub-committee of ADC, were organized that a decision to use titanium for the doom roof of the TEPCO Museum, was made.
This decision, however, was made solely by a progressive architect, Mr. Koichi Takahashi, and this was the first case where an architect decided to use titanium for part of a modern building.

After the ADC was organized, the committee looked for an activity to promote.
The Stainless Steel Association of Japan which had many successful results from their activities to develop new applications of stainless steel was consulted. Reference was made to the remarkable growth in demand for stainless steel in indoor piping and roofing applications, and we chose indoor piping application, putting roofing aside for the time being.

In fact. none of the group members expected that the application of titanium to roofs would be realized so soon, even before indoor piping application.

The result was completely contrary to our expectation. I suppose most of you still question the merit of using such expensive material as titanium in architecture. We shared the same feeling in Japan until recently. We did not realize that a change in the potential needs of a new age had evolved.

Using the case of the TEPCO Museum, we have begun to pay due attention to architecture applications and to approach architects who have been looking for new materials. There are high grade metallic materials such as copper, aluminum and stainless steel but architects have been looking for much higher grade materials to substitute the conventional ones which they have been using for many years.

According to our old common sense, titanium appears to be too expensive and too luxurious for architecture application. However, no higher grade metallic material other than titanium, which surpasses the conventional materials, could be found. So naturally architects have begun to show great interest in titanium.

However, no manufacturer or distributor had tried to approach architects recommending titanium as a building material. It was not easy for an architect who wanted to study about titanium, to find out who they should contact, and even if someone had been found, he could not be a good person to consult because generally speaking, most of the people engaged in the titanium business did not have sufficient knowledge about architecture.

Such being the situation, the architect who was interested in titanium was inconvenienced without knowing who he should consult and without the necessary data or information around him. Namely, the opportunity to inter-change the seeds of titanium and the potential needs of architects was non-existent. Thanks to the TEPCO Museum and Mr. Koichi Takahashi, the important and hidden channel was connected and a new titanium market for architecture application was born.

2. Shipment and uses of titanium for architecture application

As shown in Table 1, shipments of titanium for architectural application from 1973 through 1989 total close to 350 metric tons, about 90% of which was delivered in the last three years from 1987 to 1989. You will find not only an increase in the volume of titanium used but also an increase in the number of projects as well. Many people, such as progressive architects and rich properties owners, general contractors, and sub-contractors as well as distributors engaged in the architecture business are now showing more interest in titanium and consequently, enquiries are increasing. Judging from these facts and the current movement, it is presumed that a new market for titanium is beginning to grow in Japan although the current demand of about 100 metric tons per year is still small.

Fig. 1 shows the breakdown of the total shipments of titanium for architecture application from 1973 through 1989. About 67% is for roofing and about 20% is for curtain walls, both of which cover about 87% and the balance of about 13% is for miscellaneous uses such as monuments, towers, boards, gutters and sashes. Above all, most of the cases are for exterior components.

Fig. 2 shows shipments of different roofing materials in Japan in 1989. Total shipment is about 238 million square meters. The major share is covered by clay tiles (about 48%) and slate tiles (about 22%) and metal covers only 30%. Fig. 3 shows shipments of different metallic roofing materials which cover only about 30% of the total roofing materials. Coated steels cover a big majority of 89% and the balance of only 11% is shared by copper (7%), stainless steel (4%) and aluminum. Titanium is now trying to enter into this small area.

3. Characteristics of different roofing materials and their historical transitions

Thatchet	heat/noise insulation is good but inferior in fire proof
Tile	water/fire proofing is good but inferior in heavy weight and shock resistance
Metal	light weight, water proof, workability and formability are good and incombustible, but inferior in heat/noise insulation

Copper	since 1640
Coated steel	since 1955
Aluminium	since 1965
Stainless steel	since 1974
Titanium	since 1984 (TEPCO Museum)

4. Properties required for roofing materials and characteristics of titanium in comparison with other materials

Table 2 shows the properties required for roofing materials and the relative merits of different materials. Sales points of titanium are as follows:

4-1. Superiority over other materials in the area of corrosion resistance

4-2. Easy to transport and easy to lift up to high places because of its lightness

4-3. Thinner sheets could be used because of its durability

4-4. Considerably less deformation and less stress concentration at the junction because of its low coefficient of thermal expansion

4-5. Availability of many beautiful and assorted coloration by anodyzing

4-6. Economical on an overall cost basis if maintenance cost is considered

4-7. Good affinity, good compatibility and good harmony with natural environment because of its soft, warm, delicate, noble and chic surface appearance

4-8. Possibility of being maintenance-free

5. Important Marketing Target

5-1. Project or object

--large scale high grade luxurious memorial public building such as:

- religious building
- acquarium
- museum
- gymnasium
- prefectural government building
- city hall
- club house of golf course

5-2. Area

- water front (salt spray atmosphere)
- hot and highly humid area
- hot springs resort (hydrogen sulfide atmosphere)
- city center
- industrial area (air polluted atmosphere)

5-3. Customers

- big project planning department of governmental or public organization
- rich property owners
- young and new progressive architects
- general contractors and sub-contractors
- building component fabricators
- distributors

5-4. Timing and key point

- to get titanium specified in building components and additional budget allocated for titanium at the time of concept designing or basic designing

6. Some current issues regarding marketing of "titanium for architecture application --- penetration of right image of titanium ---

Until very recently, use of titanium in the building industry was virtually unknown. The metal's traditional image as an expensive and hard-to-work with material is a major obstacle to its acceptance as a reasonable alternate to other metals.

6-1. Cost competitiveness of titanium

With respect to its price, titanium materials do cost approximately ten times more than copper, aluminum and stainless steel if the unit cost per weight is compared. But a well researched design can reduce this price differential to less than two times that of these other metals when titanium is made into fabricated or finished components. For example. by making the best use of titanium's unique qualities, such as its lightness and high strength. you can reduce the difference in material costs by more than half if a thinner wall is specified. thereby making titanium a top-rated and yet highly competitive material.

Although the initial cost of the finished component is still expensive, it does not affect the total cost of the completed building in which the cost differential becomes almost negligible.
In assessing the overall costs, titanium's long-term low maintenance requirements and its proven durability present tremendous advantages even at its current price level.

In recent years, in order to meet increasing consumer demands for high quality luxurious materials and products, many architects have been actively seeking new metals and alloys to replace the conventional ones such as copper, aluminum and stainless steel. It has, therefore, become imperative that the image of titanium as an expensive and impractical metal be dispelled as soon as possible. This mistaken impression needs to be replaced with the correct view of titanium as a practical, economical, yet a high-quality building material, second to aluminum and stainless steel. Simultaneously, people involved in all aspects of the construction industry need to be familiarized with this accurate view of titanium, a view more in line with its true practical value.

6-2. Workability in metalworking and fabrication

Titanium is not as easy to work with as copper and aluminum. However, compared with stainless steel, it presents no significant problems with cutting, shearing, drawing, bending, forming, machining and other general working provided the characteristics of titanium, such as spring back, gauling and galvanic corrosion are taken into account.

(Welding)

As to welding operation, TIG and MIG welding must be conducted in Argon gas atmosphere, but seam and spot welding popularly used in roofing of stainless steel can be adopted as it is. In addition, titanium presents no risk in its corrosion resistance or the deterioration of the mechanical properties of the weld as is the case with stainless steel. Furthermore, titanium's weldability and low thermal expansion coefficient provide a distinct advantage in building application.

(Enlightenment of workers)

What is most necessary at the present time is a concerted effort to make up-to-date information about titanium known and available to general contractors, sub-contractors, and component fabricators. Namely, that it is not an especially difficult material to handle. That it is a relatively easy material to deal with once its properties have been properly understood and taken into account. To this end, the preparation of guide books and manuals outlining in a simple manner the precautions that must be kept in mind when handling titanium should be done immediately.

6-3. Development of application technique

One matter that awaits further attention is the development of more refined techniques for using titanium as a building material. Up to now a variety of techniques have been developed for adopting titanium for industrial use, but methods for using titanium in building material application have begun to be developed only recently.

Although it is necessary that these techniques, such as simple jointing other than welding, be further developed, it is equally vital that titanium's attractive appearance and decorative features be enhanced.
In addition to durability and economy, these features will naturally be required if titanium is to evolve into a truly high-quality building material at the beginning of the next century.

Titanium lags for behind stainless steel on this point. It is particularly important that techniques such as those required for surface finishing be further developed soon so that titanium may achieve a reputation as a high-quality metal, capable of meeting needs which conventional materials cannot.

Technical problems of titanium as a building material which should be investigated are as follow:

- technology to improve surface properties (uneven brightness)
- technology to improve flatness (in raw material as well as in finished roofs and panels for waveless surface)
- technology to improve the difference of color appearance between the lots of coil sheets.

- technology to develop uniform coloration in complicated profile components (including simple profile products)
- surface treating technology that provides fast snow releasing capability
- surface treating technology that does not show stains
- simple and easy cleaning technology if stained
- technology to form massive surface appearance in thin sheets
- technology to develop black, white, brown, amber and red colors

7. Future challenges

As I mentioned earlier, a remarkable progress in the practical application of titanium has been made in recent years. This progress can be directly attributed to on-going efforts of the members of the Japan Titanium Society. Further development of practical applications of titanium building materials will be the result of perseverance and cooperation of the member companies. This will allow us to take maximum advantage of the Japanese government's recent new policy to expand the domestic demand by spending 430 trillion yen for public investment in ten years. This big investment will provide many opportunities for new titanium applications in various development projects, especially in waterfront areas. It is also a very important matter in Japan to pay due attention to create a beautiful environment in promoting development projects in big cities, small towns and in rural areas as well, where titanium can play an important role as a new building material which can meet the needs of a new age.

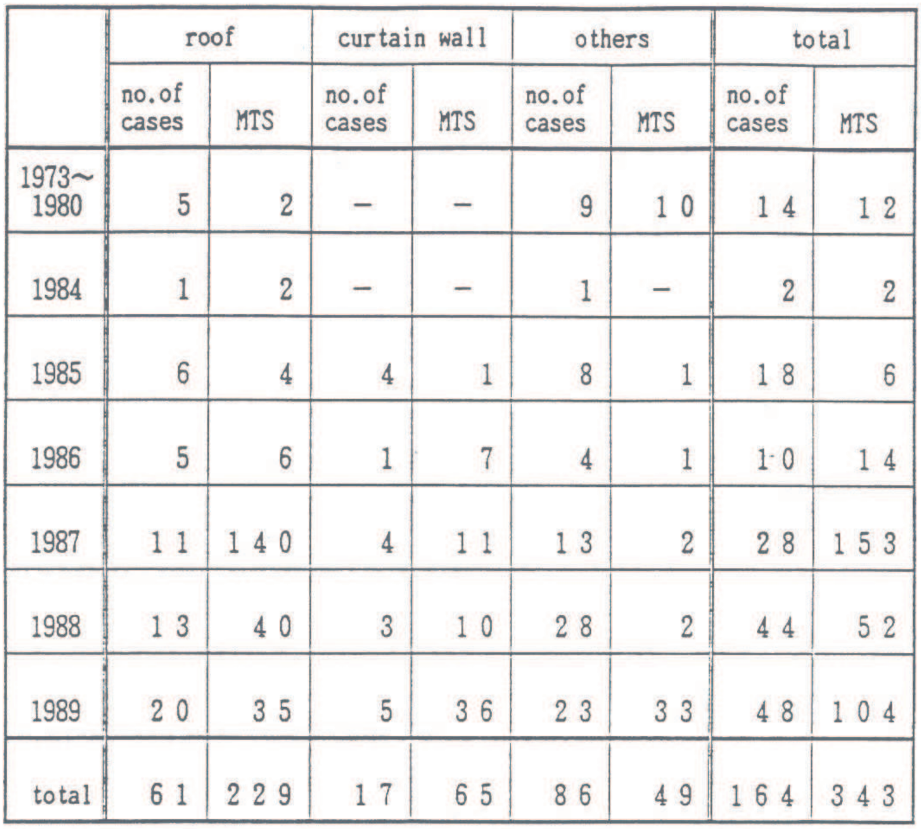
In order to create a demand for titanium in large-scale megaoprojects, a campaign for the promotion of titanium must be inaugurated to promote the idea of titanium as a versatile and practical material for architectural design. The concept that titanium can be a new paradigm to the construction industry needs to be reinforced with reference to its obvious advantages. Themes such as, “Titanium for the Waterfront”, or “Titanium: The Durable, High-quality Metal of the 21st Century” need to be publicized.

This should now be the focus of the titanium industry's efforts. We need to work diligently if this metal's potential as a building and construction material is to be realized. On the basis of our success so for we have good reason to believe that titanium has a bright future. However, continuous effort is needed to ensure that titanium becomes, in the coming century the metal most frequently used in building materials next to aluminum and stainless steel.

We are convinced that it is not unrealistic that at least 10% or several thousand metric tons of building materials normally made with copper, aluminum and stainless steel can be replaced with titanium in the beginning of the 21st century.

The idea of using titanium as a building material has not yet been adopted in the United States and in Europe, although this situation is expected to change in the future. The market situation outside Japan may be very different from that of Japan but I hope that you learned something from us which you can apply to your marketing activity, and hopefully, the application of titanium as a building material will grow on a world-wide basis.
Your kind comments or suggestions will be deeply appreciated.

Thank you for your kind attention.



	roof		curtain wall		others		total	
	no.of cases	MTS	no.of cases	MTS	no.of cases	MTS	no.of cases	MTS
1973～1980	5	2	–	–	9	10	14	12
1984	1	2	–	–	1	–	2	2
1985	6	4	4	1	8	1	18	6
1986	5	6	1	7	4	1	10	14
1987	11	140	4	11	13	2	28	153
1988	13	40	3	10	28	2	44	52
1989	20	35	5	36	23	33	48	104
total	61	229	17	65	86	49	164	343

Table 1 - Shipments of titanium for architecture application in Japan (1973 to 1989)

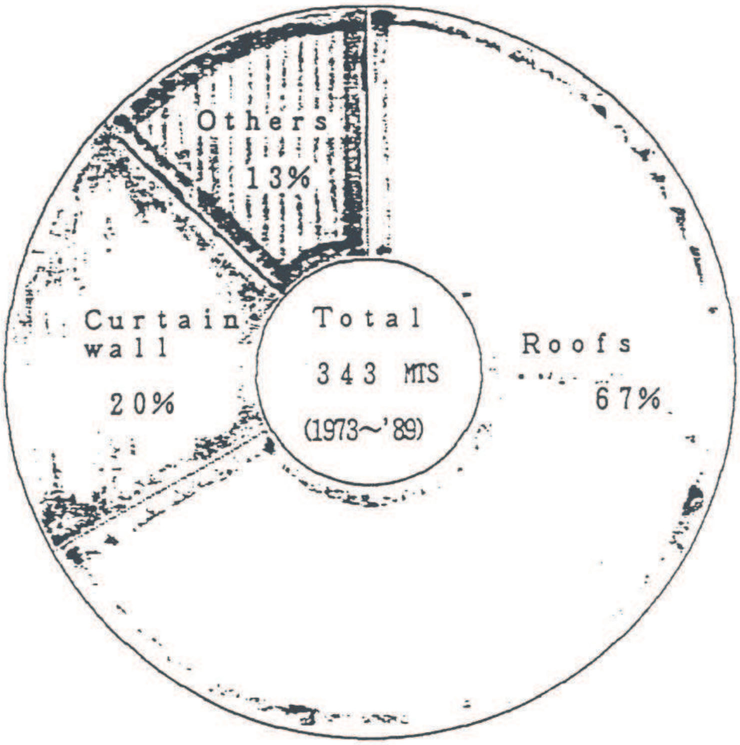


Fig. 1 – Shipments of titanium for architecture application in Japan

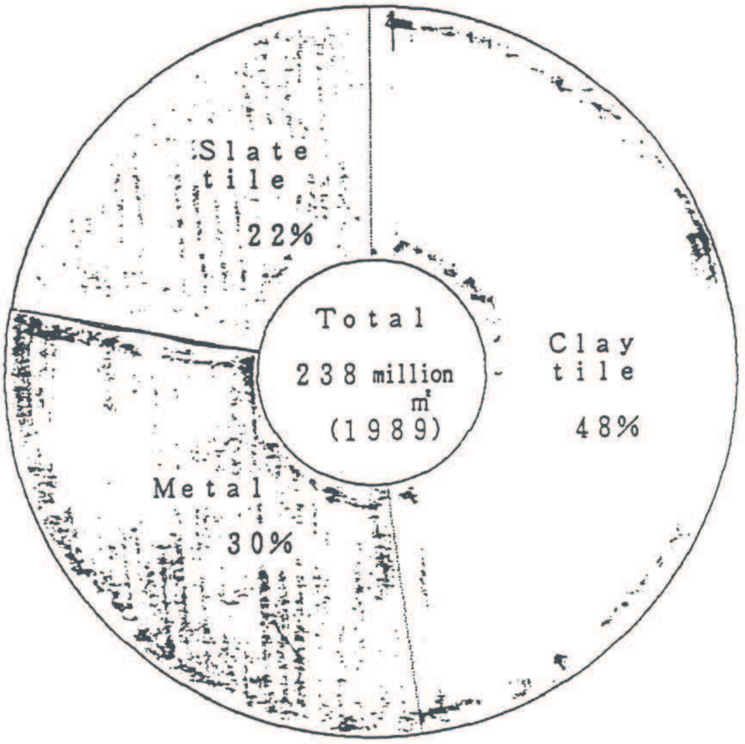


Fig. 2 - Shipments of differential roofing materials in Japan

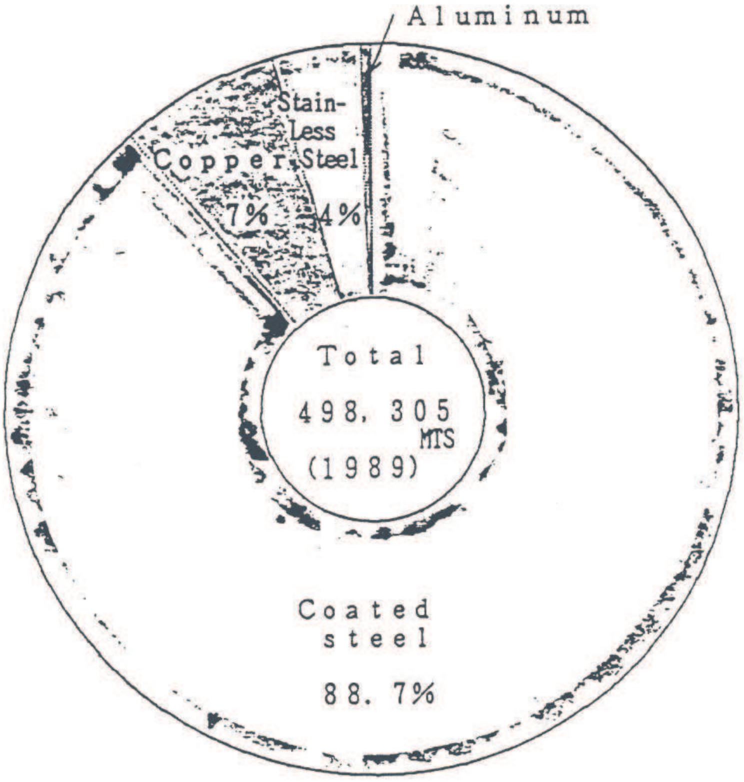


Fig. 3 - Breakdown of shipments of different roofing metals in Japan

Material Properties	Coated stainless steel	Precoated galvanized steel	Japanese roof tile	Colored asbestos slate	Copper	Titanium
Water-proof/water tightness	○	○	○	△	○	◎
Thunder proof	◎	◎	△	△	◎	◎
Wind proof	○	○	○	△	○	○
Earthquake proof	◎	○	△	△	○	◎
Heat insulation/antisweating	△	×	◎	○	×	△
Sound insulation	×	×	◎	○	×	×
Fire protection	◎	○	◎	○	○	◎
Dead weight	◎	◎	×	×	◎	◎
Strength	◎	○	△	△	○	◎
Corrosion resistance/ weatherability	◎	△	◎	◎	◎	◎
Durability	◎	△	◎	◎	◎	◎
Machinability	○	◎	△	△	◎	○
Workability	○	◎	△	△	◎	○
Design	◎	◎	○	△	◎	◎
Economy	○	◎	△	◎	○	○

