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TREND IN PROCESSING, FABRICATION AND APPLICATION OF TITANIUM

1 - INTRODUCTION

Prior to discussion of the text of my presentation this morning, I would like to review the availability and properties of titanium (Fig. 1).

Titanium is not a rare element. In fact, you can see (Fig. 2) that titanium is the fourth most abundant metal in the earth's crust, following after aluminium, iron and magnesium.

Titanium is well dispersed throughout the earth and, as you can see in Fig. 3, there are workable deposits of titanium ore throughout the globe. Thus, it is not sensitive to geographical or political problems that may exist in the world.

Fig. 4 shows the growth of the titanium industry by markets in the United States from 1966 through 1985.

The free world consumption of titanium would be about twice the numbers you see here. As you see, the defence usage has been fairly constant over the period. Significant growth has occurred in the commercial aerospace and industrial markets since about 1976.

From Fig. 5 you can also see that the projected free world capacity exceeds the demand. This is further illustrated (Fig. 6) when one considers that only 5% of the TiO_2 consumption goes into metal production.

So we might ask, if titanium is so abundant, if it is so well dispersed, why is it not used more?

The growth of titanium has been restricted to a certain extent by the cost of the metal, cost of winning it from the ore. It is fairly expensive in terms of energy. However, there has been a gradual decrease in the amount of energy.
There has also been a rather large increase in the usage of titanium.

So it seem reasonable to expect that the driving force for changing trends in material use is to design around the key properties of titanium, improve the performance and operating costs, while at the same time, reducing the manufacturing costs.

The key properties (Fig. 7) of titanium are fairly well known. To review, they centre around two characteristics. First of all, corrosion resistance. Titanium has excellent corrosion resistance in all natural media, including chlorides and organics, very resistant to salt water and chloride solutions.

The second main characteristic is that it has a low density, about one-half that of iron and slightly higher than aluminium.

However the metal, as you can see, has high strength capabilities. So, when you combine the low density with high strength, you have a very efficient engineering material.

Another favourable characteristic of titanium includes its high temperature strength.

Other interesting properties that, on occasion, are very useful in design applications include:

- it has very good ballistic resistance;
- it has low thermal expansion, which is very similar to that of glass and composites, so it is very compatible with those materials;
- it has a low elastic modulus, which makes it a unique spring material, a very efficient spring material;
- it has, on the corrosion side, good heat transfer;
- it is very effective in heat exchangers.

Titanium also has some very unique electrochemical characteristics, and it also has a very short radioactive half-life, which can be useful in processing uranium and spent uranium. I will expand on some examples of these properties later in my presentation.

With this in mind, I would like to review the trends in processing, fabrication and applications. Since time does not permit me to cover all aspects, I will elaborate only on those areas of major activity in the USA during the past three years.

2 - PROCESSING TRENDS

Responding to the aerospace, chemical process and electronic industries needs for high-cleanliness, high purity titanium, nonconsumable, cold-hearth melting is receiving a lot of attention. The key is cold-hearth as opposed to drip-melting directly into a cold-wall mold.

Production of these high performance engineering materials requires highly controlled processing conditions. Both demands of high purity processing environment and high performance heating source can be met using:

- Electron Beam
- Plasma

melting conditions. These technologies are similar with regard to hearth melting.

Electron-beam melting (Fig. 8) is a vacuum process which utilizes the thermal energy of the electron beam for melting and refining operations. The heat in the prevailing vacuum environment permits distillation of volatile elements including vaporization of suboxides, evolution and removal of gases, and vaporization of metal impurities with vapour pressures above that of the titanium. Most notable in titanium is aluminium, since it is common to most alloy systems.

Alec Mitchell of the University of British Columbia is working on inline compositional analyses aimed at making compositional adjustments during the melting process. Using the principles of energy dispersion analysis (EDS), Mitchell has done pioneering work in this area. The x-rays that generate the information are excited by the very energetic beam which is used to heat the surface of the liquid metal. Fig. 9 is an installation and Fig. 10 is the molten pool and metal cascading over the hearth into the mold.