◎ Excellent ○ Good △ Fair × Poor

Table 2 - Properties required for roofs and comparison according to materials

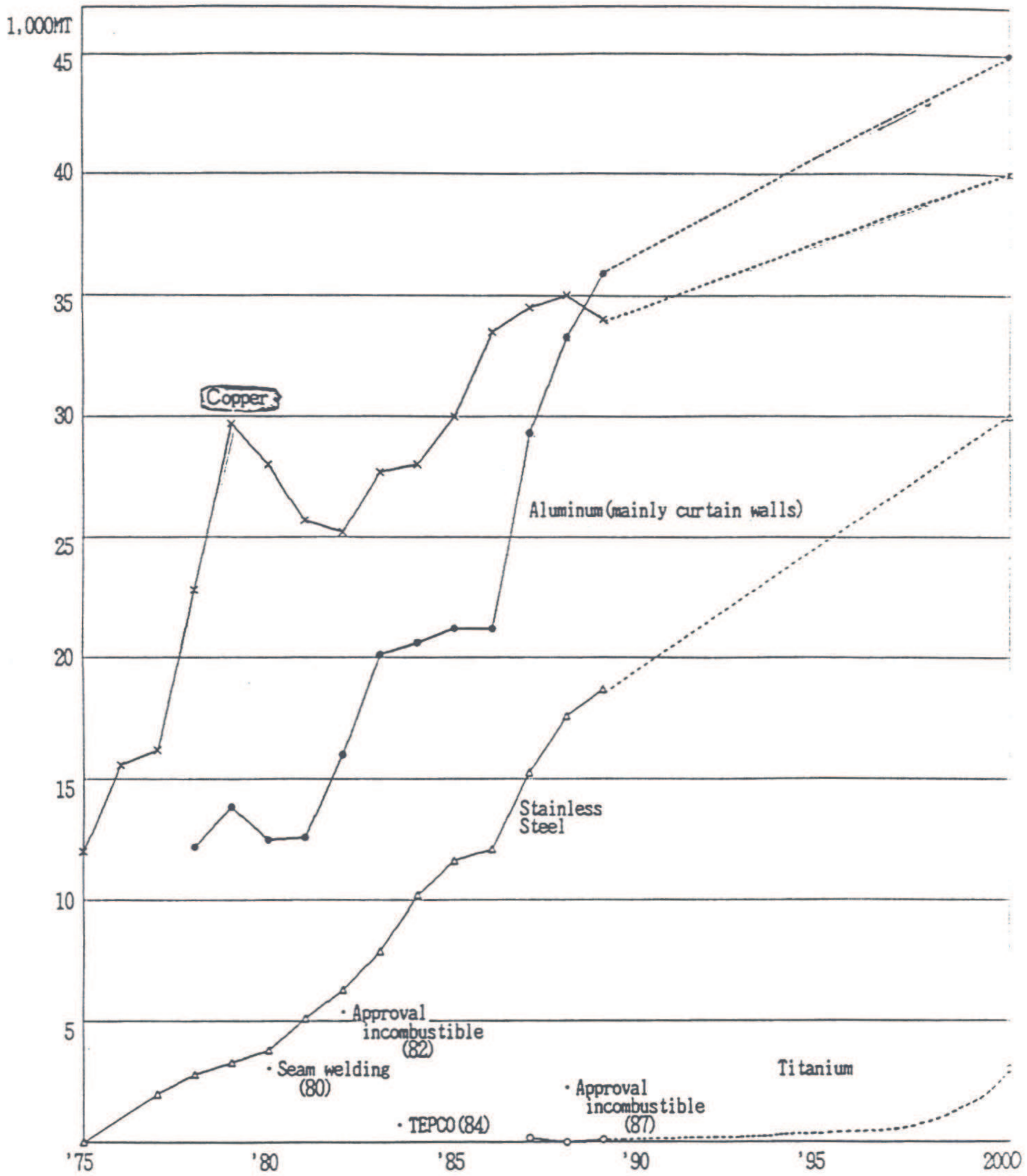


Fig. 4 - Demand of high grade roofing materials in Japan

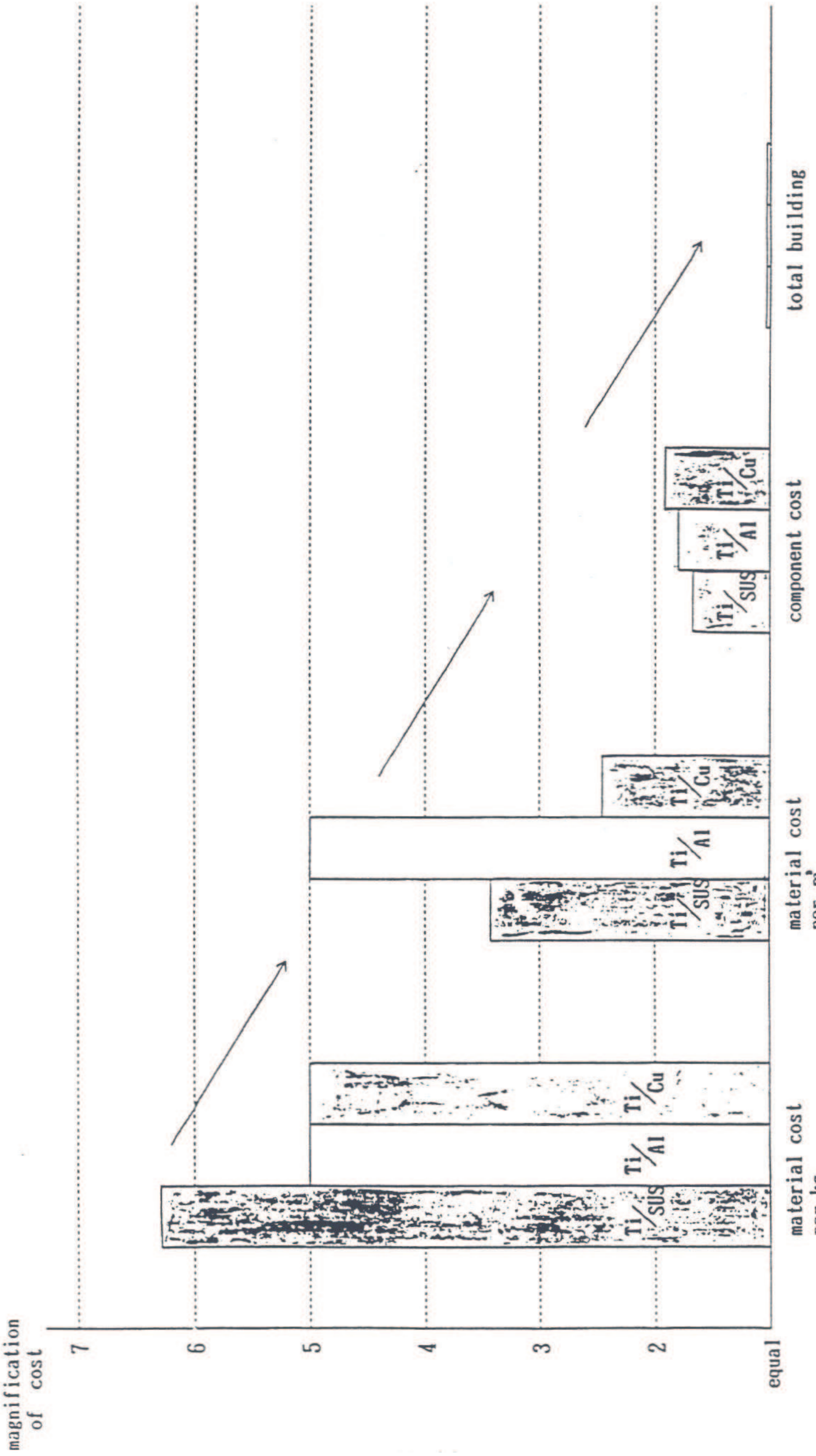


Fig. 5 - Cost differential, Ti to SUS, Ti to Al, Ti to Cu, in material cost per kg, material cost per m^3, Component cost and total building cost

COLORAZIONE ANODICA DEL TITANIO E APPLICAZIONI

Luca Colombo
Titania s.r.l.

Signore e Signori buongiorno!

Ringraziamo la G.T.T. S.p.A. per l'invito rivoltoci, con l'augurio che gli obiettivi di questo meeting siano felicemente raggiunti.

L'esistenza della Titania s.r.l. dimostra che la colorazione del titanio ha superato la fase sperimentale raggiungendo quella semi-industriale.
Infatti la tecnologia da noi sviluppata e messa a punto consente produzioni su scala industriale e l'automazione del processo.

Chi siamo

La Titania s.r.l. è nata agli inizi del 1988 con l'obiettivo di studiare e mettere a punto una tecnologia di colorazione semi-industriale, che ha trovato immediata applicazione nel campo della bigiotteria e gioielleria.

Alcune caratteristiche del titanio, come la leggerezza e la non reattività con elementi organici, ne assicurano l'impiego anche in settori di più largo consumo.

L'ottimizzazione del nostro processo di colorazione ha permesso quindi che l'attività dell'azienda si sviluppasse anche in altri settori, come illustreremo successivamente.

Il nostro prodotto

L'elemento caratterizzante che incentiva l'uso del titanio anche in campi non strettamente industriali o medici, è la sua proprietà di assumere diversi colori, con risultati cromatici interessanti.

La colorazione è ottenuta mediante un procedimento elettrochimico attraverso il quale il metallo cambia la propria struttura molecolare in superficie, e quindi il colore.

In breve il processo si può così descrivere:

- un trattamento di sgrassaggio e lavaggio della superficie;
- un secondo trattamento di attacco acido con tempi e temperature controllate;

- Attacco elettrochimico, con l'ottenimento delle diverse sfumature di colore in funzione della quantità di corrente erogata.

Un' ulteriore importante caratteristica del nostro processo è che il pezzo finito con necessita di alcun trattamento superficiale anti-impronta o per fissare il colore.

I colori ottenuti con questo metodo spaziano dal giallo all'azzurro, al rosa, insomma: i colori dell'iride con mille sfumature di luce.

Nella colorazione del titanio sono note le difficoltà per ottenere il nero opaco; grazie ad un'ulteriore messa a punto della nostra tecnologia, ancora allo stato sperimentale e che in questa fase non vogliamo divulgare, si può arrivare ad ottenere sfumature di grigio, fino al colore nero.

<u>Oggi</u>

L'oro e l'argento (e altri metalli preziosi) hanno sempre fatto la parte del leone nel mondo dell'ornamento, ma anche questi nobili metalli hanno avuto un calo e così è subentrato un grande interesse, anche e soprattutto da parte degli stilisti, verso l'utilizzo di materiali meno costosi, facili da modificare e da reperire: ecco che alla bigiotteria e gioielleria tradizionali si sono affiancate nuove linee e tendenze.

Abbiamo quindi creato degli oggetti utilizzando un materiale praticamente nuovo nella moda, incredibilmente moderno, con costi e reperibilità accettabili.

La lavorazione del titanio, pur richiedendo accuratezza ed accorgimenti particolari, come ad esempio nella saldatura, è paragonabile a quella dei materiali come gli inossidabili e gli ottoni.

In ogni caso si riescono ad ottenere sia per deformazione plastica, sia per tranciatura, perforazione e calandratura, le forme più varie ed originali.

Non si può dire che il titanio sia un metallo facile da lavorare, sembra qualche volta animato ed ha la capacità di creare grosse difficoltà a chi lo maneggia, se non lo si utilizza con amore.

Per quanto ci riguarda riusciamo ad ottenere degli oggetti particolarmente originali, i bijoux in titanio infatti sono un mixage tra preziosismi in oro e oggetti-moda.

Inoltre, da alcuni anni, le patologie indotte da elementi e/o metalli allergizzanti hanno avuto un notevole incremento con conseguenze notevoli su usi e comportamenti della popolazione.

Nel settore della bigiotteria ciò ha comportato una selezione da parte del consumatore verso prodotti più sicuri. E le caratteristiche anallergiche del titanio lo rendono particolarmente indicato in questo contesto anzi, sono un plus esclusivo che si somma ad altri, come i colori dell' arcobaleno che questi bijioux sfoggiano rendendo ogni oggetto unico e irripetibile.

Un altro campo in cui l'impiego del titanio è ormai consolidato è quello dell'occhialeria: in Giappone la montatura in titanio (grigio o nero) è da anni prodotta regolarmente; la tendenza europea, ed in particolare nordamericana, è invece quella di sviluppare montature in titanio colorato.

A questo proposito l'utilizzo del titanio in Giappone (sembra che la quota di mercato superi il 30%) è dovuta ad alcune delle caratteristiche tipiche del metallo, come:

- leggerezza;
- elasticità;
- resistenza alla corrosione.

<u>Domani</u>

Altri settori d'impiego sono:

1) Oggettistica.
   Alcuni oggetti (cornici da tavolo, fermacravatte, fermasoldi) sono già di nostra produzione.
2) Orologeria.
   Sono già in commercio da diversi anni orologi in titanio grigio prodotti da prestigiose aziende, per una di queste la Titania ha recentemente campionato modelli con casse colorate.
3) Accessori d'abbigliamento.
   In questo settore i contatti intercorsi con una azienda italiana leader nel proprio settore hanno confermato la richiesta di bottoni leggeri e di pregio da impiegare in particolare su maglieria in chachemere in alternativa ai materiali tradizionali (metalli e plastiche). Il titanio per la sua proprietà (leggerezza e colore) è quindi un valido sostituto.
4) Illuminazione e complementi d'arredamento.

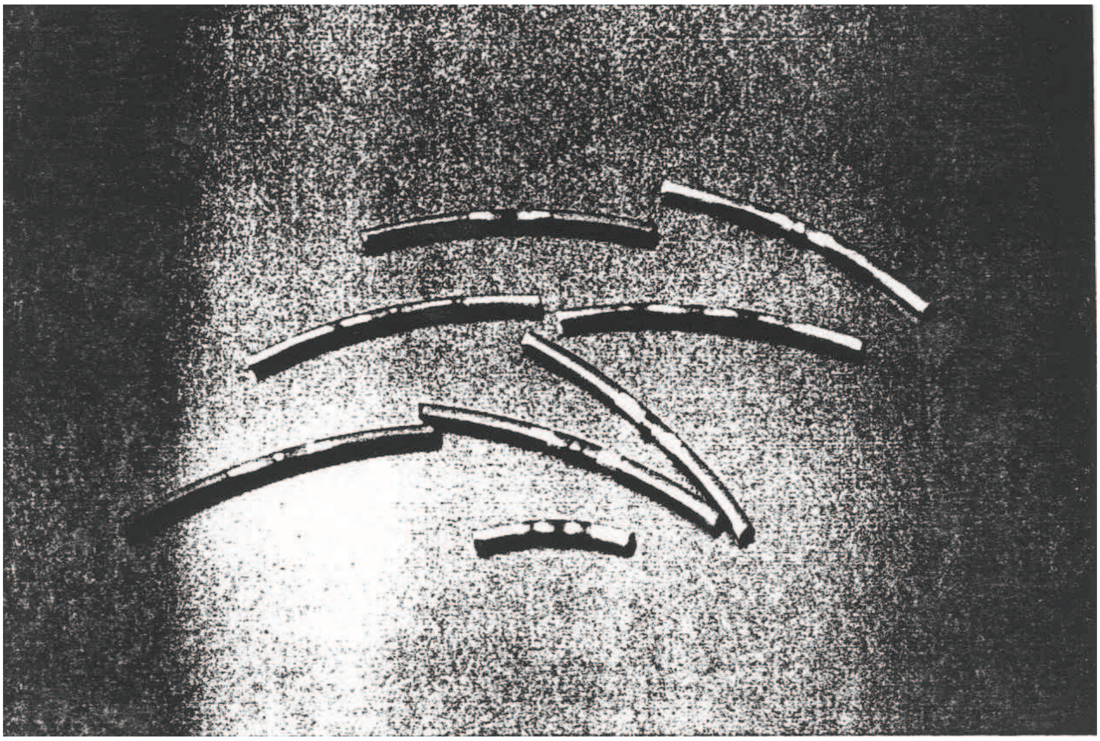
E' un settore che per le sue continue esigenze di design e di ricerca di nuovi materiali offre delle buone potenzialità di inserimento e sviluppo.

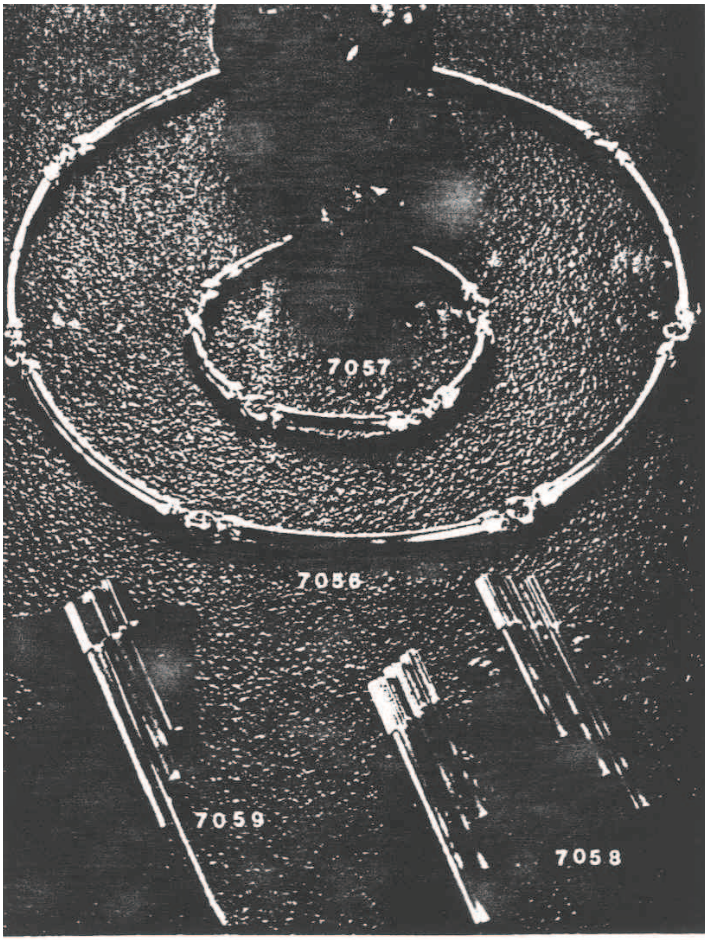
5) Strumentazione varia.
La possibilità di ottenere un "color nero" con assorbimento della luce quasi al 100%, ed il comportamento costante in un intervallo di temperatura da -70/70°C a *50/50°C fa del titanio il metallo ideale per strumentazione, macchinari fotografici, rilevatori di misure da adottare in condizioni così severe.

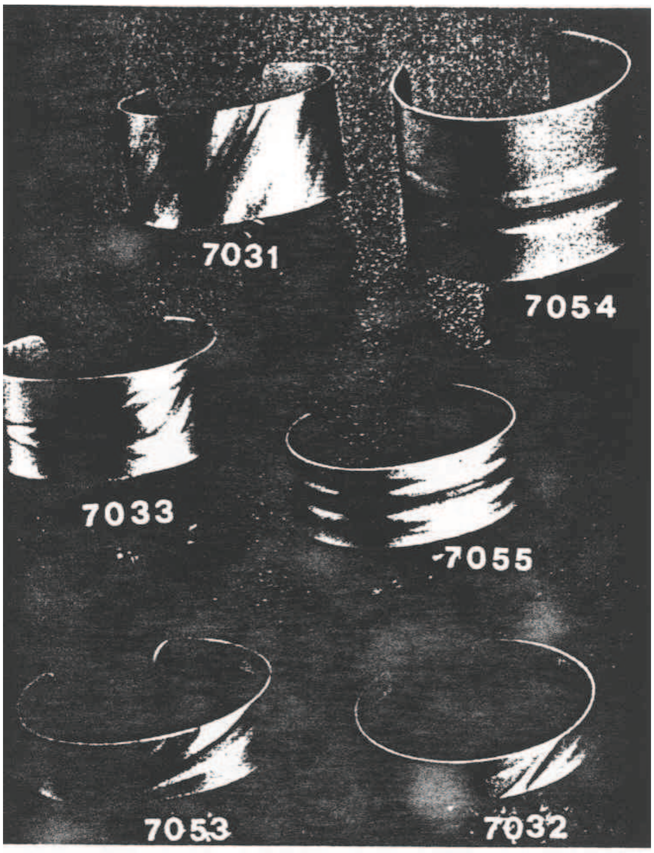
Signore e Signori, non vogliamo ulteriormente tediarVi con altri elenchi di possibili applicazioni del titanio colorato, ma è sufficiente avere un po' di fantasia e di reale interesse verso questo metallo, che non deve essere considerato esclusivo patrimonio della tecnologia più raffinata, per sviluppare e realizzare nuovi impieghi.

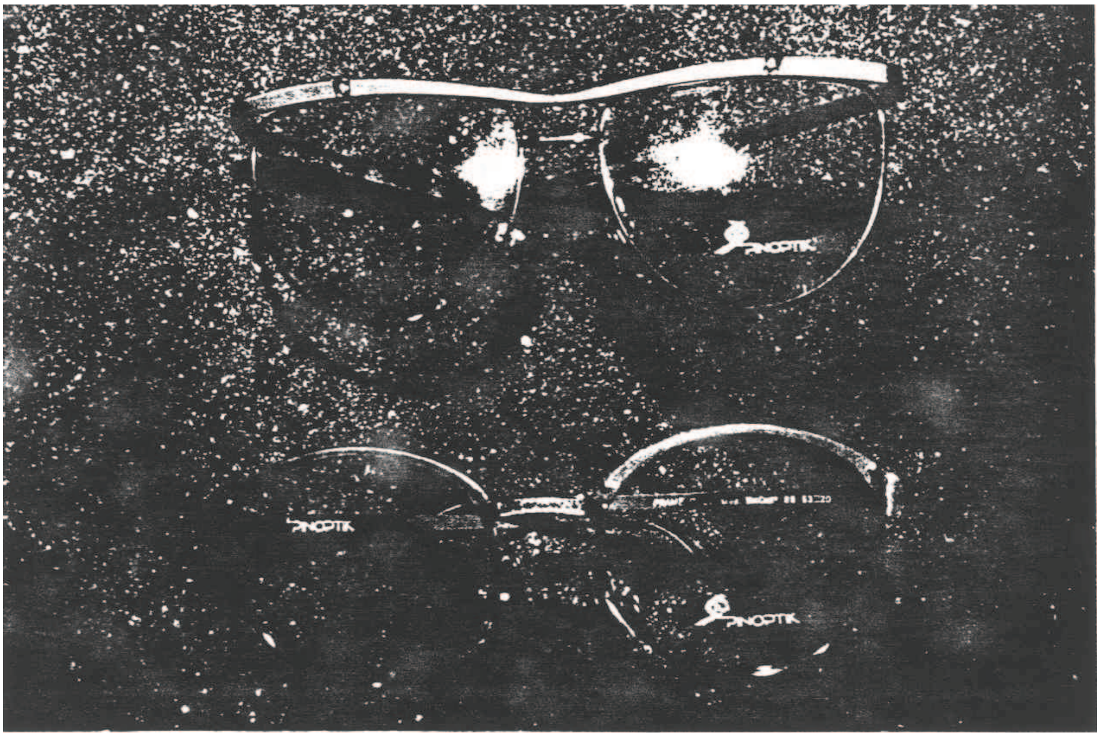
Grazie per l'attenzione.

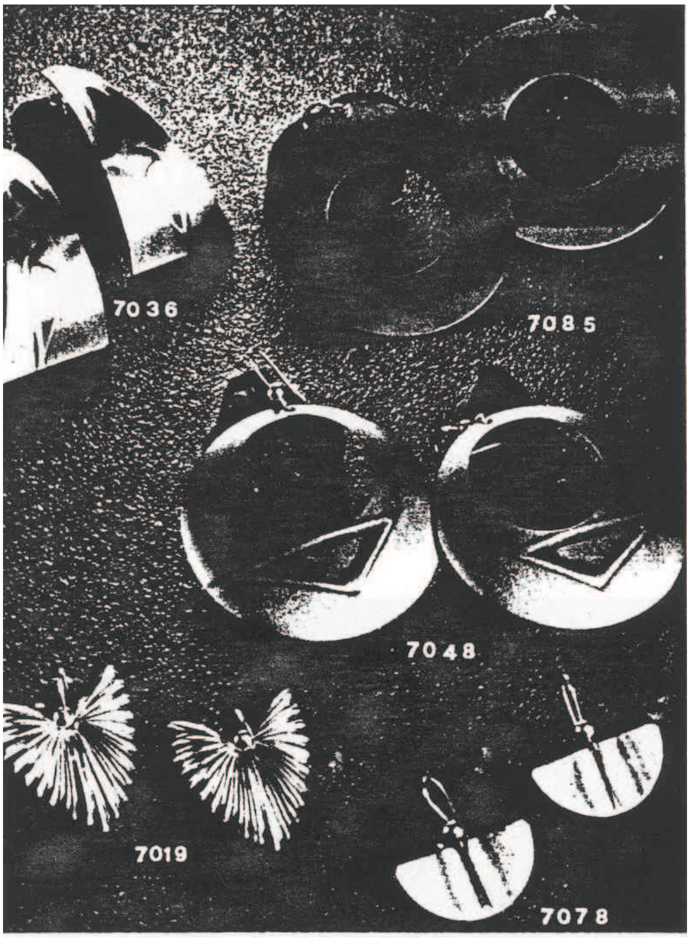
Nelle pagine seguenti alcuni esempi di colorazione anodica del titanio.




7057
7056
7059
7058


7031
7054
7033
7055
7053
7032


PINOPTIK
PINOPTIK
PINOPTIK


7036
7085
7048
7019
7078

DIFFUSION WELDING OF TITANIUM ALLOYS OF DIFFERENT TYPES

E.S. Karakozov, Doctor of Technology
M.B. Nickgolov, ph.D. of Technology

I. Introduction to the Problem

The application scope of titanium welded constructions in various fields of techniques is steadily widening [1]. A high level and a variety of requirements of such constructions make it efficient and economically more effective to apply chemically heterogeneous alloys in the above constructions. The problem is to obtain permanent welded joints from titanium alloys of different types. Presently there are more than 30 types of titanium alloys in the USSR. Traditionally different types of fusion welding were used because of a good scientific base and adequate application experience [2]. The diffusion welding application is more perspective in cases of welding of long and sandwich constructions of different types [3].

The problems of diffusion welding of titanium alloys in similar combinations (SC) are described in many publications [4] and others. Publications on the problems of diffusion welding of different combinations (DC) are extremely limited [5]. The available information on this problem is referred to the research of weldability of some different combinations of titanium alloys and does not resolve the complex problem. At the same time titanium alloys differ not only by a system but also by a degree of alloying.