Plasma-melting can be performed with a cold-hearth as well, but in an inert gas atmosphere in the pressure range of 150 mbar and 2 bar. Hence, one does not get the ultimate refinement as with a vacuum system.

Electron-beam melting is the only process which simultaneously can take advantage of the cold-hearth effect and the refining effect of high and ultra-high vacuum.

Almost since its commercial inception, prompted by the development of the gas turbine in the mid-forties, titanium has been plagued by a defect (Fig. 11) known as:

Type 1
LDI - low density inclusion
Hard Alpha
IRI - Interstitially Rich Inclusion

This defect is characterized by high hardness and higher melting point, its composition is higher in nitrogen, may also be higher in oxygen, and is usually depleted in major alloying elements. Although it is denser (approximately 15%) than molten titanium, it derives its low density connotation from the fact that it is usually associated with a void. It acts as a crack initiator and results in a premature fatigue failure.

Although an additional CEVAM has greatly reduced the incidence, inspection techniques, namely ultrasonic, which has also improved in the level of detection over the period, still remains as the last chance of preventing a defect from getting into the field.

Hence, the interest in hearth-melting, since defects that are denser than the molten metal will sink to the bottom and become entrapped in the skull which lines the hearth.

The procedure for removal of these denser materials has been coined Defect-Free Titanium (DFT).

Commercially, hearth-melting is very attractive for consolidation of scrap that otherwise would not be suitable by CEVAM. In particular, small pieces and machining chips that are generated with carbide tooling.

CEVAM (Fig. 12 and Fig. 13) begins with the fabrication of electrodes (Fig. 14) made up of compressed sponge compacts containing the alloy additions. Chemically compatible scrap can become part of the electrode makeup, but they are rather large in size because they must be individually affixed to the electrode. Smaller pieces can be included in the compact, but such additions are limited by the compact strength. One can also add limited quantities during the melting process by means of a side-feeder.

With this type of scrap processed through a cold-hearth, any segment of the electrode cross-section can be cast as dictated by the mold-configuration. Hence, the attractiveness of a combined nonconsumable hearth and CEVAM ingot.

This is reflected in the increased titanium scrap consumption in ingot (Fig. 15) for the period 82-86.

Thus, one can take advantage of the refinement afforded through cold-hearth melting and satisfy most industry specifications with subsequent CEVAM melts since alloys shall be multiple melted under vacuum or inert gas with the last melting cycle under vacuum.

3 - FABRICATION TRENDS

In fabrication, I would like to discuss two areas, namely:

- Forging;
- Superplastic Forming and/or Diffusion Bonding.

Forging

I will discuss forging from two perspectives: 1) from what is happening in the USA; 2) this combined with forging of titanium.

Thus, all my remarks relate to trends in the USA forging industry as related to only titanium forgings. First I will discuss the most popular titanium alloys used by the U.S. forging industry; this will be followed by a brief description of several developmental alloys. Second, I will discuss developmental forging techniques related to attaining net shape and improved properties. Illustrations n. 16 and 17 contain information of general interest to forgers on current popular titanium alloys. Included is the transformation temperature, the forging range, the pressures required and the general cracking resistance.

The alloys are classified in three primary groups: the alpha, the alpha-beta and the new beta. As the beta increases the cracking resistance improves, the transformation temperature decreases, the forging temperature decreases, and the pressure required decreases. As a result I suppose it is not surprising that several near beta alloys have been used or considered for forging applications. These include: 10V 2Fe 3Al (10-2-3) transage alloys and the 38-6-44 or BetaC alloy. The importance of this newer materials will be evident shortly when we discuss the advances in the forging techniques (Fig. 18). Most of the conventional forging methods can be applied to titanium and the titanium alloys: forging, hammer forging, ring rolling, mechanical or screw press forging. Because of the influence of the die chilling on the deformation characteristics, properties, structure and surface cracking, the conventional forging process does have significant liabilities. This has led to appreciable interest in technologies utilizing hot dies which have an added benefit of achieving near or net shapes.

Let us now review two key differences in conventional, on the left, versus net shape forging, on the right. These are:

- Structure/Property
- Product Yield/Cost

Fig. 19 shows studies by Dr. Chen and compares the macrostructures of Ti-6242Si alloy pancake made by the different processes. As you can readily see, the macrostructure becomes increasingly uniform as we progress from conventional to warm die to isothermal forging.

Most commercial titanium alloys are forged near 1750° F (954° C). As a result, isothermal forging - meaning die temperatures near 1750° F (954° C) is extremely difficult since:

- Die materials like IN 100 are unrepairable
- Die heating systems are complicated
- Possibility of oxygen penetration into Ti

Hot die forging is conducted using normal metal temperatures 1750° F (954° C) and die temperature near 1400° F (750° C).

Advantages are:

- wrought alloy dies Astralloy, Waspalloy: lower cost and weldable
- die heating simpler
- can produce near net and net shape

The impact of this technology is not only in improved structure control, but in achieving shapes nearer the final configuration.

Figure 20 illustrates metal utilization for various forging processes for a typical titanium alloy such as Ti-6Al-4V.

Some examples of near and net shape forgings:

Figure 21: Ti-10-2-3 Near Net Instrument Housing

Figure 22: Ti-6Al-4V Near Net Disc

Net shape (Figure 23). In this example, a transage alloy pressure vessel dome was isothermally forged at 1500° F (800° C). Top surface with bosses was forged net. Machining was required only on the top of the bosses to get the desired flatness and inside the dome which was a simple turning operation.

A cost comparison (Figure 24) of several processes by Kuhlman of Alcoa shows the advantage of net shape forgings of beta-type alloys.

This analysis was done on an engine mount and is based upon production of 100 forgings. In summary, the machined part from plate is 10% greater than a close-die part. However, the net 10-2-3 is 40% less expensive.

As you can see, new developments are being driven by reduced cost through net shape forgings or improved performance through property optimization.

4 - SUPERPLASTIC FORMING/DIFFUSION BONDING

Since superplastic forming and/or diffusion bonding offers major savings in weight and manufacturing cost, there is increased interest in the feasibility of applying the techniques to the manufacture of a range of complex structural aerospace components.

Diffusion Bonding is sometimes called diffusion welding. It is a solid state welding process in which the surfaces are placed in proximity under a moderate pressure at elevated temperature. Coalescence occurs across the interface. Because diffusion bonding requires heat, pressure and a vacuum, inert gas or a reducing atmosphere, equipment is frequently custom built by the user.

Figure 25 is a wing carry through fabricated by diffusion bonding 533 individual details.
Superplastic forming of titanium plate and sheet was also developed as a reduced-cost method for processing of material.

From Figure 26, it can be seen that most of the titanium alloys can be formed superplastically. The M-value or strain rate sensitivity factor is a measure of superplasticity of the alloy at a given strain rate. Any value greater than 0.5 is considered a candidate for superplastic forming. In conjunction with typical SPF elongation, it can be seen that Ti-6Al-4V is the most desirable candidate. In Figure 27 one can see the influence of grain size on flow stress. RMI has a grain size of 5μm. At this grain size, one can see how the flow stress and M-factor are enhanced for superplastic forming. Figure 28 is the typical microstructure of RMI sheet. Note that the microstructures are similar before and after a simulated SPF cycle.

Figure 29 is an example of the superplastic forming process. These are examples of free blowing. That is, the final geometry is not restricted or controlled by dies.

For the sphere, clean and treated sheets are edge-welded to exclude air, but a pipe is attached for pressurization. After bringing the unit to temperature, gas pressure, usually argon, is applied until the desired shape has been achieved.

A combination of superplastic forming and diffusion (SPF/DB) is being used on titanium to produce complex structures. Figure 30 is an example of the process. The sheets are prepared as with SPF, except they are treated with stop offs where bonding is not desired. Initial bonding occurs under pressure at temperature and then internal pressure, through the pipe, causes superplastic flow of the outer two sheets to fill the die and create the configuration shown.

Integrally stiffened structures are produced in this manner.