Therefore different DC of titanium alloys will differ in character and degree of chemical heterogenuity in a contact area. That will result in substantial differences in their weldability. The lack of information on these problems does not permit to predict the weldability of the variety of DC of titanium alloys. As a rule, the attempts of applying usual technological schemes do not lead to positive results, that is illustrated by the following experiment.

Cylindrical specimens (in diameter 16x30 mm) with polished (R_Z = 0,05) contact surfaces were welded in vacuum 10^{-2} mm of a mercury column at T_W = 900°C. The joint area was screened by getter, the welding pressure was applied at the room temperature and ensured the same for SC and DC deformation rate $\varepsilon = 2,0\cdot10^{-5}s^{-1}$.

The experimental data point to the fact that while time of welding t_W is increased the KCV_{SC} values are gradually rising up with obtaining $KCV_{SC} = 1,0$ at ε = 8,0-10,0%. At first there is some ascent and later on a descent of KCV_{DC} (t_W) curve (fig. 1). However it was impossible to obtain a combination adequate in strength to the base metal even at ε = 16,0%. The metallographic analysis showed that the SC joint area did not practically differ from the base metal (fig. 2a) and that the DCs had a strongly developed porosity (fig. 2b).

II. Theoretical Analysis of Weldability

In case of diffusion welding the possibility of obtaining qualitative joints of chemically heterogeneous metals firstly depends on characteristics of the welding final phase - the volumetric interaction phase [3,4].

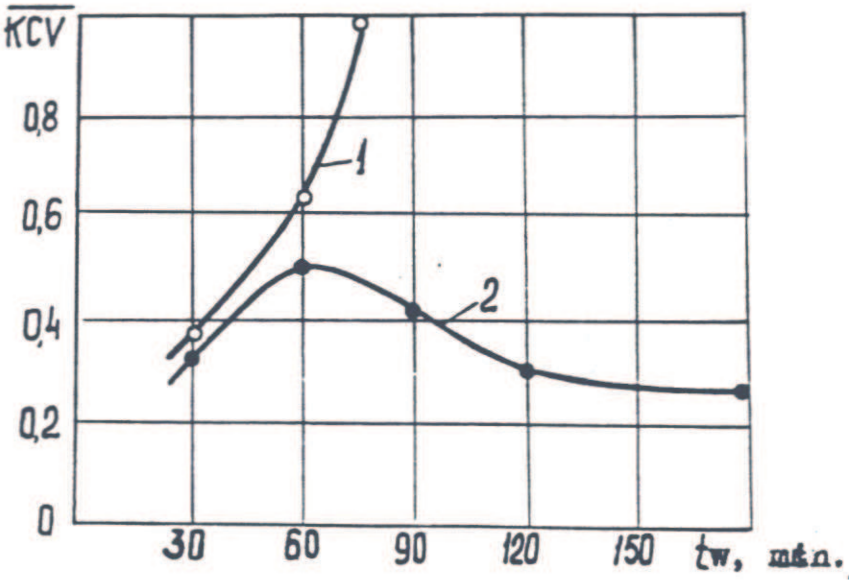


Fig. 1

Dependence KCV(t_W) for combinations OT4-1 + OT4-1 (1) and OT4-1 + BT3-1 (2)

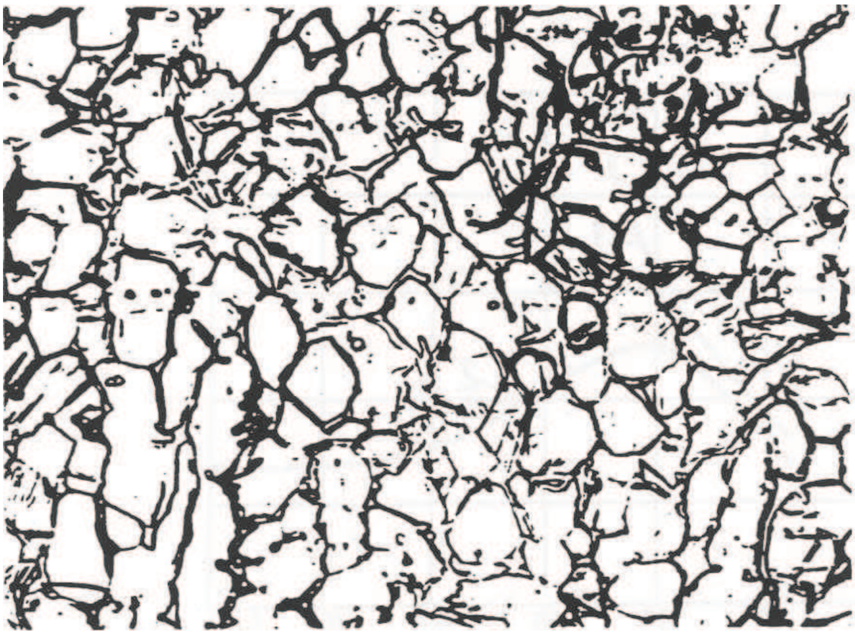


Fig. 2a

Structure of welded joint area of SC (a) and DC (b) after welding at T_W = 900 °C, t_W = 75 min.

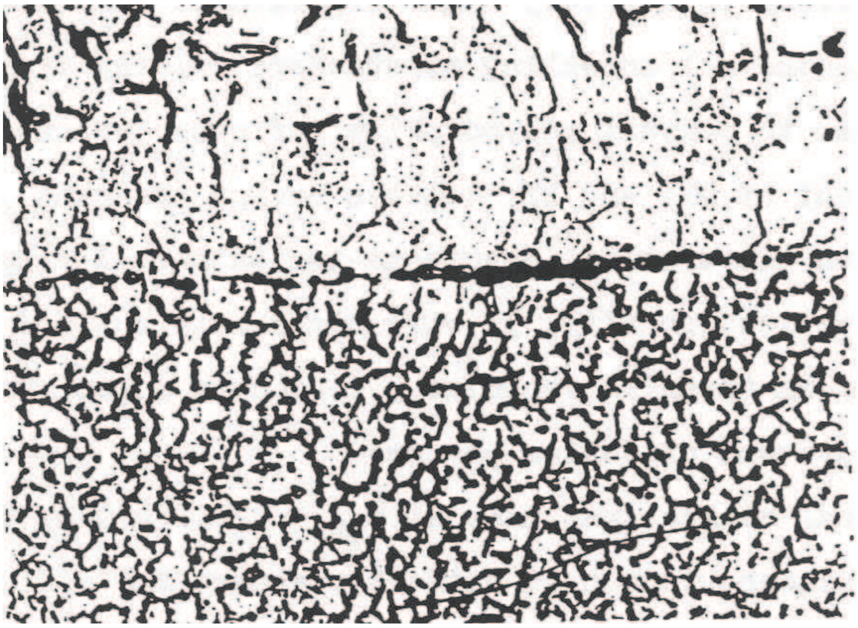


Fig. 2b

Structure of welded joint area of SC (a) and DC (b) after welding at T_W = 900 °C, t_W = 75 min.

Therefore in this publication the evaluation of DC titanium alloy weldability was made due to special features of realization of just this phase. A well-known technological scheme [6] more fully gains the above aim. Due to the scheme a physical contact was previously formed at not very high temperature. It was followed by further isothermal annealing at standard welding temperature rate. In order to prevent polymorphism influence the research was carried out at OT4 and BT14 alloys having the same $\alpha+\beta$ transformation temperature. Specimens-immitators of rought surface 1 microprojectors (fig. 3) were previously scalded by hermetic welds 2 in titanium capsules 3 in a pure argon atmosphere in order to prevent oxidation process.

A physical contact was made at T_{ph} = 625...650°C. afterwards the specimens were held without pressure for different time t_{an} at different annealing temperatures T_{an} in $\alpha+\beta$ - area. The welding operation was conducted at radiant heating installation [4]. The quality of welded joints was determined by comparative impact toughness

$$KCV = \frac{KCV_W}{KCV}$$

where: KCV - impact toughness of a tougher welded joint,

KCV_W - welded joint impact toughness.

At fig. 4 dependencies KCV (t_{an}) show that there is a monotonous increase of KCV values at all T_{an}. There is quite a different dependence for DC: while t_{an} is increased, an interval of intensive KCV increase is transforming into perceptible decrease. An interval of KCV increase is more intensive for DC than SC, that is $KCV_{DC} > KCV_{SC}$, one can see an opposite regularity during a decrease interval. precisely $KCV_{SC} > KCV_{DC}$. Consequently at first one can observe an effect of DC improved weldability in comparison with SC, later on it is changed by a loss of strength effect.

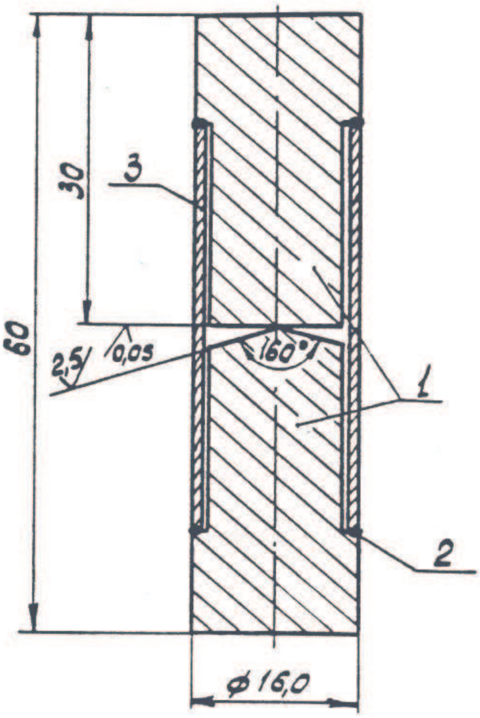


Fig. 3

Welded specimens

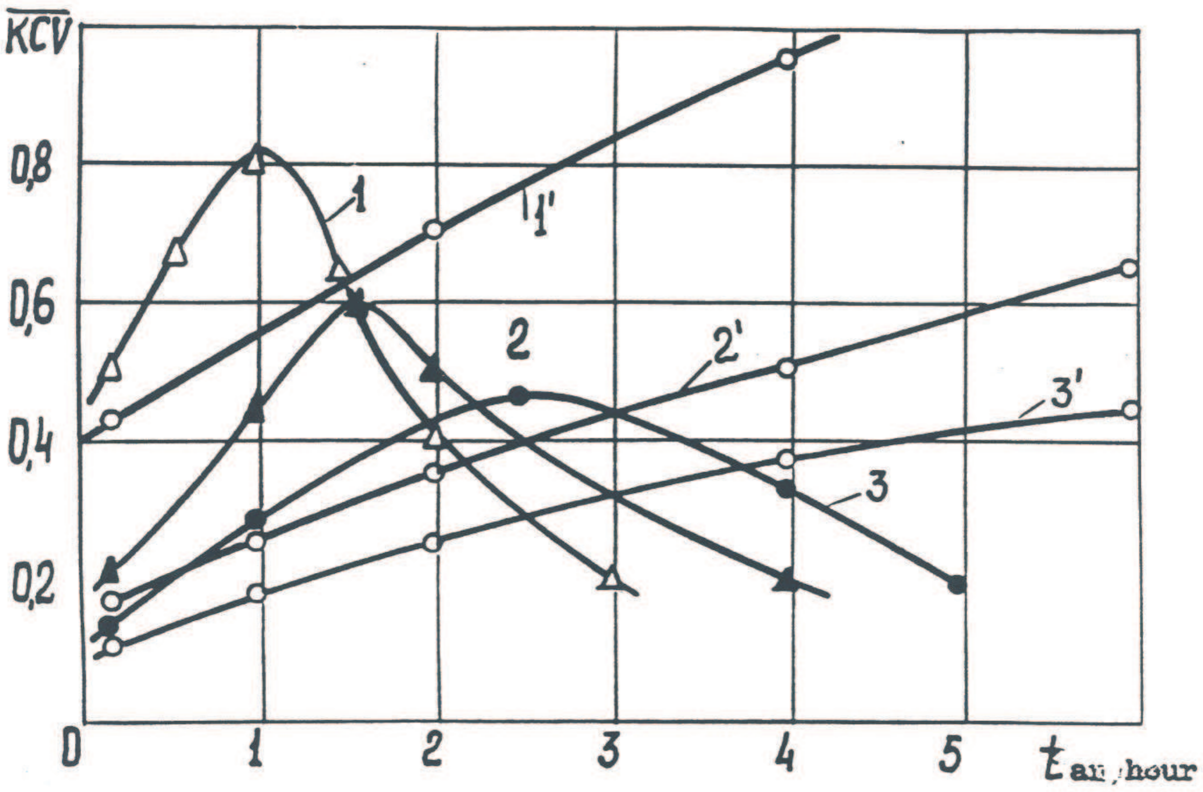


Fig. 4

Dependence KCV (t_{an}) for combinations OT4+OT4 (1', 2', 3') and OT4+BT4 (1, 2, 3) at T_{an} °C: 3,3' - 850, 2,2' - 900, 1,1' - 940.

Thermoactivation analysis of KCV (t_{an}) was carried out by plotting functions on lg coordinates KCV_{SC} - 1/T (where KCV_{SC} is a comparative impact toughness rate). The analysis has determined an effective energy of $E_{ef.}$ activation process controlling the impact toughness growth of SC welded joints (fig. 5). The determine value $E_{ef.}$ = 102 kJ/mol makes ~0.4 from known [7] value of volumetric self-diffusion activation energy (E_s = 251 kJ/mol) in α-titanium, that corresponds to energy of vacancies migration activation [8].

A thermoactivation analysis or a period of an intensive increase of KCV_{DC} (t_{an}) dependencies determined that $E_{ef.}$ = 96 kJ/mol values were similar to the corresponding $E_{ef.}$ values for SC. Consequently despite the differences in kinetic curves character an impact toughness growth is controlled in both cases by the same process connected with vacancies migration in the are near the contact. $E_{ef.}$ values prove it. However, in studied cases the vacancies flows dynamics is not identical, this process is connected with titanium and i ts alloys diffusion anomality. One aspect of the anomality problem is connected with the fact that the diffusion coefficients of many alloyed elements considerably exceed the coefficient of titanium volumetric self-diffusion [9]. In this case parameters of self- and heterodiffusion of titanium alloys essentially depend on a system and a degree of their alloying [9]. Therefore diffusion mobility of atoms of DC titanium alloys will greatly differ from SC titanium alloys and when putting them into contact there'll be an uncompensated vacancies flow to the direction opposite to the masstransference. Probably this difference results in intensive development of DC volumetric interaction at the initial stages of welding. Furthermore it is known that the diffusion process in metals is followed by the dislocations formation in the diffusion zone[10].

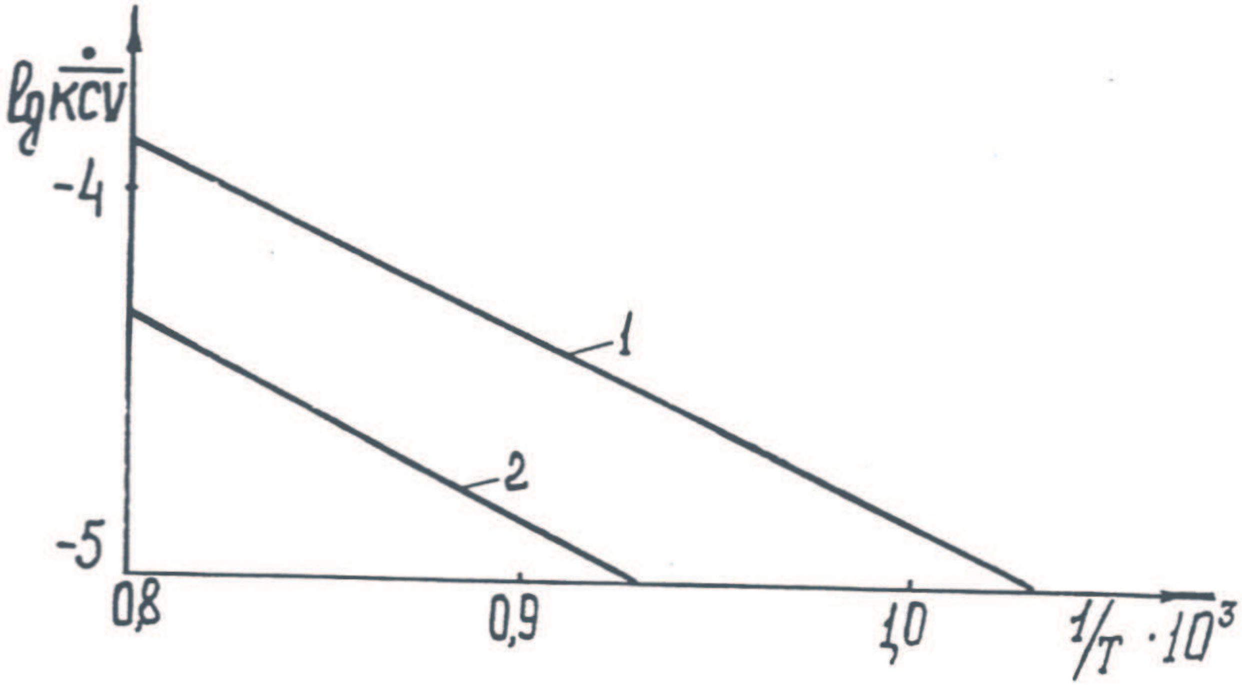


Fig. 5

Dependence KCV - 1/T for DC (1) and SC (2)

Therefore with low t_{an} when maximum gradient of concentraions is in the welded joint surface, dislocations will take place directly near the contact surfaces activizing them additionally and making adhesion more intensive. Consequently the difference chemical composition of DC of titanium alloys with low t_{an} may be considered as an activizing factor which increases the density of interaction zones on the contact surface and intensifies the development of all phases of volumetric interaction stage. Probably this factor causes more intensive KCV_{DC} increase at the initial stages of annealing (fig. 4).

The fact of deterioration of properties of heterogeneous metals welded joints under long thermal influence is usually connected with formation of brittle intermetallides [11]. However as a rule, systems of alloying of titanium elements prevent from intermetallides formation on heating more than temperature of eutectoid decay [12]. Measuring of microhardness of welded joint area of specimens (fig. 1) did not also reveal any brittle inclusions. Probably the KCV_{DC} decrease (fig. 4) was caused by further development of the vacancies flows dynamics. It is known [13] that the existence of uncompensated vacancies flow according to Frenkel effect results in the formation of pores in the diffusion zone. Therefore one can consider that during the process of isothermal holding surplus vacancies condense on micro-areas of a welded joint with an unformed physical contact and promote their growth.

Consequently experimental data (fig. 4) may be interpreted in the following way; due to the low reaction activity depending on the terms of experiment [14], the improved weldability effect is not completely realized, and the loss of strength effect becomes predominant.

To one or another degree determined features of the volumetric interaction stage are realized in different terms of welding of the most DC. In this case essential differences are made during the realization of other stages of the process including a stage of a physical contact formation. This influences both the special features of a welded joint formation on the whole and its mechanical properties. Therefore to resolve the problem of DC titanium alloys weldability it is necessary to study the heteroalloying influence on characteristics of a physical contact formation and quality of welded joints. This will help to optimize a technological scheme of welding of different DC of titanium alloys.

III. Special Features of Formation of a Physical Contact

In case of diffusion welding formation of a physical contact is a necessary condition of obtaining qualitative welded joints. As far as DC of titanium alloys are concerned formation of a physical contact was studied at alloys mentioned in table I.

Table 1

Nos.	Type of alloy	Middle Chemical Composition	Total content of alloyed elements C, %	β-stabilisators content, C_β , %	T°C $\alpha+\beta-\beta$ transformation	Middle size of grain, d mcm	KCV, J/c
1	2	3	4	5	6	7	8
1.	BT1-0	unalloyed	-	-	890	5,0	150,
2.	OT4-1	1,5Al-1,0 Mn	2,5	1,0	910	6,0...8,0	76,
3.	OT4	3,5Al-1,5 Mn	5,0	1,5	950	4,0...6,0	70,

1	2	3	4	5	6	7	8
4.	BT5	5,0 Al	5,0	-	960	4,0...6,0	45
5.	BT14	4,5Al-3,0Mo-1,0V	8,5	4,0	950	3,0...5,0	60
6.	BT3-1	6,0Al-2,5Mo-2,0Cr-0,3Si-0,5 Fe	11,3	4,5	970	3,0...5,0	50
7.	BT16	2,5Al-5,0Mo-5,0 V	12,6	10,0	870	5,0...8,0	40

Welding operation of cylindrical specimens 16x30 mm in diameter in SC and DC was conducted at radiation heating installation [4].

One of the welded surfaces was polished (R_Z = 0,05 mcm), the other was turned (R_Z = 10,0 - 500 mcm) or finished (R_Z = 1,5 mcm). The specimens were welded in vacuum 10^{-2} mc of a mercury column for different time t_W, and the butt was additionally screened by a getter. Relative area of a physical contact

$$F=\frac{F_c}{F_n}$$

(where F_c - a physical contact area; F_n - nominal area of contacting) was valued by factogramms of previously polished surface and methods of profilographing and optical metallography were used. Profilograph-profilometer of 252 model and MBS-7, MIM-8, "Neofot" optical microscopes were used for that purpose. Relative macrodeformation ε_H was valued by total shortening of both welded specimens. When SC and DC were tested, one of the welded in SC specimen was previously annealed in $\alpha+\beta$ -area, its initial microstructure was purposefully changed. In this case the equality of rates of high-temperature creep of compared combinations was ensured.

Near the top limit of $\alpha+\beta$ -area temperature is optimal in case of welding of many titanium alloys [4]. Therefore welding of

OT4-1 and VT3-1 (R_Z 0,05 + R_Z 10,0) alloys was conducted at T_W = 900°C.

Experimental data show (see fig. 6a) that a physical contact of DC with all t_W and ε' is formed more slowly than of SC, that is the following inequality takes place:

$$F'_{DC} < F'_{SC} \quad (1)$$

where F'_{DC} and F'_{SC} -middle rates of physical contact formation of DC and SC correspondingly.

The initial size of grain of welded alloys (table 1) approximately ensures their equal rate of high temperature deformation, and thus excludes a formation of mechanical heterogeneity in the contact area. Therefore it' s impossible to explain inequality (1) by difference in microplastic deformation character in the joint area.

In this case the influence of other processes may become important. The above processes are responsible for a formation of a physical contact in case of titanium alloys welding. One of the most important of the above processes is connected with a formation of high-temperature surface microrelief [4].

Actually in $\alpha+\beta$ -area the intensity of this process depends on chemical and phase composition of an alloy, the process is more active near the point A_{c3} [15]. That's why in the analyzed case (fig. 6) formation of microrelief of BT3-1 alloy occurs slower than of OT4-1, because point A_{c3} of the first alloy is essentially lower than welding temperature. In case of the above alloys welding total contribution of formed microrelieves of both welded surfaces to the process of disappearance of macro-discontinuities will be lower than in case of SC welding.

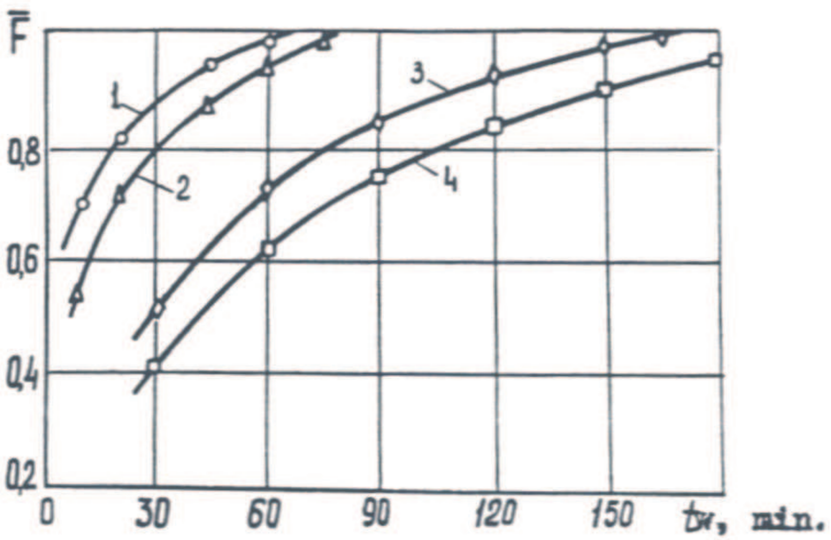


Fig. 6a

Dependence F(t_W) (a) and F(ε) (b) in case of welding of combinations (R_z 10,0 + R_z 0,05) OT4-1 + OT4-1 (1,3) and OT4-1 + BT3-1 (2,4) with different deformation rate ε', C^{-1}; $0,82\cdot10^{-5}$ (1,2)

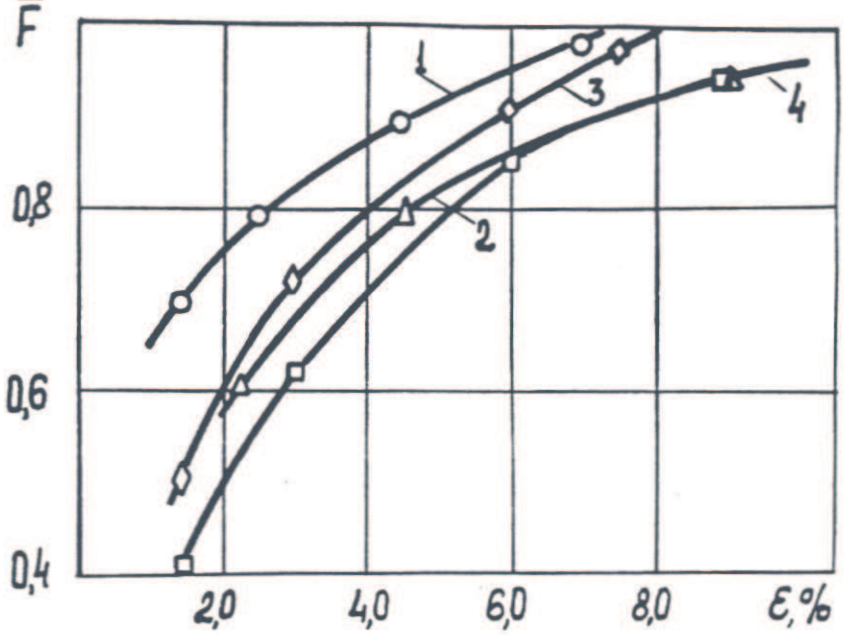


Fig. 6b

Dependence F(t_W) (a) and F(ε) (b) in case of welding of combinations (R_z 10,0 + R_z 0,05) OT4-1 + OT4-1 (1,3) and OT4-1 + BT3-1 (2,4) with different deformation rate ε', C^{-1}; $0,82\cdot10^{-5}$ (1,2)

Different geometry of defects in contact proves it: SC have flat long marcodiscontinuities (fig. 7a), and DC have thicker macrodiscontinuities (fig. 7b). One can judge of contribution value of formed microrelieves to the formation of a physical contact by results of welded joints annealing [4]. Thus welded joints anneling in vacuum (R_Z 0,05 + R_Z 70,0) at T_{an} a 900°C results in F_{SC} rise up to 0,95 value after preliminary contact formation F = 0,75, the annealing does not practically change F_{DC}.

The influence of special features of microrelieves formation on characteristics of $F(t_W)$ dependencies will be minimum if welded alloys have similar values of point A_{c3}. However the inequality (1) is correct for similar combinations. The welding of OT4 and BT3-1 alloys proves it (fig.8). Consequently special features of microrelieves formation can't be the single factor slowing down the growth of DC physical contact. At the same time it is proved that dependencies $F_{DC}(t_W)$ and F_{SC} (t_W) differ little in case of welding of DC alloys having lesser gradient of concentrations of alloyed elements in contact $\Delta C = C_2 - C_1$ (where: C_1, C_2 -content of alloyed elements in less or more alloyed composition of the given DC correspondingly).

The above phenomenon takes place in case of welding of OT4 + OT4-1 and BT14 + BT3-1 alloys. Consequently, the inequality (1) is connected with diffusion processes in the joint area. These processes are caused by a gradient of alloyed elements concentration. The inequality may be determined by realization of Frenkel effect for analysed DC group.

The realization is simplified if there are prepared areas for vacancies flows in the diffusion zone (1.3). In case of diffusion welding such may be microareas of welded joint with an unformed physical contact. Extra vacancies will promote the growth of microareas condensating on them and slowing down the formation of

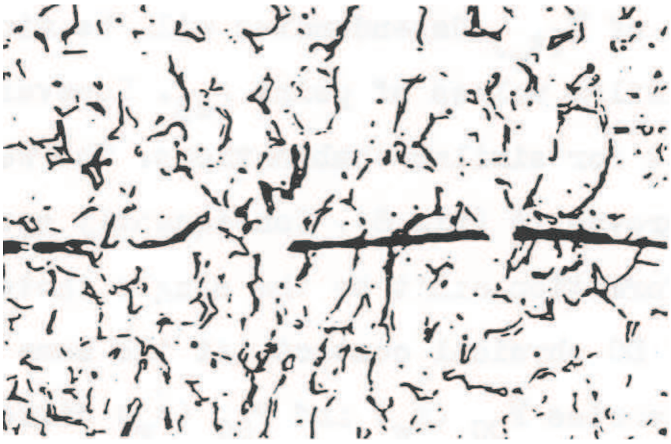


Fig. 7a

Welded joint area structure OT4-1 + OT4-1 (a,b) and OT4-1 + BT3-1 at t_W = 30 min. (a,b) and t_W = 150 min. (c,d), x1000.

Fig. 7b

Welded joint area structure OT4-1 + OT4-1 (a,b) and OT4-1 + BT3-1 at t_W = 30 min. (a,b) and t_W = 150 min. (c,d), x1000.

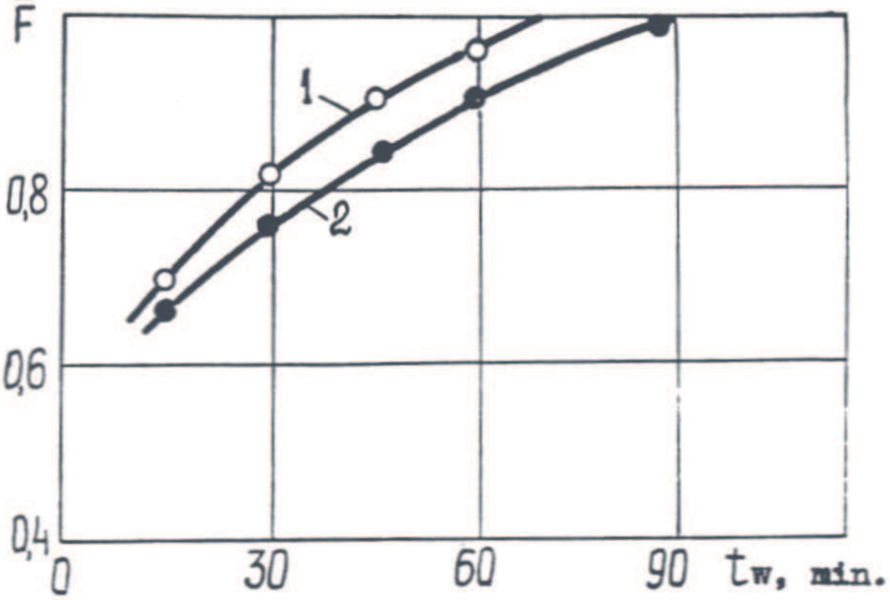


Fig. 8

Dependence F(t_W) in case of welding (T_W = 940°C, $\varepsilon = 2{,}0 \cdot 10^{-5}$ c^{-1}) of combinations (R_Z 10,0 + R_Z 0,05) OT4 + OT4 (1) and OT4 + BT3-1 (2) a physical contact in such a way. The results of a metallographic analysis show this (fig. 7). With ε_H and t_W growth the SC defects become less in both dimensions of the surface of a section metallographic specimen (fig. 7c). There appear interrupted stitch defects transforming into pores which are removed later on accord to the regularities of the caking process. There is quite an opposite phenomenon in case of DC welding with high values of ε_H and t_W in the contact area and the existence of a great number of small pores there remain discontinuities of large sizes. Their thickness does not differ greatly from the initial one, though they become much shorter (fig. 7d). Experimental data on welding of BT3-1 and OT4 alloys show that F_{DC}(tw) and F_{SC}(tw) dependences are similar when the contact surfaces have low R_Z values (fig. 9). At final stages there is an inequality: $F_{DC} > F_{SC}$.

Probably extra vacancies promote the growth of only rather large discontinuities and intensify the removal of small ones. This fact makes quite reasonable the technological requirement to increase a class of purity of welded surfaces of DC alloys.

Alloyed elements in titanium alloys may promote both lowering (β = stabilizators) and rise (α = stabilizators) of point A_{c3}.

The development of diffusion processes of DC results in redistribution of alloyed elements in the joint area and may change point A_{c3} in a local zone of a contact surface. In case of welding in $\alpha+\beta$ = area the realization of this possibility is determined in the first term by the correlation of approaching diffusion flows of β-stabilizators in the contact area. The flows of the above group of combinations are balanced. Therefore local changes of point A_{c3} do not occur and the structural state of the surface layers differs little from the base material (fig. 7). This occurs when a value of gradient of β-stabilizators

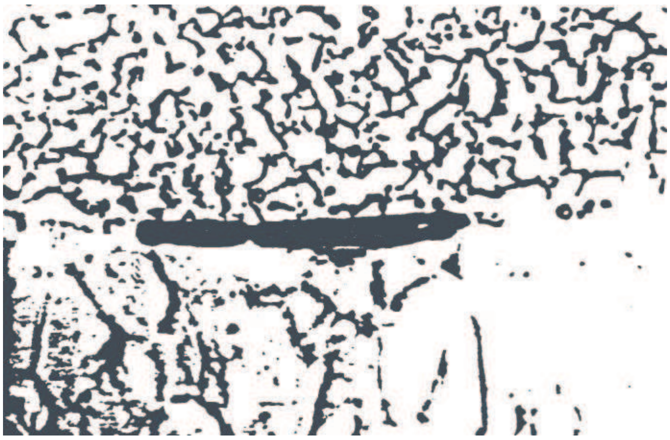


Fig. 7c

Welded joint area structure OT4-1 + OT4-1 (a,b) and OT4-1 + BT3-1 at t_W = 30 min. (a,b) and t_W = 150 min. (c,d), x1000.

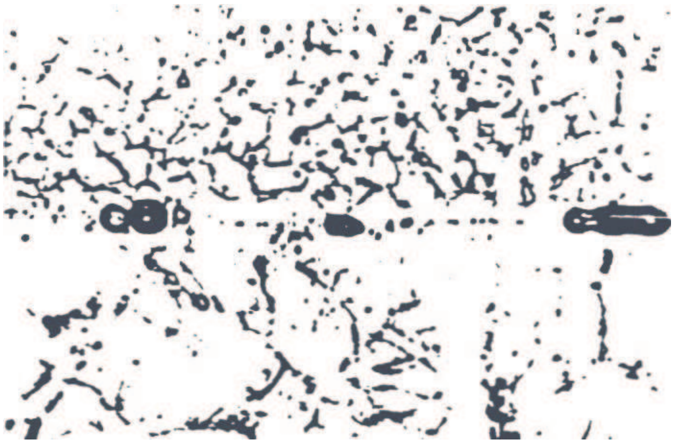


Fig. 7d

Welded joint area structure OT4-1 + OT4-1 (a,b) and OT4-1 + BT3-1 at t_W = 30 min. (a,b) and t_W = 150 min. (c,d), x1000.

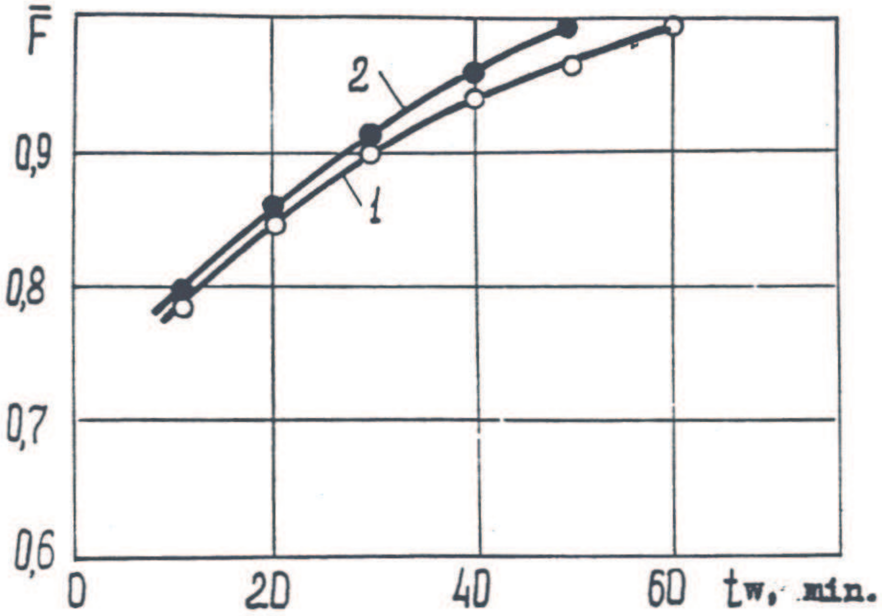


Fig. 9

Dependence $F(t_W)$ in case of welding (T_W = 940°C, $\varepsilon = 1,0\cdot10^{-5}$ c^{-1}) of combinations (R_Z 1,5 + R_Z 0,05) OT4 + OT4 (1) and OT4 + BT3-1 (2) concentrations ΔC_β in the contact area is not high or when one of the welded alloys has the surplus of them, and that is compensated by greater diffusion mobility of the other alloy. The situation changes with ΔC_β increase, that is confirmed by the following example.

Welding of BT1-0 alloy w1th other alloys in α-area is followed by essential structural changes in its surface layer. The in-flow of β-stabilizators elements brings point A_{c3} down and causes polimorphous α+β =transformation, followed by the grain growth in the contact area on the side nearest BT1-0. While ΔC_β is increased in a succession of DC (BT1-0 + OT4-1), (BT1-0 + BT3-1) (and BT1-0 + BT16) a thickness of a large grain layer and a size of grain grow (fig. 10).

The heavy integration of grain in the contact area of one of DC alloys increases its resistance to high temperature plastic deformation and reduces the rate of the physical contact formation. In particular this phenomenon is also revealed in case of welding of heterostructural combinations (fig. 11) of alloys having the same chemical composition*. For analyzed DC group F_{DC} decrease is not of great importance (fig. 12). This fact may be explained by the influence of the correlation of initial values of welded alloys

($\varepsilon_{BT3-1} \sim 2\cdot10^{-5}\ c^{-1}$, $\varepsilon_{BT1-0} \sim 1\cdot10^{-6}\ c^{-1}$)

in the terms of experiment.

---

*Experimental data were obtained together with ph.D. of Technology Rodionov V.N.

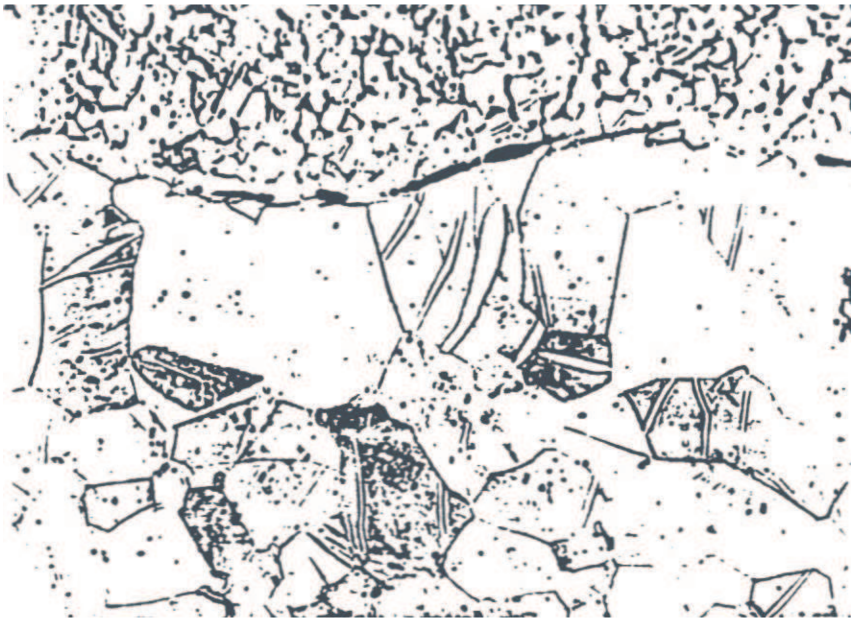


Fig. 10a

Welded joint areas structure (T_W = 857°C, t_W = 30 min.) BT1-0 + OT4-1 (a), BT1-0 + BT3-1 (b) and BT1-0 + BT16 (c) x500

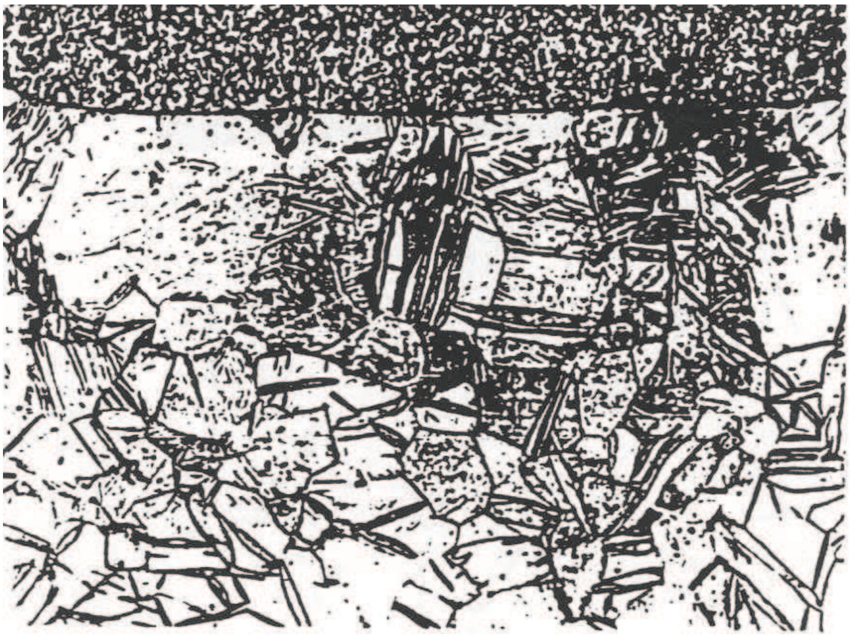


Fig. 10b

Welded joint areas structure (T_W = 857°C, t_W = 30 min.) BT1-0 + OT4-1 (a), BT1-0 + BT3-1 (b) and BT1-0 + BT16 (c) x500

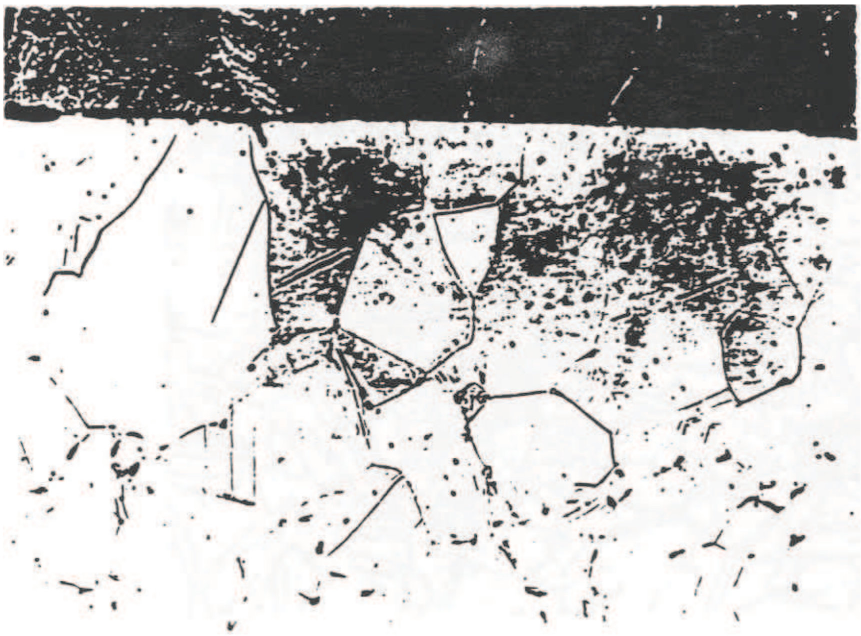


Fig. 10c

Welded joint areas structure ($T_W = 857°C$, $t_W = 30$ min.) BT1-0 + OT4-1 (a), BT1-0 + BT3-1 (b) and BT1-0 + BT16 (c) x500

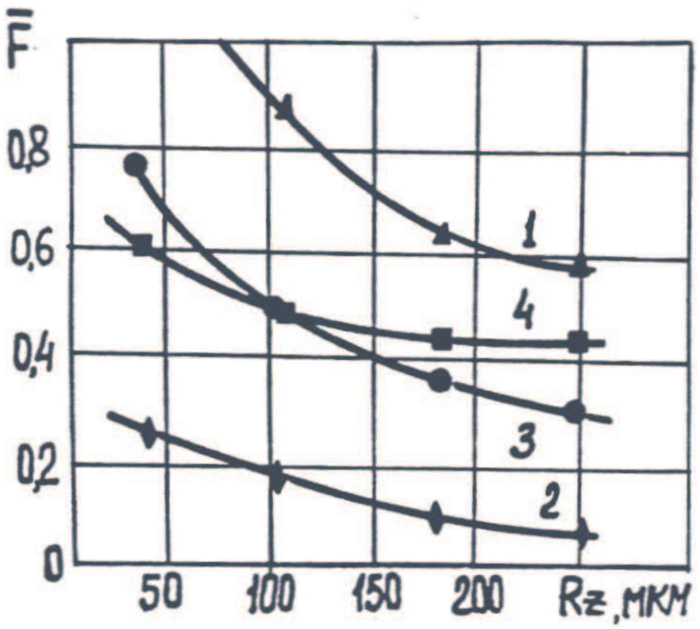


Fig. 11

Dependence $F(R_Z)$ (where R_Z – middle height of microprojections of turned surface) in case of welding T_W = 940 °C, t_W = 40 min., P = 2,0 MPa) of OT4 alloy with different combinations of contacting of small grain (S) and large grain (L) structures:

1- ST+SP; 2- LP+LT; 3- SP+LT; 4- ST+LP

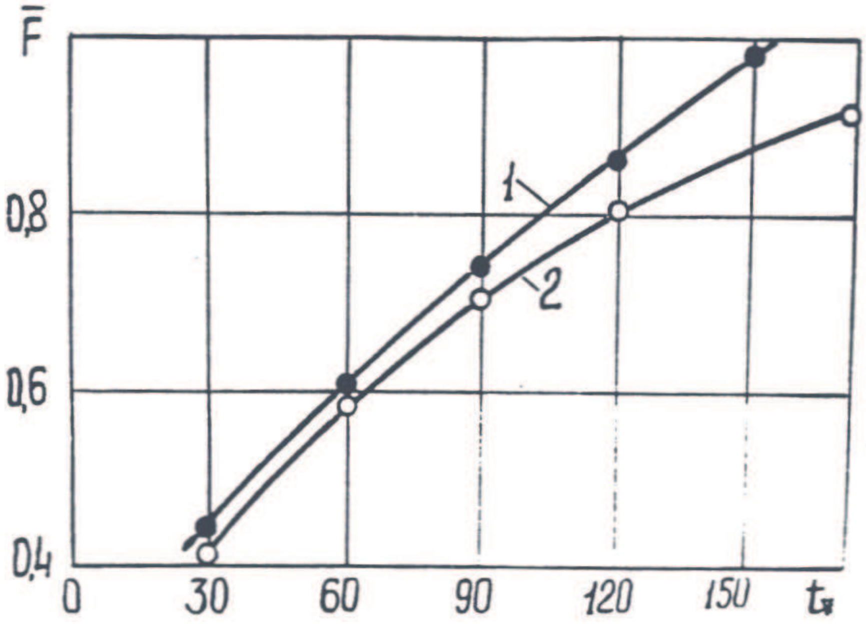


Fig. 12

Dependence F(t_W) in case of welding (T_W = 875°C, $\varepsilon = 1,0 \cdot 10^{-5}$ s^{-1}) of combinations (R_Z 10,0 + R_Z 0,05) BT3-1 + BT3-1 (1) and BT3-1 + BT1-0 (2)

In case of mechanical heterogenuity a physical contact is formed to a great extent due to microplastic deformation of the material having greater ε. Therefore the structural hardening of less plastical material does not seriously influence the characteristic of $F(t_W)$ dependencies (fig. 12). On the contrary, the hardening of a more plastic material results in an intensive F_{DC} lowering in comparison with F_{SC}. Specifically it occurs in case of welding of low α = alloys and pseudoalloyed α = compositions having high values of ε with high β = alloys and pseudo-β = alloys. In this case F_{DC} lowering is provided by the fact that β-stabilizators supersaturation in the area near the contact of a low alloy is followed by decreasing of their concentration in a high alloy. It locally raises point A_{c3} of a high alloy thus reducing the rate of a high temperature microplastic deformation. Besides high alloys are determined by low intensity of microrelief formation [15]. All this causes the most intensive F_{DC} decrease in comparison with F_{SC} in all the above analyzed cases, an example of welding of OT4-1 and BT16 alloys proves it (fig. 13).