Following are examples (Figures 31, 32 and 33) of some superplastically formed parts. Note the generally smaller bend radii, deeper drawability and larger size that can be achieved as compared to standard hot-formed (Figure 34) parts.

One U.S. aerospace company is superplastically forming a part that previously consisted of seven individually hot formed parts that were joined by conventional means, one can really see the attractiveness of these fabrication methods for producing hardware.

Spurred by the aerospace industry’s use of titanium discovery of titanium’s excellent corrosion performance opened up a host of unique applications for design engineering in the early 1960’s. Titanium corrosion resistance in neutral to oxidizing environments is mainly due to a surface oxide layer. Engineers in the chemical process industries, quick to exploit this characteristic, were the first to apply titanium. At the same time titanium unique electrochemical characteristics revolutionized the chloro-alkali industry through the use of precious metal coated titanium anodes. From these first two industrial markets, titanium has expanded its non-aerospace presence into more than 25 distinct market segments.
Figure 35 is the distribution and growth of those markets.

Its weaknesses include poor corrosion resistance to reducing acids, red fuming, nitric acids and hot organic acids. If we look at the general properties of titanium there are a few observations that need to be made (Fig. 36). As one moves towards the alpha alloys there is improved corrosion to oxidizing environments at low to moderate strength levels. As one moves to the beta alloys there is improved corrosion resistance to reducing environments at higher strength levels.

Alloyed versions including small amounts of palladium and molybdenum increase the titanium resistance to reducing acids. Additions of aluminum and vanadium increase the strength and slightly reduce the range in the oxidizing region. But note the beta alloy, the Beta C (Fig. 37), with the high attainable strength up to 315° C and the range in both the oxidizing and reducing sides. In the search for alternate energy sources, it is not surprising that this alloy is rapidly gaining acceptance in geothermal and sour gas wells.

5 - GEOTHERMAL

In geothermal, energy is extracted from the earth in the form of high temperature hypersaline brines. Some of these brines also contain H_2S and CO_2 at temperature ranges of 450° - 600° F (232° - 315° C). These brines impose severe restrictions on metals with limited corrosion resistance. In addition, high strength and heat treatability are required due to the large piping employed. In fact, beta titanium may be the only economical way to produce energy using geothermal technology. Figure 38 is an example of geothermal applications.

6 - SOUR GAS

Fossil fuel shortages have forced the oil and gas industries to produce more corrosive deposits. These deposits typically contain hydrogen sulphide (hence the term “sour”), pose an exceptional challenge to the materials engineer.

Figure 39 shows the Beta C^{TM} advantages in the oil field market. These include high strength, corrosion resistance and low density, which are all necessary for successful usage. In addition, the low elastic modulus makes it nearly perfect for

Figure 40, one can see the uses of Beta C^{TM} for down-hole applications.

Figure 41 and 42 are some of the casings and strings being used in these installations. From their size and quantity, it is easy to see the tremendous usage potential in these markets.

In summary, titanium usage will continue to grow based upon its unique combination of properties aided by improved performance and reduced total cost of the entire system.

Fig. 1 - Titanium properties

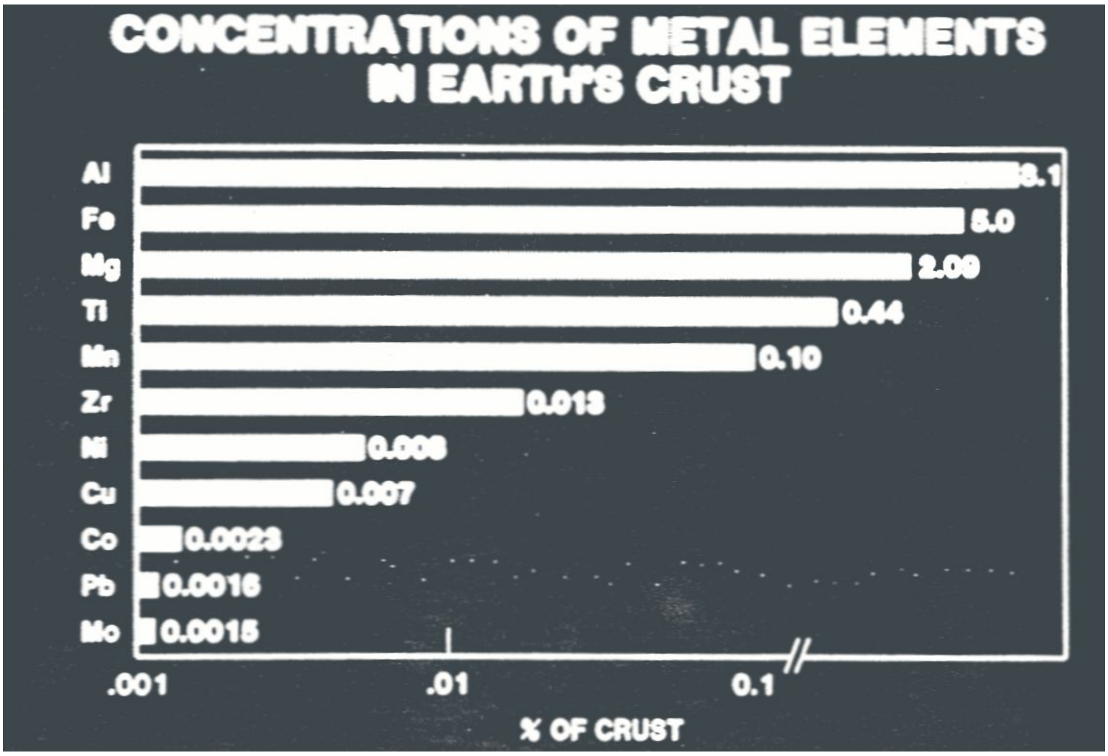


Fig. 2 - Relative abundance of materials in the heth’s crust

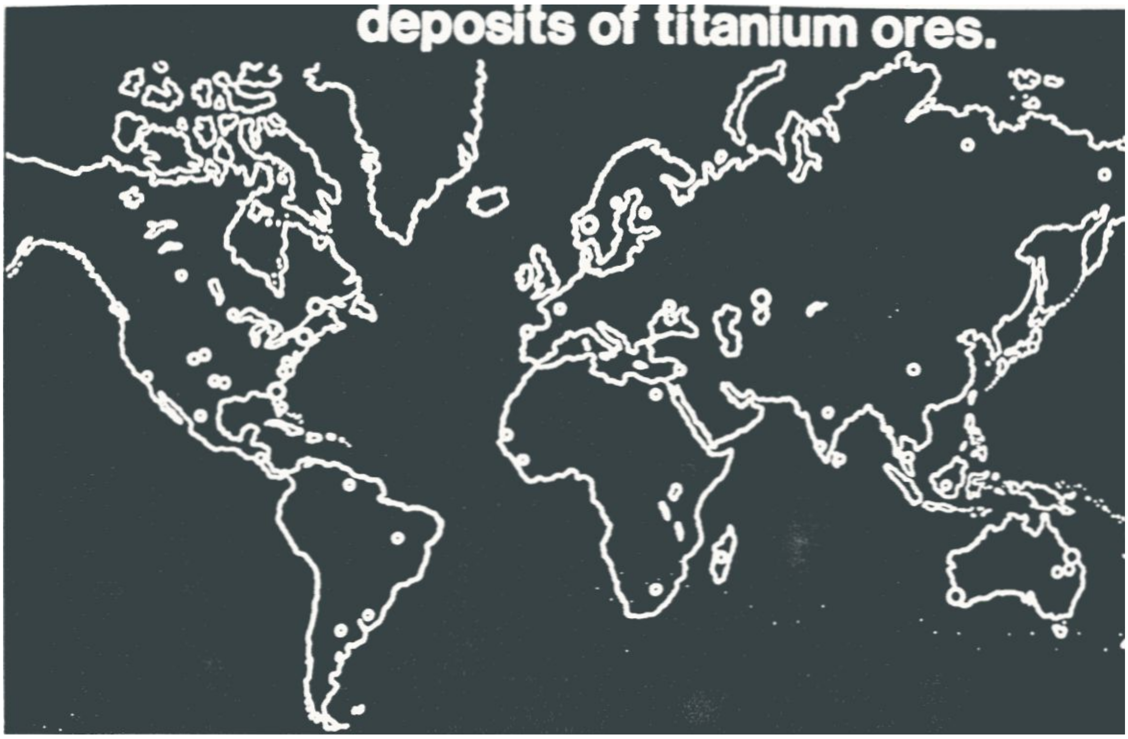