It is common knowledge that due to effect of deformation hardening in case of titanium alloys welding an inequality [4] takes place:

$$\left|\frac{dF}{d\varepsilon}\right|\cdot\varepsilon_i > \left|\frac{dF}{d\varepsilon}\right|\cdot\varepsilon_{i+1} \qquad (2)$$

In case of DC welding with adequate R_Z due to realization of Frenkel effect and the structural hardening in the contact area the inequality (2) does not take place. It is correct for the combinations characterized by low values of ΔC and ΔC_β. (OT4 + OT4 -1, BT14 + BT3-1) or in the case when structural hardening takes place in less plastic material (BT1-0 + OT4-1 t BT1-0 + BT3-1). In case of ΔC increasing (see fig. 6b) an approximate equality

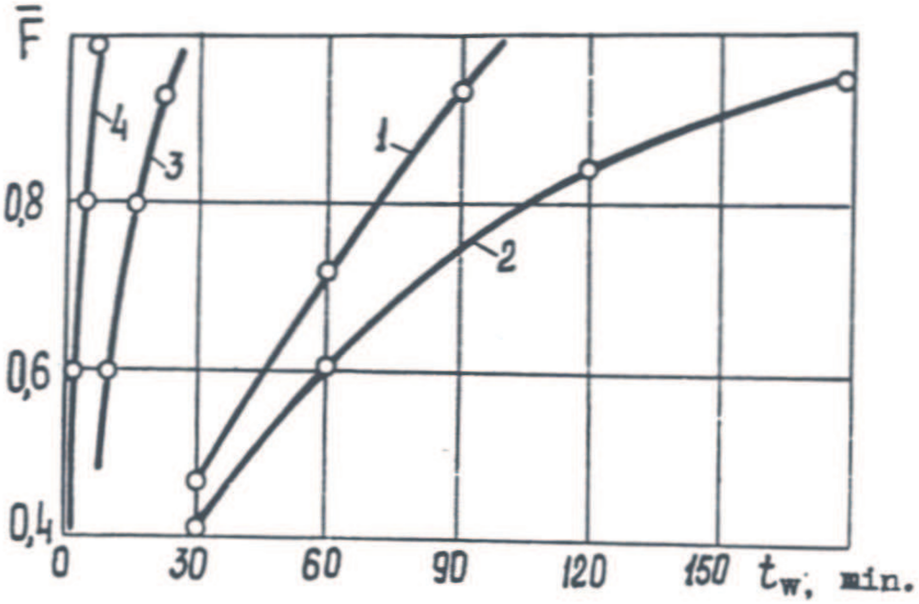


Fig. 13a

Dependence $F(t_W)$ (a) and $F(\varepsilon)$ in case of welding (T_W = 900°C) of combinations (R_Z 10,0 + R_Z 0,05) OT4-1 + OT4-1 (1) and OT4-1 + BT16 (2,3,4) with different deformation rate ε, s^{-1}: $1,22 \cdot 10^{-5}$ (3), $27,0 \cdot 10^{-5}$ (4)

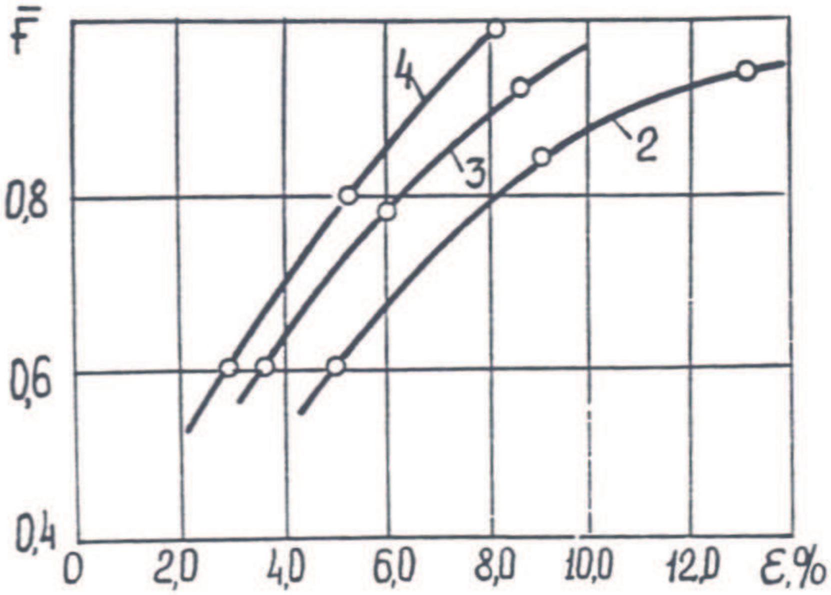


Fig. 13b

Dependence F(t_W) (a) and F(ε) in case of welding (T_W = 900°C) of combinations (R_Z 10,0 + R_Z 0,05) OT4-1 + OT4-1 (1) and OT4-1 + BT16 (2,3,4) with different deformation rate ε, s^{-1}: $1{,}22 \cdot 10^{-5}$ (3), $27{,}0 \cdot 10^{-5}$ (4)

takes place:

$$\left|\frac{dF}{d\varepsilon}\right| \cdot \varepsilon_i \sim \left|\frac{dF}{d\varepsilon}\right| \cdot \varepsilon_{i+1} \qquad (3)$$

In case of unfavourable correlation of ε values of welded alloys further ΔC and ΔC_β increase results in the opposite regularity:

$$\left|\frac{dF}{d\varepsilon}\right| \cdot \varepsilon_i > \left|\frac{dF}{d\varepsilon}\right| \cdot \varepsilon_{i+1} \qquad (4)$$

In the process of welding in $\alpha+\beta$ -area structural hardening is intensified by T_W and t_W increase. Therefore together with the inequality (4) the following correlation is correct:

$$\left|\frac{dF}{d\varepsilon}\right| t_{Wi}, T_{Wi} > \left|\frac{dF}{d\varepsilon}\right| t_{Wi+1}, T_{Wi+1} \qquad (5)$$

Patterns (4) and (5) show that in order to diminish an effect of structural hardening and to obtain joints with less residual deformation it is necessary to reduce temperature and duration of welding process by increasing deformation rate. It is evident that optima1 T_W, t_W and ε must ensure the formation of a full physical contact before the formation of low plastic layers. Diminishing of roughness of welded surfaces will also provide this aim. It is very important from technological point of view that in case of mechanical heterogenuity a physical contact is formed more rapidly if less plastic material has higher R_Z values in DC. Moreover this tendency strengthens while R_Z values become less (fig. 11). Probably forcing a hard microprojection into an opposite soft surface is followed by less deformation hardening in comparison with an apposite variant. Therefore the requirement to increase a class of purity of contact surfaces should be first of all applied to more plastic material of DC.

The determined regularities of a physical contact formation connected with structural changes of surface layers take place in one or another degree in case of welding in other temperature ranges. Thus if more high point A_{c3} corresponds to more alloyed composition of DC then it is sometimes more efficient to conduct welding at temperature between points A_{c3} of welded alloys. In addition we can also observe some F_{DC} values decrease in comparison with F_{SC}, especially for DC with low ΔC_β values and rather high ΔC values (for example, BT3-1 + OT4-1). In this case a limiting factor is a diffusion removal of α-stabilizators from more alloyed composition. This removal causes a local lowering of point A_{c3} end an increase of a size of grain in the area near the contact (fig. 14).

IV. Influence of Heteroalloying on the Quality of a Welded Joint

Titanium alloys were used for research (table 1), the alloys were welded in SC and DC.

Welded samples (fig. 15) were prepared in a pure argon atmosphere in such a way as having been used before (fig. 1). Then they were heated to the predetermined welding temperature T_W, held parted for t_p= 10 min. and pressed to ε= 1,0...1,5% for t_p= 5 min. According to the above technological scheme welding ensures high reactivity of contact surfaces in connection with formation of surface relief of micro- and substructural character [16].

After welding some specimens were annealed without pressure (in a single thermal cycle) at different T_{an} and t_{an}. The quality of welded joints was valued by KCV values. The welding alloys are characterized by correlation KCV_1/KCV_2, where KCV_1 and KCV_2 - an impact toughness of more or less tough of the welded alloys.

Fig. 14

Welded joint structure BT3-1 + OT4-1 at T_W = 940 °C, t_W = 30 min., x 1000

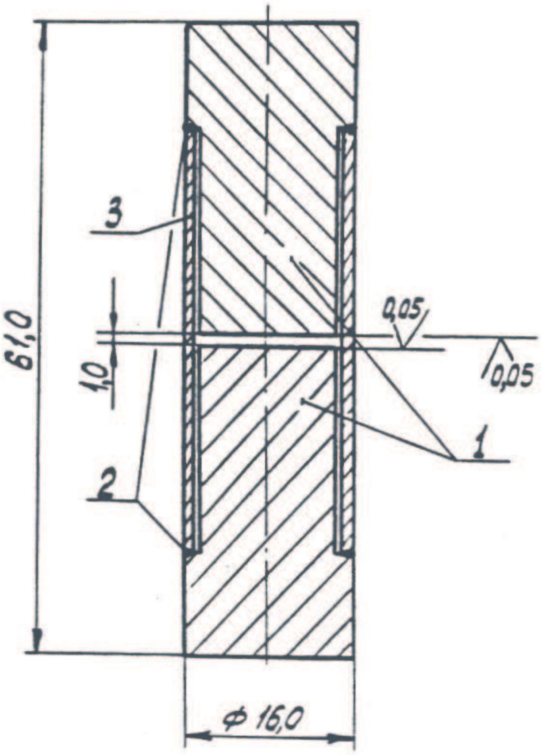


Fig. 15

Welded specimens: 1- specimens; 2- welded seams (welds); 3- titanium capsules

Therefore KCV_{DC} values are also dependent on welded materials properties. According to this fact when analyzing KCV values they took into consideration the character of destruction which may occur along the contact surface (1-type) or in some distance from an incision on tougher material (III-type). An intermediate II-type of destruction including the first two elements is also possible.

The results of impact bend tests of welded joints after welding cycle are given in table 2. It is obvious that KCV_{DC} values are mostly determined by the difference in the degree of alloying of the welded ΔC alloys and also by total content of alloyed C_1 elements in tougher (less alloyed) composition.

With minimum ΔC a welded joint is destroyed according to the first type, and KCV_{DC} values are similar to corresponding KCV_{SC} values (see table 2 pos. 6,14). With maximum ΔC and minimum C_1 KCV_{DC} values exceed corresponding KCV_{SC} values of both welded alloys, that is an effect of improved weldability is realized. This effect is maximum for combinations Nos. 3,4,7,8 and is decreasing with C_1 growth (No. 10,11) and ΔC lowering (No. 2). The realization of the effect is followed by the appearance of tough fractures of III and II types.

The determined regularities are more observable at the first group of DC (table 2). All those tendencies are preserved at the second group, but DC weldability is getting somewhat worse.

Thus it follows that in inoxidable terms under short thermal influence heteroalloying intensifies all stages of the process of point formation. Probably this is connected with characteristic features of diffusion in the contact area resulting in formation of uncompensated flow of vacancies. The latter causes

Table 2

Nos.	Combination of alloys	KCV at T_w, °C							KCV_1/KCV_2	$\Delta C_F/C_1$
		800	825	850	875	900	940	980		
1	2	3	4	5	6	7	8	9	10	11
	Group 1. Combinations when more alloyed composition has greater $T_{\alpha+\beta\to\beta}$ = transformation									
1	BT1-0 + BT1-0		0,46(I)		0,65(I)		0,55(I)		1,0	
		0,4(I)**		0,55(I)		0,7(I)		0,4(I)		0
2	BT1-0 + OT4-1		0,5(I)		0,8(III)		0,4(I)		1,98	
		0,45(I)		0,7(II)		0,8(III)		0,4(I)		2,5
3	BT1-0 + BT14		0,6(II)		0,75(III)		0,7(III)		2,5	
		0,5(I)		0,7(III)		0,75(III)		0,5(I)		8,5
4	BT1-0 + BT3-1		0,82(III)		0,87(III)		0,78(III)		3,0	
		0,80 (III)		0,85(III)		0,80(III)		0,5(I)		1,3
5	OT4-1 + OT4-1		0,6(I)		0,75(I)		0,65 (I)		1,0	
		0,45(I)		0,7(I)		0,8(I)		0,6(I)		0
6	OT4-1 + OT4		0,5(I)		0,7(I)		0,6(I)		1,07	
		0,4(I)		0,6(I)		0,7(I)		0,5(I)		2,5
7	OT4-1 + BT14		0,6(II)		0,95(III)		0,75(III)		1,25	
		0,50(I)		0,9(III)		1,05(III)		0,6(I)		6,0
8	OT4-1 + BT3-1		1,0(III)		1,1(III)		0,7(III)		1,5	
		0,72 (II)		1,1(III)		1,05(III)		0,6(I)		8,8
9	OT4 + OT4		0,44(I)		0,61(I)		0,65(I)		1,0	
		0,37(I)		0,5(I)		0,75(I)		0,45(I)		0
10	OT4 + BT14		0,6 (II)		0,78(II)		1,0(III)		1,17	
		0,45 (I)		0,76(II)		0,8(II)		0,45(I)		3,5
11	OT4 + BT3-1		0,7 (II)		0,8(II)		1,0(III)		1,4	
		0,5(I)		0,78(II)		0,85(II)		0,5(I)		6,3
12	BT14 + BT14		0,15(I)		0,32(I)		0,58(I)		1,0	
		0,1(I)		0,22(I)		0,52(I)		0,4(I)		0
13	BT3-1 + BT3-1		0,14(I)		0,32(I)		0,51(I)		1,0	
		0,1(I)		0,25(I)		0,42(I)		0,4(I)		0
14	BT14 + BT3-1		0,15(I)		0,33(I)		0,55(I)		1,2	
		0,1(I)		0,25(I)		0,5(I)		0,4(I)		2,8

1	2	3	4	5	6	7	8	9	10	11
	Group 2. Combinations when more alloyed composition has less $T_{\alpha+\beta\to\beta}$ = transformation									
15	BT16 + BT16		0,04(I)		0,07(I)		0,1(I)		1,0	
		0,03(I)		0,05(I)		0,1(I)		0,8(I)		0
16	BT16 + BTI-0		0,4(II)		0,5(III)		0,4(I)		3,75	
		0,05(I)		0,55(III)		0,45(III)		0,4(I)		12,
17	BT16 + OT4-1		0,3(I)		0,5(II)		0,4(I)		1,9	
		0,05(I)		0,36(II)		0,8(III)		0,4(I)		10,
18	BT16+ OT4		0,1(I)		0,2(I)		0,33(I)		1,75	
		-		0,15(I)		0,25(I)		0,2(I)		7,
19	BT16 + BT14		-		0,17(I)		0,3(I)		1,5	
		-		0,1(I)		0,32(I)		0,3(I)		4,
20	BT16 + BT3-1		-		0,11(I)		0,27(I)		1,25	
		-		0,05(I)		0,20(I)		0,2(I)		1,

*C_1 and C_2 - composition of alloyed elements in welded alloys more or less alloyed correspondingly (table 1)

** - character of destruction is stated in brackets the dislocations formation in diffusion zone [10] and probably results in displacing of the initial surface of the contact according to Kirkendall effect [13].

In $\alpha+\beta$ -area isothermal annealing of welded joints results in decreasing of KCV_{DC} values (fig. 16-23). Consequently due to duration of thermal influence a heteroalloying factor may provide both improving of titanium alloys weldability and its deterioration. Besides the degree of KCV_{DC} lowering depends on the value of chemical heterogenuity in the contact area and the origin of diffusion elements.

The publication [17] states that Kirkendall effect exists to a low degree for systems (Ti)-(Ti-4,OAl) and (Ti)-(Ti-8,OAl) with annealing in α-area due to similar coefficients of titanium and alluminium diffusion (D_{al}~1,1D_{Ti}), but Frenkel pores-formation does not take place all. Therefore in case of BT1-0 + BT5 alloys welding an effect of improved weldability does not occur (fig. 16) and in case of annealing there is an increase of KCV_{DC} values, fractures of II and III types appear. The KCV_{DC} values increase transforms into slight decrease only at t_{an} > 2,0 h.

The process of softening is improved if along with Al there are some other elements in the composition of welded alloys which diffusion mobility is more than titanium.

Sufficient softening occurs (fig. 17,18) if with adequate ΔC diffusion flows of elements of β-stabllizators over contacting surface are approximately the same. It is possible with a low gradient of concentrations of β-stabilizators (ΔC_{β}) or when β-stabilizators surplus of one of the welded alloys is compensated by their greater diffusion mobility of another (OT4-4 + BT3-1; OT4-1 + BT14; OT4 + BT14; OT4 + BT3-1). In this case volumetric interaction happens according to common [11] kinetics.

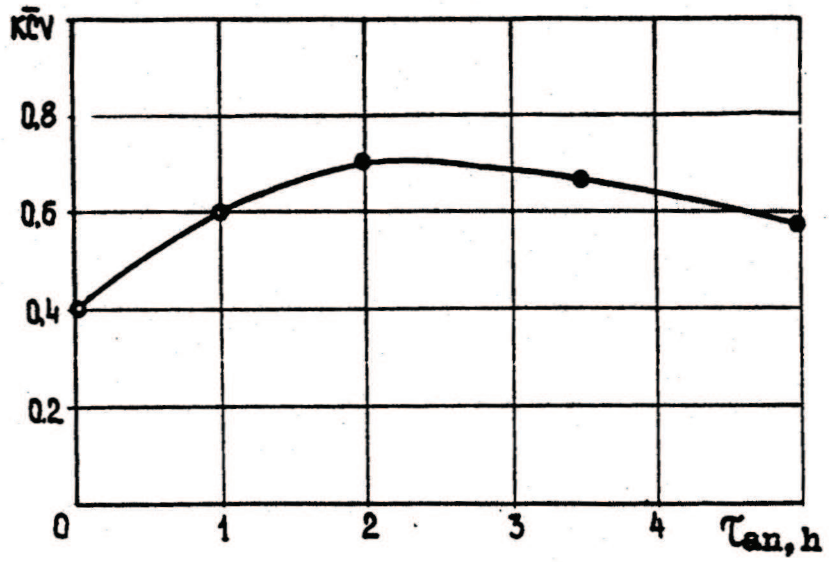


Fig. 16

Dependence KCV(t_{an}) for BT1-0 + BT5 combination after welding and annealing at $T_W = T_{an} = 875$ °C

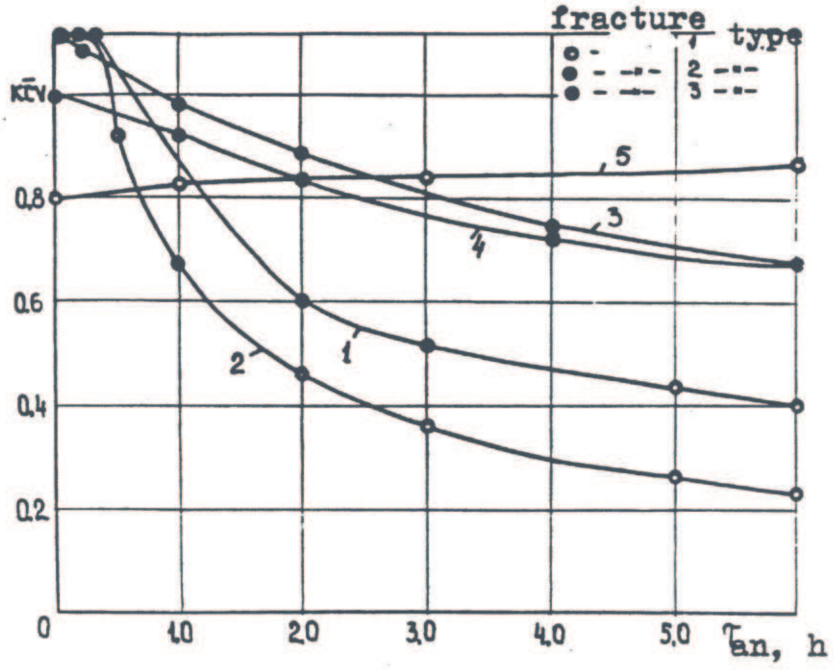


Fig. 17

Dependence KCV(t_{an}) for combinations OT4-1 + BT3-1 (1-4) and OT4-1 + OT4-1 (5) after welding (T_W = 900 °C) and annealing at T_{an} °C: 1 - 850; 2,4,5 - 900; 3 - 940; BT3-1 -initial small grain structure; OT4-1 -small grain (1-3,5) and large grain (4) structure

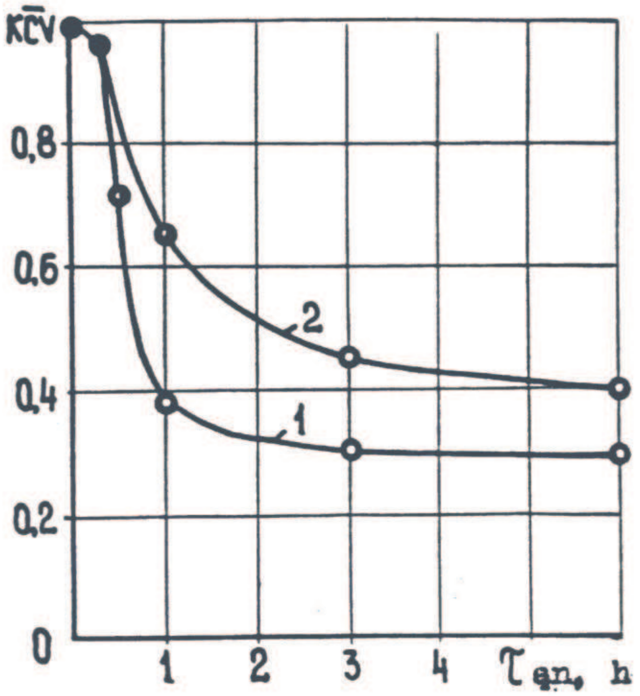


Fig. 18

Dependence KCV(t_{an}) for combinations OT4 + BT14 (1) and OT4 + BT3-1 (2) after welding and annealing at $T_W = T_{an} = 940$ °C

The boundary orientated along the contact surface (fig. 19a) is modified with t_{an} growth, the grains common for both welded blanks appear on it maintaining the initial globular structure. However a chain of small pores appear (fig. 19b) over the initial surface of contacting. The appearance of the chain is probably connected with Frenkel effect realization. Probably this is the main cause of softening that is followed by changing of fracture character from the III type to the II and the I.