Fig. 3 - Deposits of Titanium ores throughout the globe

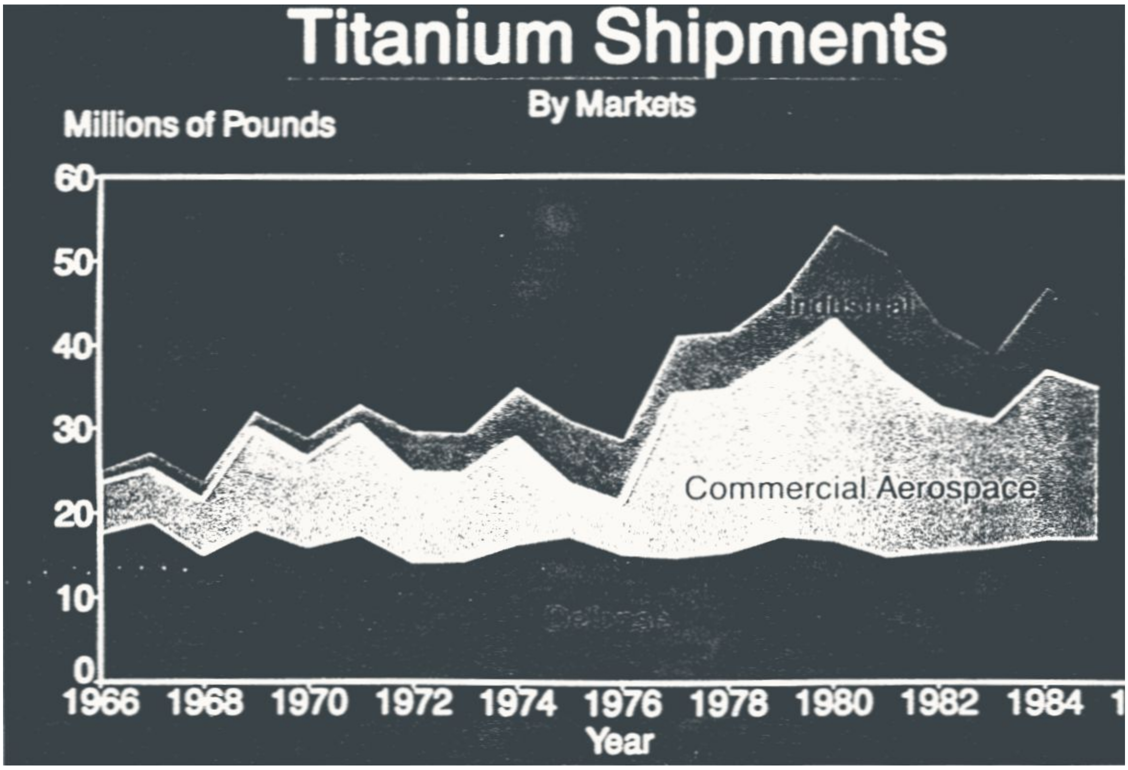


Fig. 4 - Growth of the titanium industry by markets in the U.S. from 1966 through 1985

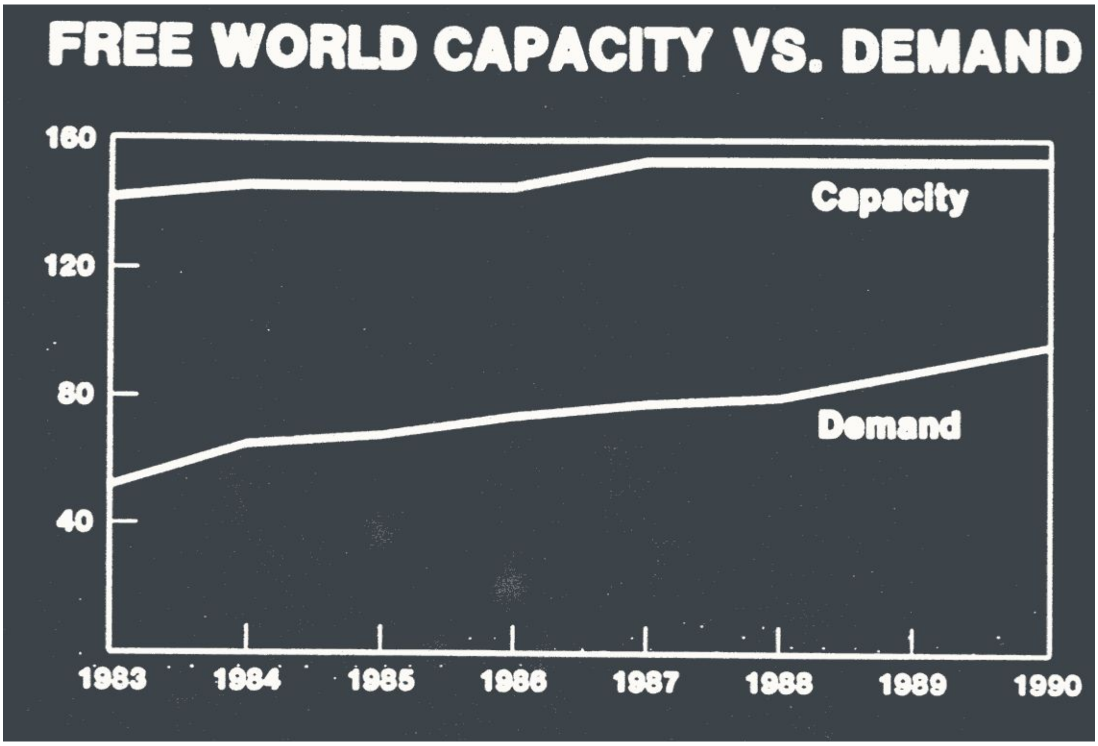


Fig. 5 - Projected free world capacity and demand

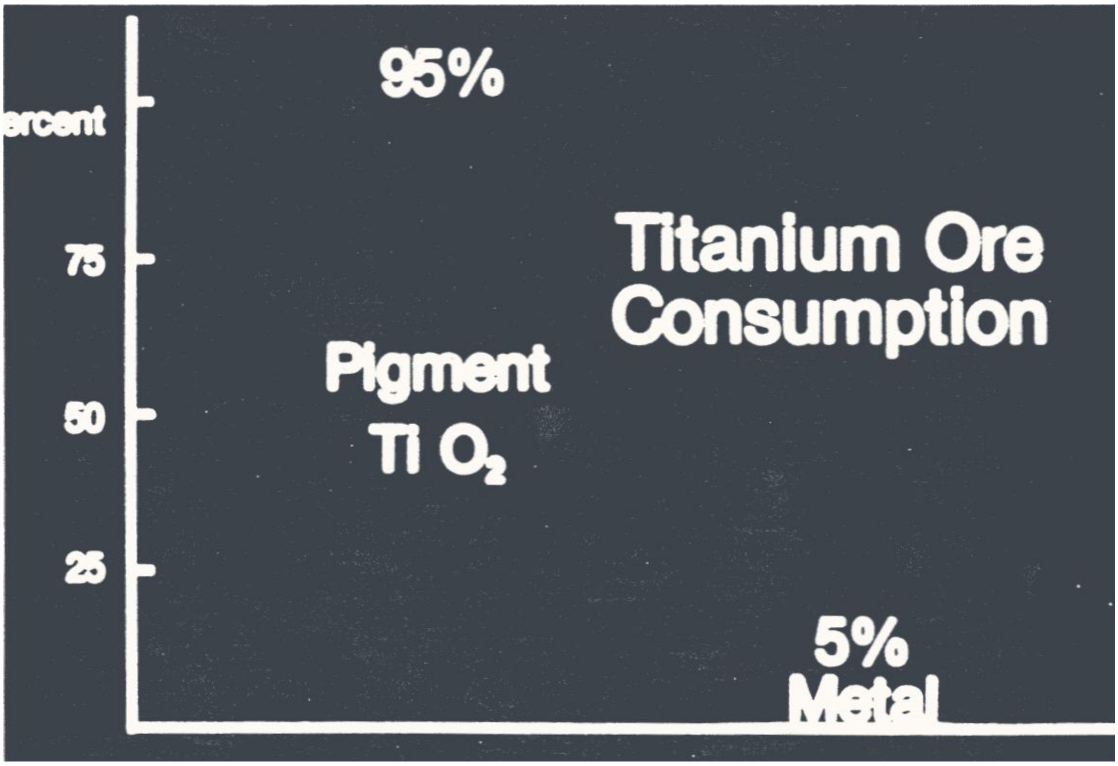