The loss of strength becomes less with T_{an} decrease (fig. 17, curves 1,2) and with approaching DC (OT4 + OT4-1; BT14 + BT3-1) with less ΔC (fig. 20).

The structure of welded alloys greatly influences the degree of the loss of strength. As the coefficient of diffusion along the grains boaders is higher than in the grains volume the existence of the small-grains-structure in the contact area promotes the increase of approaching flows. This results in the growth of uncompensated flow of vacancies and the increase of porosity. In case of large-grain-structure a resulting diffusion flow becomes less and decreases softening. Consequently all technological methods leading to the integration of grains of even one of the welded alloys promote decreasing of softening. Welding in β-area is among such methods (fig. 17, curve 3). Specifically, the previous annealing of OT4-1 in β-area (1000 °C, 30 min.) resulting in the growth of initial grain to 300 mcm., excludes fractures of the I type (fig. 17. curve 4). It should be noted that KCV_{DC} lowering is also observed when there ara no pores in the contact area. In such a case this is determined by simple equalizing of concentrations of alloyed elements in the joint area. Besides with t_{an} growth KCV_{DC} values approach the corresponding index for more alloyed composition with maintaining tough fracture (fig. 17, curves 3.4).

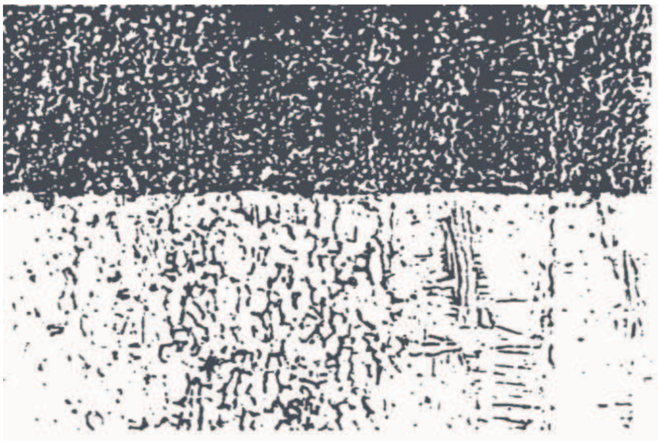


Fig. 19a

Welded joint structure of OT4-1 + BT14 combination after welding (T_W = 900 °C, x 500 – a) and annealing T_{an} = 900 °C, t_{an} = 64, x 1000 – b)

Fig. 19b

Welded joint structure of OT4-1 + BT14 combination after welding (T_W = 900 °C, x 500 – a) and annealing T_{an} = 900 °C, t_{an} = 64, x 1000 – b)

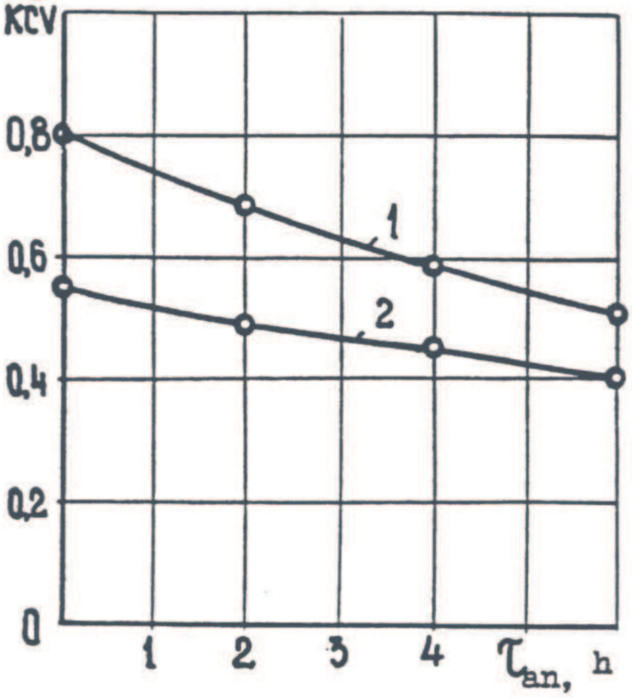


Fig. 20

Dependence KCV(t_{an}) for OT4 + OT4 (1) and BT14 + BT3-1 (2) after welding and annealing at 900 °C (1) and 940 °C (2)

The loss of strength becomes less if diffusion flow of β-stabilizators elements dominates in one of directions of the contact area. Such a situation takes place when one of DC alloys unlike the other does not comprise β-stabilizators or when ΔC_β values are high enough. In this case the influx of β-stabilizators to the surface layer of less alloyed composition results in local decreasing of α+β -transformation temperature. Specifically it happens in case of annealing of welded joints BT1-0 + BT14, BT1-0 + BT3-1 (fig. 21). In this case a surface layer with large-grain-structure is formed (fig. 22a), that cardinally decreases a resulting flow of vacancies. Therefore even after long electropolishing porosity was not revealed in the joint area (fig. 22b), this fact excludes the destruction of the 1st type.

For DC BT1-0 + OT4-1 ΔC_β is lower, therefore the grain in the surface layer BT1-0 is integrated less (fig. 22c). As a result in case of electropolishing there appears a chain of very small pores in the joint area (fig. 22d). In this case KCV_{DC} dependence is identical in quality to the previous one (fig. 21). However after long annealing at 850 °C the destruction happens according to the I and II types.

Intensive softening happens with DC, having maximum ΔC and ΔC_β values. High ΔC_β value results in a large-grain-layer formation in the contact area and high ΔC value causes porosity. Such a situation occurs in case of annealing of welded joints of BT16 alloy with other alloys (fig. 23), especially with low alloyed.

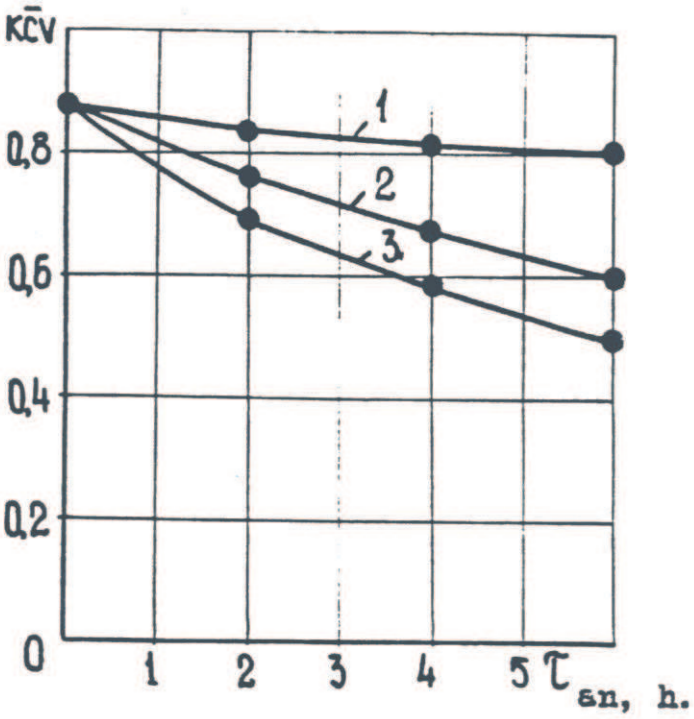


Fig. 21

Dependence KCV(t_{an}) for BT1-0 + BT3-1 combination after welding (T_W = 875 °C) and annealing at T_{an} °C: 1- 850; 2- 875; 3- 900.

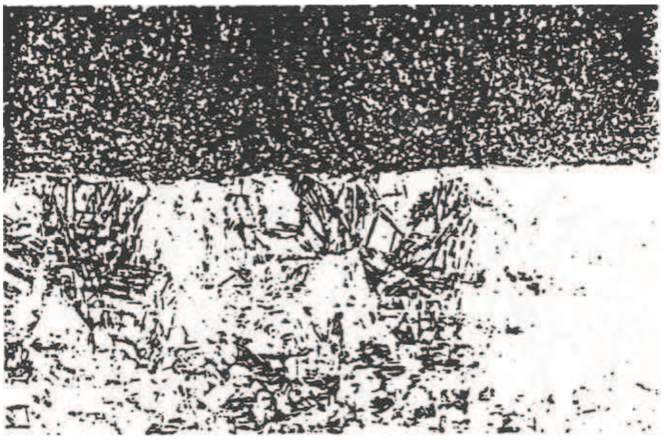


Fig. 22a

Welded joint zone structure of BT1-0 + BT14 (a,b) and BT1-0 + OT4-1 (c,d) combinations after welding and annealing $T_W = T_{an} = 850$ °C, $t_{an} = 6h$; a,c (x100) - etching: b, (x 1000), d (x 500) - electropolishing

Fig. 22b

Welded joint zone structure of BT1-0 + BT14 (a,b) and BT1-0 + OT4-1 (c,d) combinations after welding and annealing $T_W = T_{an} = 850$ °C, $t_{an} = 6h$; a,c (x100) - etching: b, (x 1000), d (x 500) - electropolishing

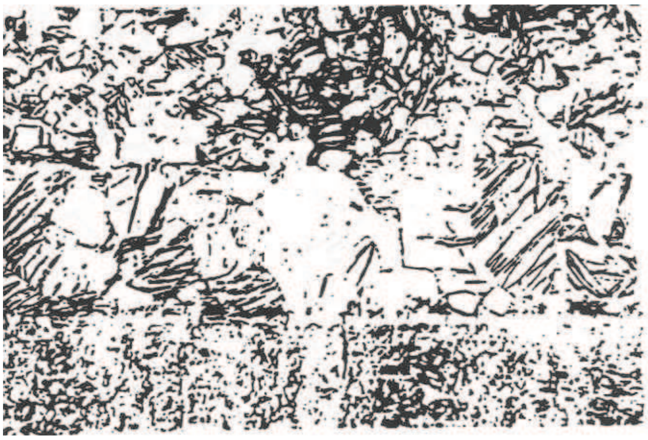


Fig. 22c

Welded joint zone structure of BT1-0 + BT14 (a,b) and BT1-0 + OT4-1 (c,d) combinations after welding and annealing $T_W = T_{an} = 850$ °C, $t_{an} = 6h$; a,c (x100) - etching: b, (x 1000), d (x 500) - electropolishing

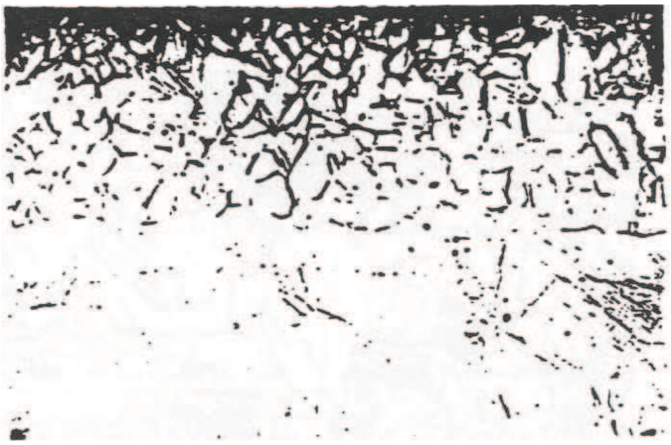


Fig. 22d

Welded joint zone structure of BT1-0 + BT14 (a,b) and BT1-0 + OT4-1 (c,d) combinations after welding and annealing $T_W = T_{an} = 850$ °C, $t_{an} = 6h$; a,c (x100) - etching: b, (x 1000), d (x 500) - electropolishing

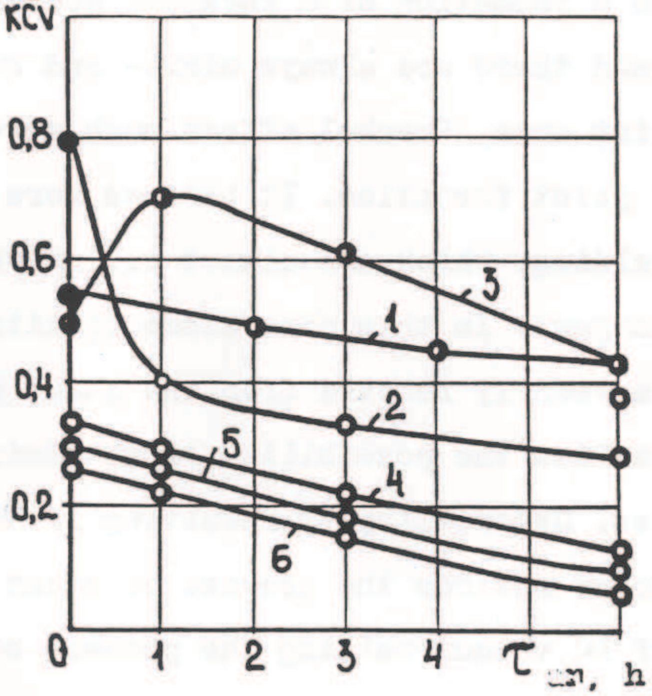


Fig. 23

Dependence KCV(t_{an}) for combinations BT1-0 + BT16 (1), OT4-1 + BT16 (2,3), OT4 + BT16 (4), BT15 + BT16 (6). Welding and annealing at T °C: 850 (3), 875 (1), 900 (2,4,5,6).

V. Technological Aspects of Weldability. The Choice of Optimal Technological Schemes

Kirkendall and Frenkel effects are exposed simultaniously and they are competitive, but if there are prepared areas for uncompensated vacancies flows in the diffusion zone, then Frenkel effect becomes predominant [13]. Therefore in real terms of welding when a formation of a physical contact occurs comparatively slow and there are always micro- and macrodiscontinuities in the joint area, Frenkel effect much more slows down the process of joint formation. It becomes more obvious in case of inert gas welding, which ere almost not solved in titanium (for example, argon). In this case discontinuities filled by gas are not practically removed from the joint area and it become difficult to realize the possibility of obtaining a joint with KCV=1,0 values. Heteroalloying resulting in Frenkel effect realization much more retards the process of joint formation.

In case of DC vacuum welding the process of joint formation is facilitated though definite difficulties are also preserved in this case. The results of welding of specimens with different initial geometry of welded surfaces prove it. Specimens (in 16x30 mm diameter) were welded in vacuum 10^{-2} mm of a mercury column with additional screening of joint area by getter.

The most difficult problem is to obtain qualitative DC joints characterized by maximum ΔC and ΔC_β with absolutely different resistance of welded alloys to high temperature plastic deformation (for example, OT4-1 + DT16).

The formation of a large grain layer on the side of less alloyed composition slows down the physical contact formation. But even after a full macrocontact formation in the joint area a great number of micropores mainta1ns. They are situated both over the initial surface of contacting and along a new structural border of the joint. Moreover the joint microareas last coming into contact are the most defective ones (fig. 24). Such a structure of joint zone results in low KCV_{DC} values. Found defects are stable enough, therefore even in case of substantial deformation there is no perceptible increasing of KCV_{DC} (fig. 25).

Consequently in a studied case volumetric interaction is the stage limiting the formation of a qualitative joint. The reduction of duration of thermodeformation cycle of welding due to increase of the deformation rate provides the porosity decreasing and physical contact formation with lesser accumulated deformation (fig. 13). However even in this case KCV_{DC} values remain not high (fig. 25) because an area near the contact of high alloy is not practically deformed and its contact surface remains non-active. In this case the activation stage becomes limitary and to obtain high KCV_{DC} values it's necessary to take special measures for increase of the reaction activity of a high alloy surface.

In case of DC welding characterized by high enough ΔC_{β} with moderate ΔC (BT-1-0 + BT3-1 and so on) the tendency to pores format1on is minimum, therefore $KCV_{DC}=1,0$ joint is formed practically almost after achieving a full physical contact. Consequently this stage of the process is limitary, however its realization is somehow slowed down in comparison with SC due to formation of low plastic layers. Therefore for similar DC a technological scheme providing a physical contact formation at low temperatures with further heating to a high boarder of $\alpha+\beta$ -

Fig. 24

Welded joint zone structure OT4-1 + BT16 (R_Z 0,05 + R_Z 10,0) at T_W = 900 °C, t_W = 2h; ε = 10%; x1000.

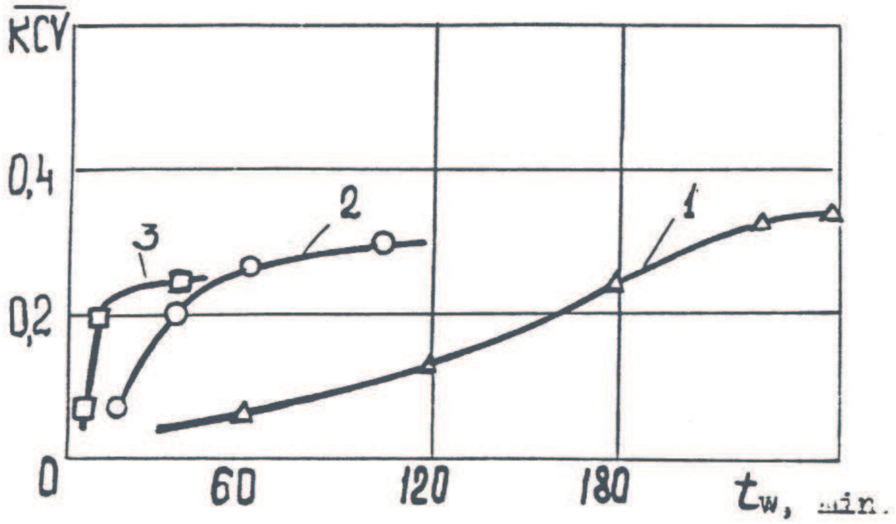


Fig. 25

Dependence KCV(t_W) in case of DC welding BT16 + OT4-1 (R_Z 0,05 + R_Z 10,0) at ε , C^{-1}: $1,22\cdot10^{-5}$ (1), $7,0\cdot10^{-5}$ (2), $27,0\cdot10^{-5}$ (3)

area is the most efficient.

In case of DC welding characterized by low ΔC_{β} but sufficient ΔC (OT4-1 + BT3-1, OT4 + BT3-1) the influence of heteroalloying may be different. With comparatively high R_Z (10,0 mcm) and low deformation rate the chemical heterogenuity slows down a physical contact formation causing Frenkel pores-formation.

In addition discontinuities remain in the contact area even after a full macrocontact formation. Furthermore an additional deformation promotes their removal and obtaining qualitative joints with high enough KCV_{DC} in case of a tough fracture (fig. 26a, 27a). On the other hand, unlike SC a deformation rate increase results in obtaining qualitative joints with less accumulated deformation (fig. 26a, 27a,b). In this case KCV_{DC} values increase may happen more intensive than of DC (fig. 26a). This tendency also evident for lower R_Z (fig. 26b). Consequently to obtain higher KCV_{DC} values with less accumulated deformation it is necessary to increase a class of purity of welded surfaces and to reduce time of thermodeformation influence. With substantial R_Z after macrocontact formation in $\alpha+\beta$ -area the annealing of welded joint in β-area would be desirable.

The above-mentioned recommendations for different groups of DC will permit to diminish the negative concequencies connected with chemical heterogenuity in the contact area. However, a better weldability effect will not be realized in this case.

Its realization is possible only in case of short contact interaction of surfaces with high reaction activity (fig. 1, table 2), moreover for combinations with maximum ΔC and ΔC_{β} this is the only possibility of obtaining qualitative joints with limited accumulated deformation.

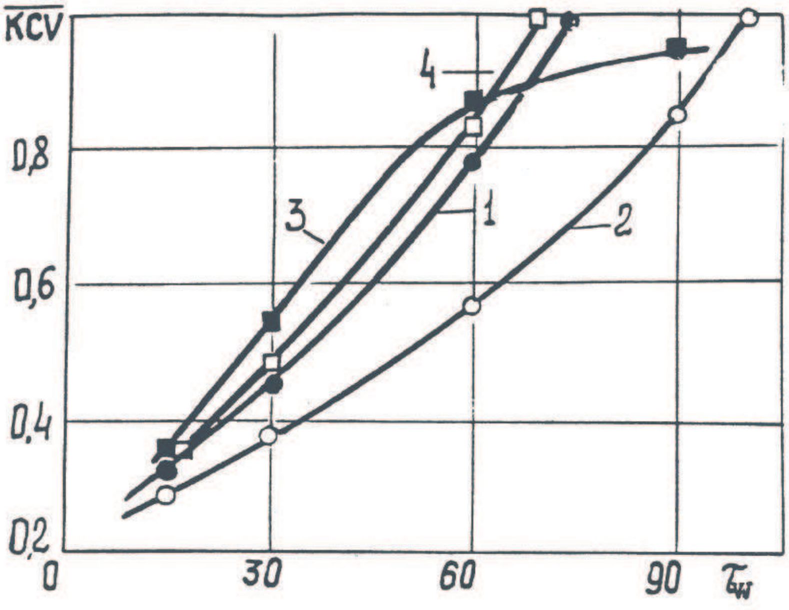


Fig. 26a

Dependence KCV(t_W) for DC OT4 + BT3-1 (2,4) and SC OT4 + OT4 (1,3) at T_W = 940 °C: a- R_Z 10,0 + R_Z 0,05 at ε, C^{-1}: $2 \cdot 10^{-5}$ (1,2) and $3,5 \cdot 10^{-5}$ (3,4); b- R_Z 1,5 + R_Z 0,05 at ε = $0,8 \cdot 10^{-5}$ s^{-1}

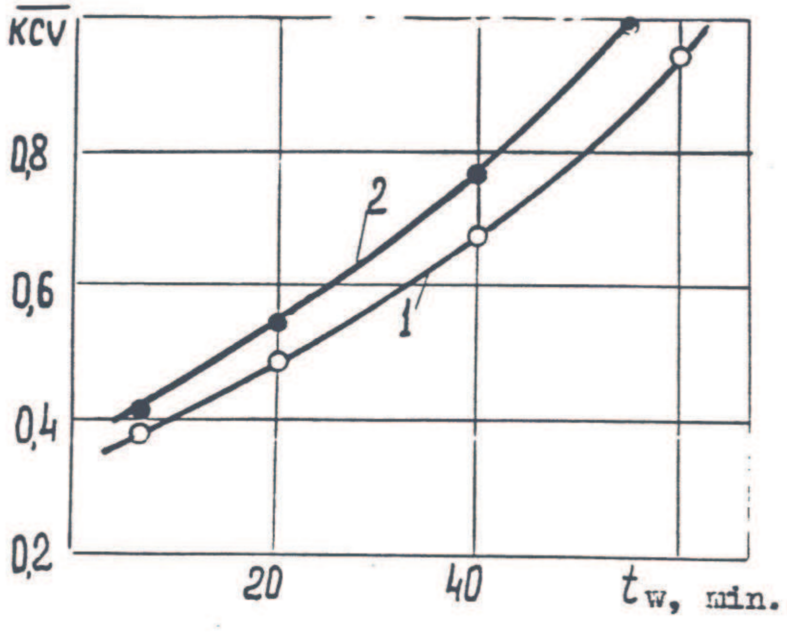


Fig. 26b

Dependence KCV(t_W) for DC OT4 + BT3-1 (2,4) and SC OT4 + OT4 (1,3) at T_W = 940 °C: a- R_Z 10,0 + R_Z 0,05 at ε, C^{-1}: $2\cdot10^{-5}$ (1,2) and $3,5\cdot10^{-5}$ (3,4); b- R_Z 1,5 + R_Z 0,05 at $\varepsilon = 0,8\cdot10^{-5}$ s^{-1}

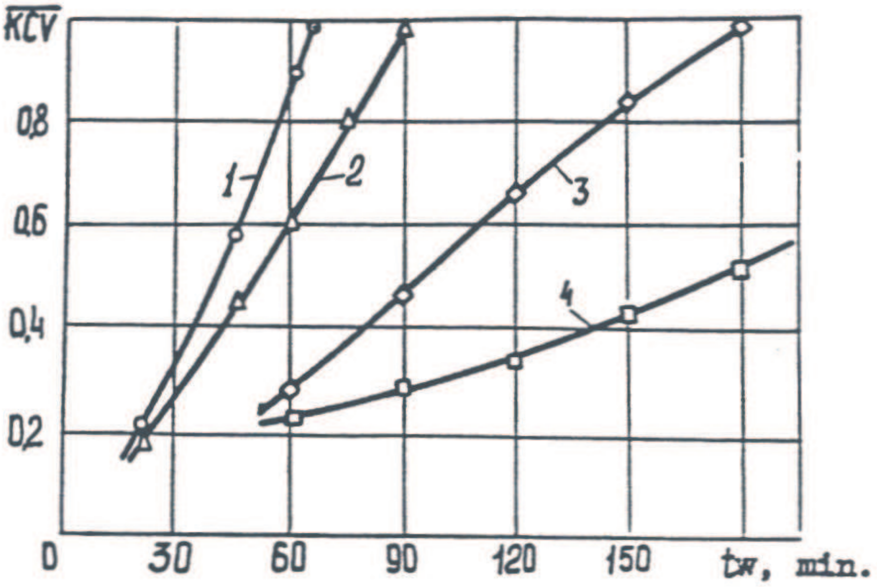
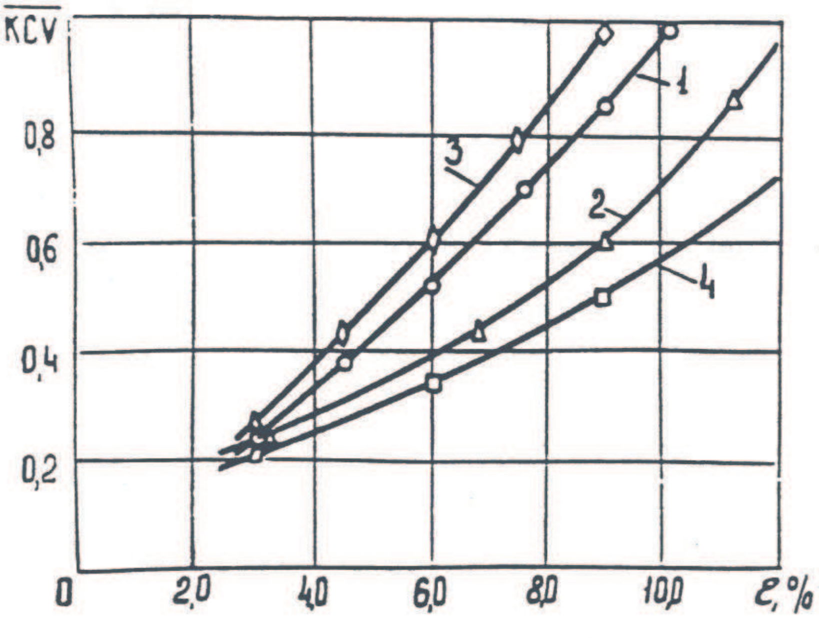


Fig. 27a,b

Dependence KCV(t_W) (a) and KCV(ε) (b) for combinations (R_Z 10,0 + R_Z 0,05) OT4-1 + OT4-1 (1,3) and BT3-1 + OT4-1 (2,4) at T_W = 900 °C and ε= $0,82\cdot10^{-5}$ s^{-1} (3,4) and $2,5\cdot10^{-5}$ s^{-1} (1,2)



VI. Conclusion

The analysis of special features of realization of volumetric interaction stage has determined that weldability of different titanium alloys has substantial differences in comparison with similar titanium alloys.

There have been analyzed the special features of a physical contact formation for various groups of different combinations of titanium alloys in comparison with similar combinations.

It has been shown that the process rate is lower for DC than for SC. This results in the growth of accumulated macrodeformation in the first case.

The determined tendency caused by realization of Frenkel effect and structure herdening in the contact area is intensified in accordance with the growth of chemical heterogenuity in the contact area and also depends on plasticity of welded materials at welding temperature.

There has been studied the influence of heteroalloying on the welded joints properties in case of different duration of thermal influence in the contact area. The obtained data were analyzed in accordance with the special features of a physical contact formation and the recommendations on optimization of thermodeformation cycle of welding for different groups of different titanium alloys were given.

Captions

Fig. 1 Dependence KCV(t_W) for combinations OT4-1 + OT4-1 (1) and OT4-1 + BT3-1 (2)

Fig. 2 Structure of welded joint area of SC (a) and DC (b) after welding at T_W = 900 °C, t_W = 75 min

Fig. 3 Welded specimens

Fig. 4 Dependence KCV (t_{an}) for combinations OT4+OT4 (1', 2', 3') and OT4+BT4 (1, 2, 3) at T_{an} °C: 3,3' – 850, 2,2' – 900, 1,1' – 940

Fig. 5 Dependence KCV – 1/T for DC (1) and SC (2)

Fig. 6 Dependence F(t_W) (a) and F(ε) (b) in case of welding of combinations (R_Z 10,0 + R_Z 0,05) OT4-1 + OT4-1 (1,3) and OT4-1 + BT3-1 (2,4) with different deformation rate ε', C^{-1}; $0{,}82\cdot10^{-5}$ (1,2)

Fig. 7 Welded joint area structure OT4-1 + OT4-1 (a,b) and OT4-1 + BT3-1 at t_W = 30 min. (a,b) and t_W = 150 min. (c,d), x1000

Fig. 8 Dependence F(t_W) in case of welding (T_W = 940°C, $\varepsilon = 2{,}0\cdot10^{-5}\ c^{-1}$) of combinations ($R_Z$ 10,0 + R_Z 0,05) OT4 + OT4 (1) and OT4 + BT3-1 (2)

Fig. 9 Dependence F(t_W) in case of welding (T_W = 940°C, $\varepsilon = 1{,}0\cdot10^{-5}\ c^{-1}$) of combinations ($R_Z$ 1,5 + R_Z 0,05) OT4 + OT4 (1) and OT4 + BT3-1 (2)

Fig. 10 Welded joint areas structure (T_W = 857°C, t_W = 30 min.) BT1-0 + OT4-1 (a), BT1-0 + BT3-1 (b) and BT1-0 + BT16 (c) x500

Fig. 11 Dependence F(R_Z) (where R_Z – middle height of microprojections of turned surface) in case of welding T_W = 940 °C, t_W = 40 min., P = 2,0 MPa) of OT4 alloy

with different combinations of contacting of small grain (S) and large grain (L) structures:
1- ST+SP; 2- LP+LT; 3- SP+LT; 4- ST+LP

Fig. 12 Dependence $F(t_W)$ in case of welding (T_W = 875°C, ε = $1{,}0 \cdot 10^{-5}$ s^{-1}) of combinations (R_Z 10,0 + R_Z 0,05) BT3-1 + BT3-1 (1) and BT3-1 + BT1-0 (2)

Fig. 13 Dependence $F(t_W)$ (a) and $F(\varepsilon)$ in case of welding (T_W = 900°C) of combinations (R_Z 10,0 + R_Z 0,05) OT4-1 + OT4-1 (1) and OT4-1 + BT16 (2,3,4) with different deformation rate ε, s^{-1}: $1{,}22 \cdot 10^{-5}$ (3), $27{,}0 \cdot 10^{-5}$ (4)

Fig. 14 Welded joint structure BT3-1 + OT4-1 at T_W = 940 °C, t_W = 30 min., x 1000

Fig. 15 Welded specimens: 1- specimens; 2- welded seams (welds); 3- titanium capsules

Fig. 16 Dependence $KCV(t_{an})$ for BT1-0 + BT5 combination after welding and annealing at $T_W = T_{an}$ = 875 °C

Fig. 17 Dependence $KCV(t_{an})$ for combinations OT4-1 + BT3-1 (1-4) and OT4-1 + OT4-1 (5) after welding (T_W = 900 °C) and annealing at T_{an} °C: 1 – 850; 2,4,5 – 900; 3 – 940; BT3-1 -initial small grain structure; OT4-1 -small grain (1-3,5) and large grain (4) structure

Fig. 18 Dependence $KCV(t_{an})$ for combinations OT4 + BT14 (1) and OT4 + BT3-1 (2) after welding and annealing at $T_W = T_{an}$ = 940 °C

Fig. 19 Welded joint structure of OT4-1 + BT14 combination after welding (T_W = 900 °C, x 500 – a) and annealing T_{an} = 900 °C, t_{an} = 64, x 1000 – b)

Fig. 20 Dependence $KCV(t_{an})$ for OT4 + OT4 (1) and BT14 + BT3-1 (2) after welding and annealing at 900 °C (1) and 940 °C (2)

Fig. 21 Dependence $KCV(t_{an})$ for BT1-0 + BT3-1 combination after

	welding (T_W = 875 °C) and annealing at T_{an} °C: 1- 850; 2- 875; 3- 900.
Fig. 22	Welded joint zone structure of BT1-0 + BT14 (a,b) and BT1-0 + OT4-1 (c,d) combinations after welding and annealing $T_W = T_{an}$ = 850 °C, t_{an} = 6h; a,c (x100) – etching: b, (x 1000), d (x 500) – electropolishing
Fig. 23	Dependence KCV(t_{an}) for combinations BT1-0 + BT16 (1), OT4-1 + BT16 (2,3), OT4 + BT16 (4), BT15 + BT16 (6). Welding and annealing at T °C: 850 (3), 875 (1), 900 (2,4,5,6).
Fig. 24	Welded joint zone structure OT4-1 + BT16 (R_Z 0,05 + R_Z 10,0) at T_W = 900 °C, t_W = 2h; ε = 10%; x1000.
Fig. 25	Dependence KCV(t_W) in case of DC welding BT16 + OT4-1 (R_Z 0,05 + R_Z 10,0) at ε, C^{-1}: $1{,}22\cdot10^{-5}$ (1), $7{,}0\cdot10^{-5}$ (2), $27{,}0\cdot10^{-5}$ (3)
Fig. 26	Dependence KCV(t_W) for DC OT4 + BT3-1 (2,4) and SC OT4 + OT4 (1,3) at T_W = 940 °C: a- R_Z 10,0 + R_Z 0,05 at ε, C^{-1}: $2\cdot10^{-5}$ (1,2) and $3{,}5\cdot10^{-5}$ (3,4); b- R_Z 1,5 + R_Z 0,05 at $\varepsilon = 0{,}8\cdot10^{-5}$ s^{-1}
Fig. 27	Dependence KCV(t_W) (a) and KCV(ε) (b) for combinations (R_Z 10,0 + R_Z 0,05) OT4-1 + OT4-1 (1,3) and BT3-1 + OT4-1 (2,4) at T_W = 900 °C and $\varepsilon = 0{,}82\cdot10^{-5}$ s^{-1} (3,4) and $2{,}5\cdot10^{-5}$ s^{-1} (1,2)

Bibliography

1. Titanium alloys. Edited by A.T. Tumova, C.G. Glazunova, A.I. Horeva - VIAM, 1977, p. 398.
2. V.R. Rabkin, R.S. Kurochko, L.G. Strizhevskaja. Welding of heterogenious metals and alloys. -M., "Mechanical Engineering” 1984, p. 237.
3. S.S. Kerakozov. Joining of metals in a hard phaze. M., “Metallurgy", 1976, p. 264.
4. S.S. Kerakozov, Z.N. Orlova, V.V. Leshkov, V.I. Grigorjevskil. Titanium diffusion welding. -M., “Metallurgy”, 1977, p. 272.
5. O.K. Naumov, U.V. Gorshkov, N.G. Delyh. Diffusion welding of industrial titanium alloys. - Automated welding, 1979, No. 9, p. 47-51.
6. V.P. Aljohin, K.I. Mazur, M.H. Shershorov. About the character of volumetric interaction in the process of joint formation in case of ultrasonic aluminium welding with silicium. “Welding introduction”, 1973, No. 10, p.3-5.
7. V.M. Rozenberg. Bases of high-temperature strength of metal materials. M., “Metallurgy”, 1983, p. 324.
8. Y.L. Movikov. Defects of crystalline structure of metals. M. “Metallurgy”, 1983, p. 232.
9. M. Dyment. Self and solute diffusion in Titanium and titanium alloys. - Titanium SC. Sci. And Technol. Proc. 4. Int. Conf. Kuoto, May, 19-22, 1980, Vol. 1, New York, 1980, pp. 519-528.
10. M.A. Krishtal, V.I. Strelkov, I.M. Goncharenko. To the question of dislocations formation in diffusion layer. In the book “Diffusion in metals and alloys”, TMI, Tula, 1968,

p. 448.

11. E.S. Karakazov. Welding of metals by pressure. M., “Mechanical Engineering”, 1986, p. 275.
12. U. Cvikker. Titanium and its alloys. Moskow, “Metallurgy”, 1986.
13. V.B. Brick. Diffusion and phase transformations in metals and alloys. Kiev, "Scientific Idea", 1985, p. 232.
14. V.V. Peshkov, V.N. Rodionov, M.B. Nickgolov. Titanium diffusion welding with ensurance of small accumulated deformation of joined elements. "Welding Production", 1986, No. 9, p. 11-12.
15. M.B. Nickgolov, V.V. Peshkov, V.M. Rodionov. Regularities of microrelief formation on the titanium alloys surface in terms of diffusion welding. "Welding Production", 1986, No. 3, p. 37.
16. V.V. Peshkov, v.N. Rodionov, M.B. Nickgolov. Titanium diffusion welding with ensurance of small accumulated deformation. “Welding Production", 1986, No. 3, pp. 37-39.
17. Ouchi ken-ichiro, Jijima Yochiaki, Hirano ken-ichi. Inter-diffusion in Ti-Al-System. "Titanium-80. Sci. and Technol. Proc. 4 Int. Conf., Kioto, May, 19-22, 1980, Vol. 1, New York, 1980, p.p. 559-568.

CHARACTERIZATION OF A TITANIUM ALLOY FOR NUCLEAR FUSION APPLICATIONS

M. ZUCCHETTI*, D. BOERMAN**, G. PIATTI**

* Dipartimento di Energetica, Politecnico di Torino, ITALIA
* * Commissione delle Comunità Europee, IAM-JRC, Ispra (VA), ITALIA.

Riassunto.

Le leghe al titanio presentano proprietà assai interessanti, in vista del loro utilizzo come materiali strutturali per reattori a fusione termonucleare. Per selezionare una lega con proprietà adeguate, bisogna tenere in conto, in questo caso, sia delle proprietà termo-meccaniche e fisiche che di quelle nucleari. La radioattività indotta da flusso neutronico è uno dei parametri essenziali da limitare in un materiale di questo tipo: per quanto concerne la lega Ti-6Al-4V, essa si pone al di sotto dei limiti di bassa attività di cui sembra probabile l'adozione per le scorie di reattori a fusione.
Si è quindi proceduto alla caratterizzazione meccanica di due tipi di struttura della lega Ti-6Al-4V, considerando anche l'effetto della temperatura e della velocità di deformazione. Le proprietà meccaniche dei due tipi di lega si sono rivelate particolarmente interessanti, per gli elevati valori del limite elastico e a rottura. Inoltre, il comportamento a caldo (in particolare nello stato STA della lega) suggerisce l'evidente possibilità di fabbricare le complesse forme della prima parete di un reattore a fusione sfruttando la tecnica della formatura superplastica.

1. Introduction.

In some studies concerning the thermonuclear fusion systems, titanium alloys were selected on the basis of their high strength, high strength to weight ratio, excellent fatigue life, resistance to corrosion, low He production from fusion reactions, no void swelling formation, well estabilished industry and abundant availability[1]. An example of this can be found in the NUWMAK reactor study[2].

Taking into account these properties, and according to the new concepts related to low-activation materials, titanium alloys can also at present be considered an interesting candidate as a structural material for the next generation of fusion reactors.

Some problems are certainly to be kept present, like, for instance, the limited operating temperature (450 °C) and a low compatibility with hydrogen and its isotopes[3].

In order to evaluate the suitability of the titanium alloys as structural materials for a fusion reactor, we have considered first the problems coming from neutron-induced radioactivity, and then we have characterized a Ti-6Al4V alloy from the mechanical point of view, in different conditions (temperature, strain rate, morphology).

2. Neutron-induced radioactivity in a titanium alloy.

One of the main disadvantages of the fission reactors consists, with no doubt, in their production of radioactive wastes. This is one of the real technical reasons that are obstacolating (now and in the future) a wider diffusion of this power source.

Also fusion reactors will produce radioactive wastes, even if in far lower quantities. Moreover, fusion radioactive wastes will mainly consist of structural materials, radioactivated by the exposure to neutron flux; fission wastes, on the contrary, are made by fuel and reaction products.

Neutron induced radioactivity, at a fixed flux, strongly depends on the type of irradiated material. So, with a proper selection of the materials, the amount of long-lived radioactive wastes originating from a fusion reactor can be effectively limited.

This is not possible for fission reactors, in which radioactive wastes are an unavoidable by-product. This fact is, in our opinion, one of the distinctive points for fusion power.

Most part of high radioactive waste from a fusion reactor will come from first-wall and blanket components, being these ones the most flux-exposed structures. One of the main goals of the materials research for fusion is the development and selection of alloys with good thermomechanical and physical properties, coupled with low-activation characteristics too. We mean, by low-activation, the property of a material of producing a limited quantity of dangerous radioactive nuclides, when exposed to a neutron flux.

Neutron-induced radioactivity in a first-wall alloy, in fact, is greatly influenced by the concentration of its composing elements; many authors[4-5] have classified the chemical elements according to the different levels of induced radioactivity when exposed to a first-wall neutron flux in a fusion reactor. The most critical elements have been identified, while other ones with low activation properties have been recommended.

Titanium-based alloys, according to the most recent results, seem to be very interesting materials, due to the low induced radioactivity of their main constituent.

The definition of low-activity, however, depends on the planned management and disposal procedures for the reactor radioactive wastes. One of the most important results of the recent research in this field can be summarized as follows: the same procedures followed for the management and disposal of fission wastes will probably be adopted for fusion wastes[6]. This means the burial of the high-radioactive wastes in a Deep Geological Repository (DGR), after a period of decay in an intermediate storage within the plant, in order to eliminate the activity coming from the medium- and short-lived isotopes.

Other proposals were formulated in the past, dealing with the recycling of the materials or their burial in near-surface repositories; these appear to be not practicable for a first-wall component, as far as the European situation is concerned.

The low-activity limits that can be defined, in the case of burial in a DGR, are based on the acceptance criteria of the repository sites and on the safety precautions to follow during the transport of the component from the plant to the repository.

Acceptance criteria vary from one site to another, but they are essentially focused on the decay heat, that is, the thermal power density due to nuclear decay reactions. A maximum value of 10 W/m^3 can be indicatively fixed[7].

Safety procedures during the handling and transport of irradiated materials are mainly limiting the dose equivalent rate. According to the IAEA regulations, radioactive materials can be transported and handled for short periods in appropriate containers by the personnel if the dose equivalent rate at the surface of the container does not exceed 2 mSv/h; this means, taking into account the standard shielding of the container, a contact dose rate at the surface of the material of 20 mSv/h. Both these limits have to be satisfied after a decay period comparable to the plant lifetime (e.g. 30-50 years).

We have simulated the irradiation in a fusion reactor of a Ti-6Al4V alloy, as a first-wall component. The length of exposure was 5 years, with a neutron wall loading of 2 MW/m^2. Some other alloys, among those currently proposed for the first wall, have been examined for comparison purpouse: they are the austenitic steels AISI 316L and PCA, the martensitic steels MANET and FV448 and the low-activation austenitic chromium-manganese steel AMCR 0033. The vanadium alloy V-15Cr-5Ti has been considered too (see compositions in table 1).

The induced radioactivity analysis has been performed with the ANITA code[8]: some results afe shown in table 2. If we compare the activation of the alloys with the previously defined low-activity limits for DGR, we see that none of the steels can be accepted. This is true even for the low-activation one AMCR 0033, which decays below the stated limits after approximately 80 years of intermediate decay. For the other steels, many centuries of decay would be necessary. In that case, of course, the component is processed for repository adopting more complicate safety procedures: a careful selection of the characteristics of the geological site could also be necessary.

As far as the non-ferrous alloys are concerned, we see that they easily fulfil the low-activity requirements. In particular, Ti-6Al-4V (see fig. 1) shows a decay heat under 10 W/m^3 after less than 5 years of decay, while, to have a dose rate below 20 mSv/h, 30 years of decay are needed.

We can positively conclude that, unlike for steels, no composition adjustment is needed for our Ti-6Al-4V alloy. This material is a rather good candidate for a fusion reactor first wall, as far as its induced radioactivity is concerned.

3. Material.

The material investigated in this note is a Ti-6Al-4V alloy, made by ThyssenEdestahlwerke AG (Krefeld, Germany), under the designation "Contimet AIV64". The composition (weight %) is shown in table 1. This is a commercial composition; with respect to the E.L.I.-grades (Extra Low Interstitial), this alloy has higher strength and lower ductility properties. Bars of 60 mm diameter were delivered in the forged and annealed condition. The micrograph of a transverse section of the bar shows the typical (α+β) microstructure of the Ti-6Al-4V alloy (see fig. 2).

4. Heat treatments and microstructure.

Unmachined rough samples taken from the bar were heat-treated under argon atmosphere, to avoid the pick-up of interstitials, which would change the mechanical properties in a relevant way.
Two types of structures were obtained according to different heat-treatment conditions:

a) The fully recristallized annealed condition (RA-type).

The structure has equiaxed α-grains with the β-phase at the grain boundaries, mainly at the triple points (fig. 3). The advantage of this structure is its stability at higher temperatures. The conditions of heat treatment are: 4 hours at 930 °C and a very slow furnace cooling.

b) The solution treated and aged condition (ST A-type).

The two phases are primary α and a very fine (α+β) mixture, which causes the strengthening effect. The latter phase is so fine to be not visible by an optical microscope (fig. 4). This structure is limited at high temperature, because it can become over-aged: the mechanical properties are however interesting.
The conditions of heat treatment are: 0.5 hours at 930 °C and quench in H_2O (solution treatment) followed by a 0.5 hours aging at 540 °C and fumate cooling.

5. Tensile testing.

Three parameters have been changed during the mechanical characterization of the alloy:

- Structure: RA and STA conditions;
- Temperature: 20°, 400° and 800 °C;
- Strain rate: $4.2\ 10^{-1}$, $4.2\ 10^{-3}$, $4.2\ 10^{-5}\ s^{-1}$.

The initial results are collected in table 3; the following quantities have been determined:
$S_{0.2}$ = Elastic offset limit stress at 0.2% plastic strain
S_u = Ultimate stress
e_{pu} = Plastic uniform elongation
e_{pb} = Plastic elongation at breaking point

It can be seen from table 3 that all the three parameters (structure, temperature and strain rate) have a great influence on the mechanical properties. We will now examine in some detail the effect of each parameter.

5.1 Influence of structure.

The ratios of the mechanical properties of the STA condition, versus the RA condition, are put in table 4. The strengthening effect and loss of ductility are already visible at 20 °C, and even more pronounced at 400 °C; for both temperatures, the effect is stronger at lower strain rates.

At 800 °C the situation is reversed, due to the superplasticity effect, especially at lower strain rates. This effect is interesting for the production of the first-wall components: their complex shapes can be produced at high temperatures and then used at far lower ones. This superplasticity effect is more important in the STA-condition.

5.2 Influence of the strain rate.

The mechanical properties, normalized with respect to the fast strain rate of $4.2\ 10^{-1}\ s^{-1}$, have been reported in table 5. It can be seen that a decrease of the strain rate causes, in general, lower strength and higher strain, as expected. At 800 °C this effect becomes very marked, especially with a strain rate of 4.2 10^{-2} s^{-1}, due to the superplasticity effect (see also fig. 5).

5.3 Influence of temperature.

The mechanical properties, normalized against the properties at room temperature (20°C), are listed in table 6. The effect of higher temperature, namely lower strength and higher ductility, is very relevant, both at 400 °C and 800 °C.

6. Conclusions.

Titanium alloys can be good candidates as fusion reactors structural materials, due to their interesting properties.

Neutron-induced radioactivity in a Ti-6Al-4V alloy, when exposed to the neutron flux at a fusion-reactor first wall, is low enough to permit realistic hypoteses of management and disposal of radioactive wastes from a fusion reactor. On the contrary, this is not verified with presently available steels.

The mechanical properties of two types of structure of a Ti-6Al-4V alloy were investigated: the fully recristallized annealed condition (RA-type) and the solution treated and aged condition (STA-type); influence of strain rate and temperature has also been taken into account.

The superplasticity of the alloy has turned out to be a very interesting property, in view of the production of complex shapes for the first wall components of a fusion reactor.

References

1. R.E. GOLD et al., Nucl. Techn./Fusion, 1 (1981) 69.
2. B. BADGER et al., UWFDM-330, Univ. of Wisconsin (USA), 1979.
3. R.W. CONN, Journ. Nucl. Mater., 85-86 (1979) 9.
4. C. PONTI, Fusion Technol., 13 (1988) 157.
5. C.R. GOMER et al., Proc. ENC 86, Geneva, June 1-6, 1986, p.123.
6. European Workshop on Low-Activation Materials, JRC Ispra, Oct. 1-3, 1990.
7. C. PONTI, T.N.I.89.92, Comm. Eur. Commun., JRC Ispra, Jan. 1990.
8. C. PONTI, S. STRAMACCIA, EUR 12622 EN, Comm. Eur. Commun., JRC Ispra, 1989.

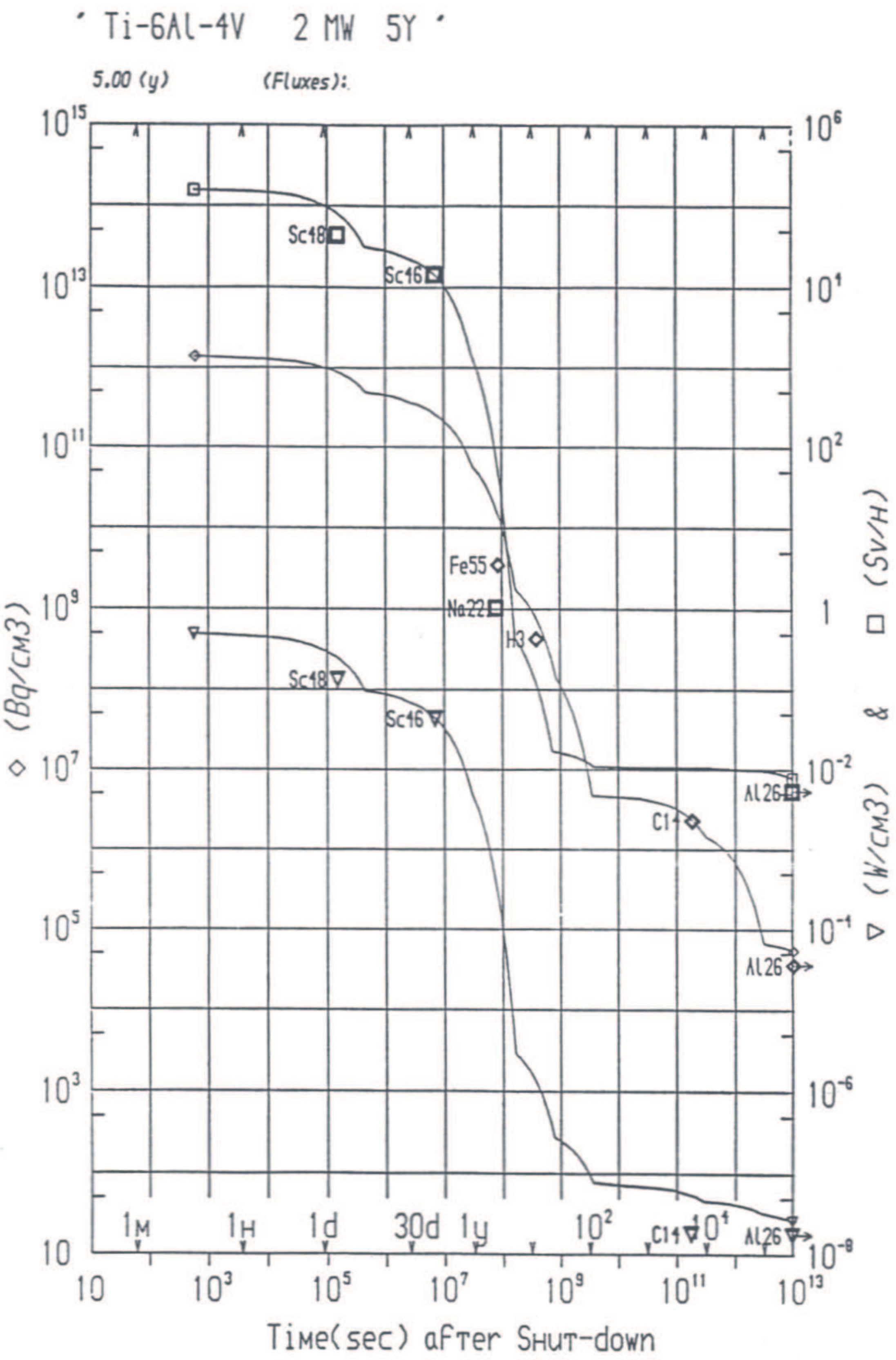


Figure 1: Induced radioactivity in a Ti-6Al-4V alloy after 5 years of exposure in a fusion reactor first wall.

Figure 2

Microstructure in the forged and annealed condition (as delivered state). (x 500)

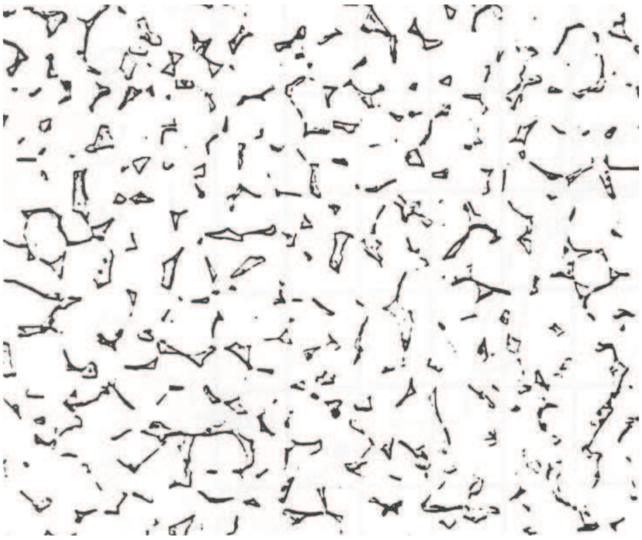


Figure3

Microstructure in the fully recristallized annealed condition (RA-type). (x 500)

Alpha phase is white

Beta phase is dark

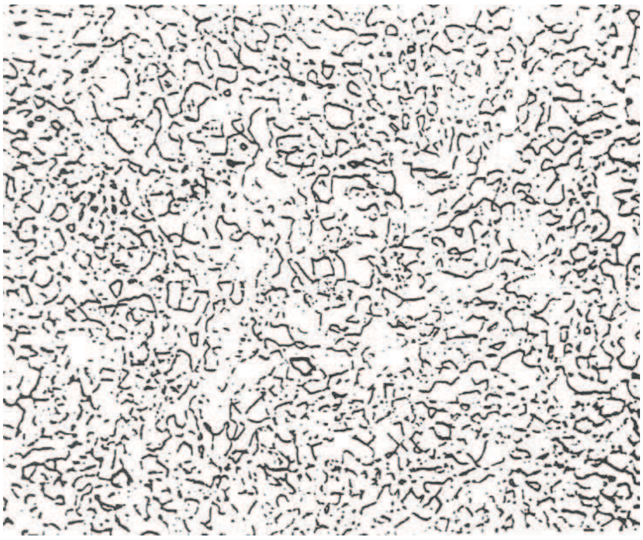


Figure 4

Microstructure in the solution treated and aged condition (STA-type). (x 500)

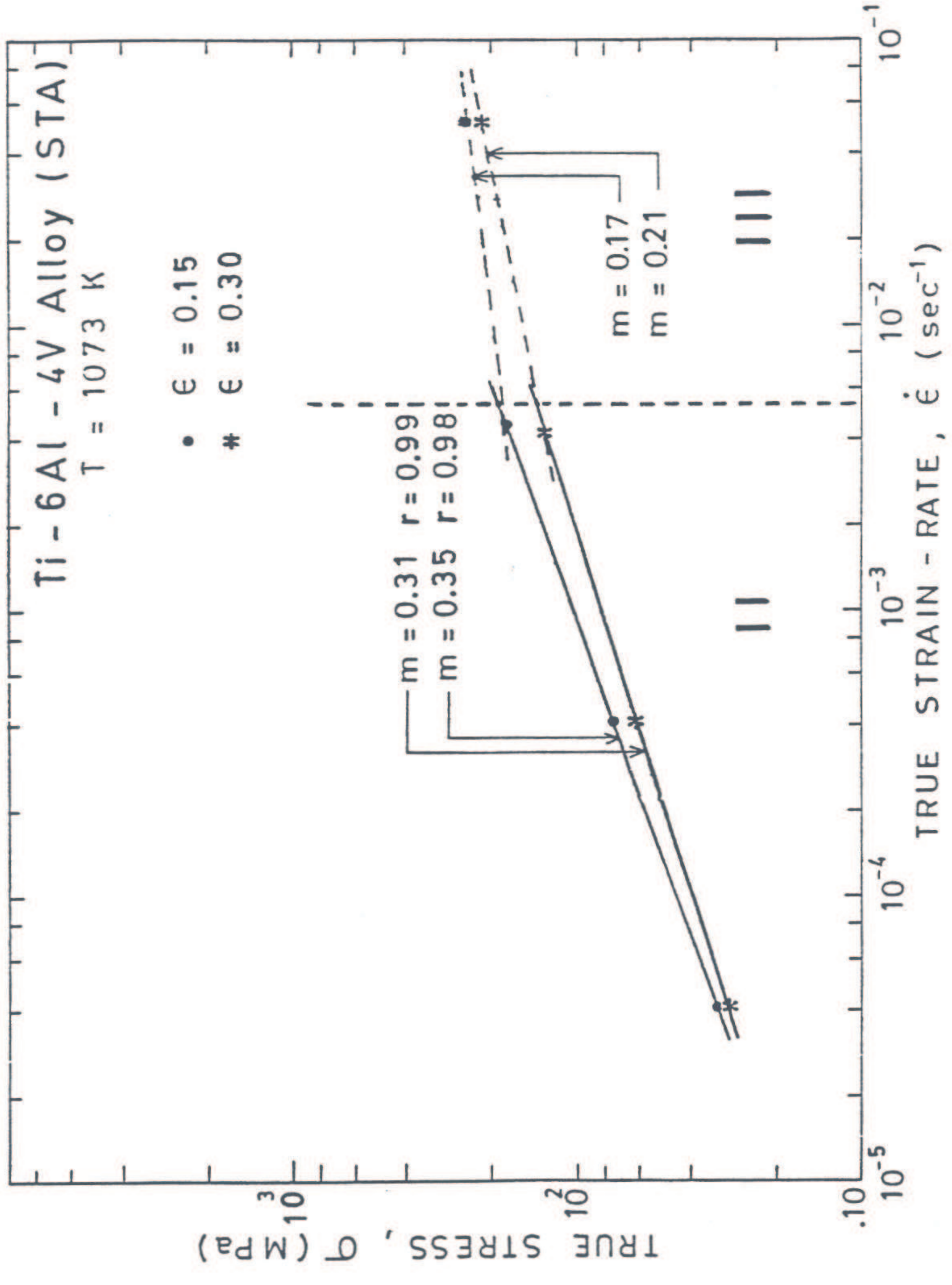
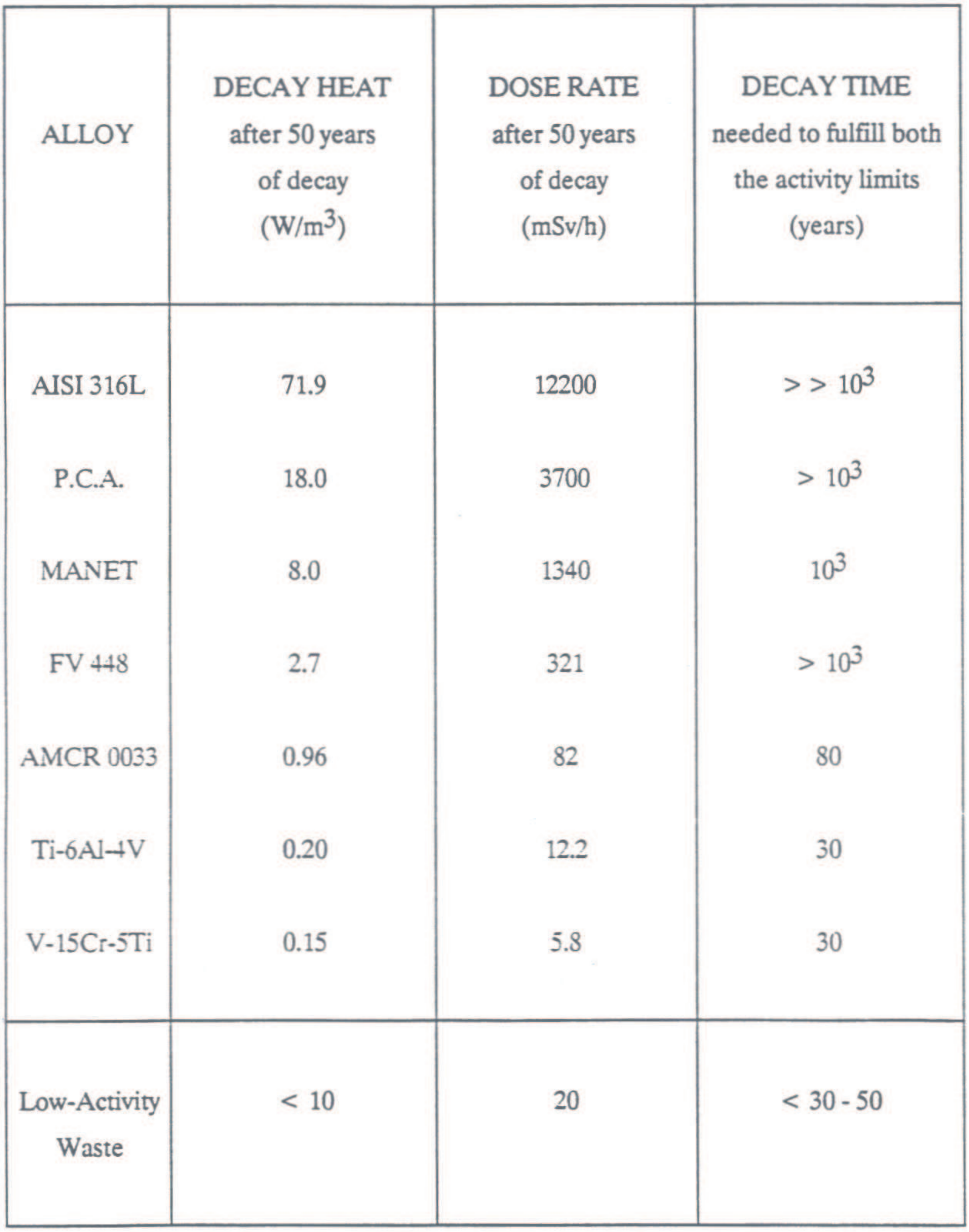


Fig. 5: Stress-strain diagram for the ti-6Al-4V alloy.

Table 1- Composition of some fusion reactor structural materials (mass%)

ELEM.	AISI316L	PCA	MANET	FV448	AMCR 0033	Ti6Al4V	V15Cr5Ti
Fe	bal.	bal.	bal.	bal.	bal.	0.25	--
C	0.024	0.05	0.12	0.15	0.1	0.08	--
Cr	17.44	14.0	10.3	11.3	10.12	--	15.0
Ni	12.32	12.2	0.60	0.75	0.1	--	--
Mn	1.81	1.8	1.15	0.8	17.5	--	--
S	0.002	0.009	0.005	0.01	0.008	--	--
P	0.027	0.027	0.005	0.01	0.016	--	--
Mo	2.5	0.05	0.65	0.66	0.06	--	--
Al	--	0.001	--	0.005	0.0025	6.0	--
Ti	--	0.24	--	--	--	bal.	5.0
Cu	0.2	--	0.02	0.01	0.06	--	--
V	--	0.04	0.20	0.25	0.02	4.0	bal.
Si	0.46	0.09	0.005	0.4	0.55	--	--
N	0.06	0.01	0.03	0.06	0.19	0.05	--
Sn	--	0.05	--	--	--	--	--
Nb	0.01	--	0.15	--	--	--	--
O	--	--	--	--	--	0.20	--
Co	0.17	--	0.02	--	--	--	--
W	--	--	--	0.02	--	--	--

Table 2 – Neutron induced radioactivity in first-wall alloys for fusion reactors.



ALLOY	DECAY HEAT after 50 years of decay (W/m^3)	DOSE RATE after 50 years of decay (mSv/h)	DECAY TIME needed to fulfill both the activity limits (years)
AISI 316L	71.9	12200	$>> 10^3$
P.C.A.	18.0	3700	$> 10^3$
MANET	8.0	1340	10^3
FV 448	2.7	321	$> 10^3$
AMCR 0033	0.96	82	80
Ti-6Al-4V	0.20	12.2	30
V-15Cr-5Ti	0.15	5.8	30
Low-Activity Waste	< 10	20	< 30 - 50

Table 3 – Tensile properties of Ti-6Al-4V Alloy

Temp.	Cross head velocity	Strain rate	Recristallized Annealed (RA)				Solution Treated + Aged (STA)			
			$S_{0.2}$	S_u	e_{pu}	e_{pb}	$S_{0.2}$	S_u	e_{pu}	e_{pb}
°C	cm/min	sec^{-1}	MPa	MPa	%	%	MPa	MPa	%	%
20	50	$4,2.10^{-1}$	981	1002	2.2	11.6	1248	1304	1.9	9.7
	0.5	$4,2.10^{-3}$	889	929	5.7	16.4	1126	1196	2.9	10.6
	0.005	$4,2.10^{-5}$	822	895	10.1	18.8	1107	1207	4.3	11.1
400	50	$4,2.10^{-1}$	542	619	11.5	20.7	773	883	4.4	12.8
	0.5	$4,2.10^{-3}$	458	581	15.8	23.0	687	886	5.2	15.6
	0.005	$4,2.10^{-5}$	467	633	16.7	24.4	706	913	5.7	17.8
800	50	$4,2.10^{-1}$	272	288	7.1	55.0	303	313	4.2	55.5
	0.5	$4,2.10^{-3}$	151	167	1.0	95.0	137	162	2.0	165
	0.005	$4,2.10^{-5}$	47	59	1.3	372	20	28	3.4	605

Table 4 – Ratio of STA-condition / RA-condition

Temp. °C	Cross head velocity (cm/min)	$s_{0.2}$	s_u	e_{pu}	e_{ph}
20	50	1.27	1.30	0.86	0.84
	0.5	1.27	1.29	0.51	0.65
	0.005	1.35	1.35	0.43	0.59
400	50	1.43	1.43	0.38	0.62
	0.5	1.50	1.52	0.33	0.68
	0.005	1.51	1.44	0.34	0.73
800	50	1.11	1.09	0.59	1.01
	0.5	0.91	0.97	2.00	1.74
	0.005	0.43	0.47	2.62	1.63

Table 5 – Strain-rate sensitivity (Properties normalised with respect to e' = $4,2\cdot10^{-1}$ s^{-1})

Temp. °C	Decrease of $\dot{e}$	Recristallised Annealed (RA)				Solution Treated, Aged (STA)			
		$S_{0.2}$	S_u	e_{pu}	e_{pb}	$S_{0.2}$	S_u	e_{pu}	e_{pb}
20	10^{-2}	0.91	0.93	2.59	1.41	0.90	0.92	1.53	1.09
	10^{-4}	0.84	0.89	4.59	1.62	0.89	0.93	2.26	1.14
400	10^{-2}	0.85	0.94	1.37	1.11	0.89	1.00	1.18	1.22
	10^{-4}	0.86	1.09	1.45	1.18	0.91	1.03	1.30	1.39
800	10^{-2}	0.56	0.58	0.14	1.73	0.45	0.52	0.48	2.97
	10^{-4}	0.17	0.20	0.18	6.76	0.07	0.09	0.81	10.9

Table 6 – Influence of temperature (Properties normalised with respect to T = 20°C)

Influence temper. at T (°C)	Cross head velocity	Strain rate $\dot{e}$	Recristallised Annealed (RA)				Solution Treated Aged (STA)			
	cm/min	sec^{-1}	$S_{0.2}$	S_u	e_{pu}	e_{pb}	$S_{0.2}$	S_u	e_{pu}	e_{pb}
400	50	$4,2.10^{-1}$	0.55	0.62	5.23	1.78	0.62	0.68	2.32	1.32
	0.5	$4,2.10^{-3}$	0.52	0.63	2.77	1.40	0.61	0.74	1.79	1.47
	0.005	$4,2.10^{-5}$	0.57	0.71	1.65	1.30	0.64	0.76	1.33	1.60
800	50	$4,2.10^{-1}$	0.28	0.29	3.23	4.74	0.24	0.24	2.21	5.72
	0.5	$4,2.10^{-3}$	0.17	0.18	0.18	5.79	0.12	0.14	0.69	15.57
	0.005	$4,2.10^{-5}$	0.06	0.07	0.13	19.79	0.02	0.02	0.79	54.5