Fig. 6 - Titanium ore consumption

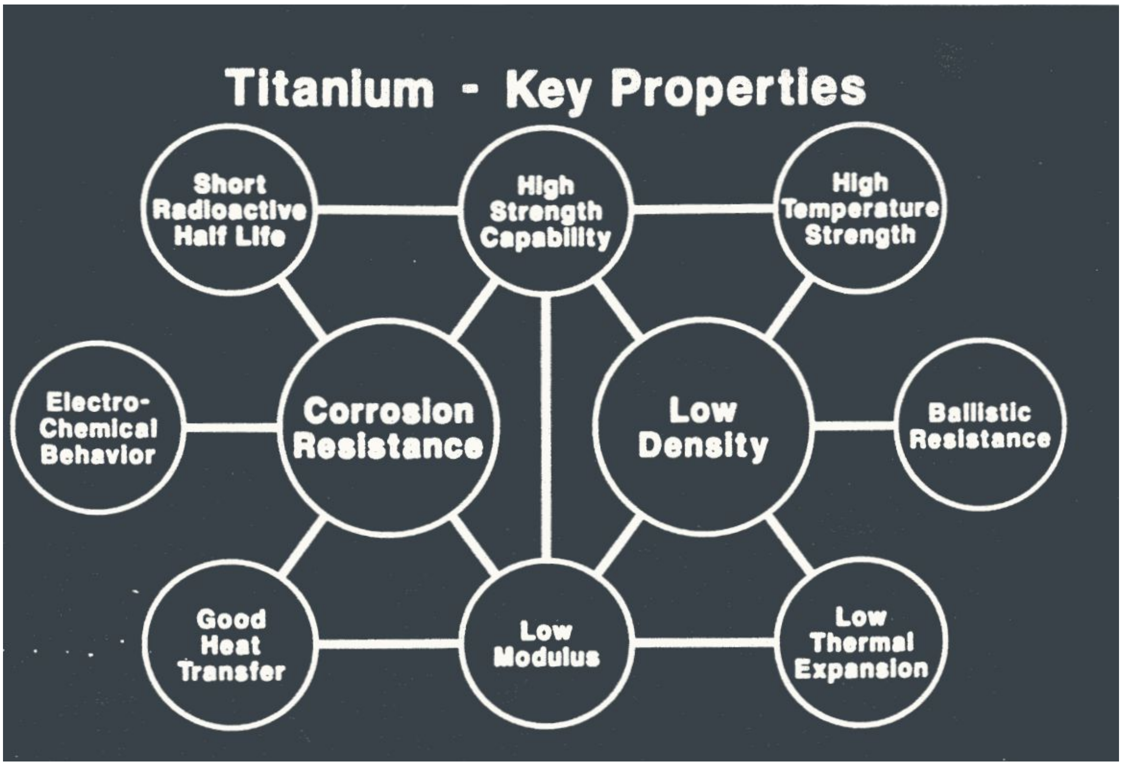


Fig. 7 - Titanium key properties

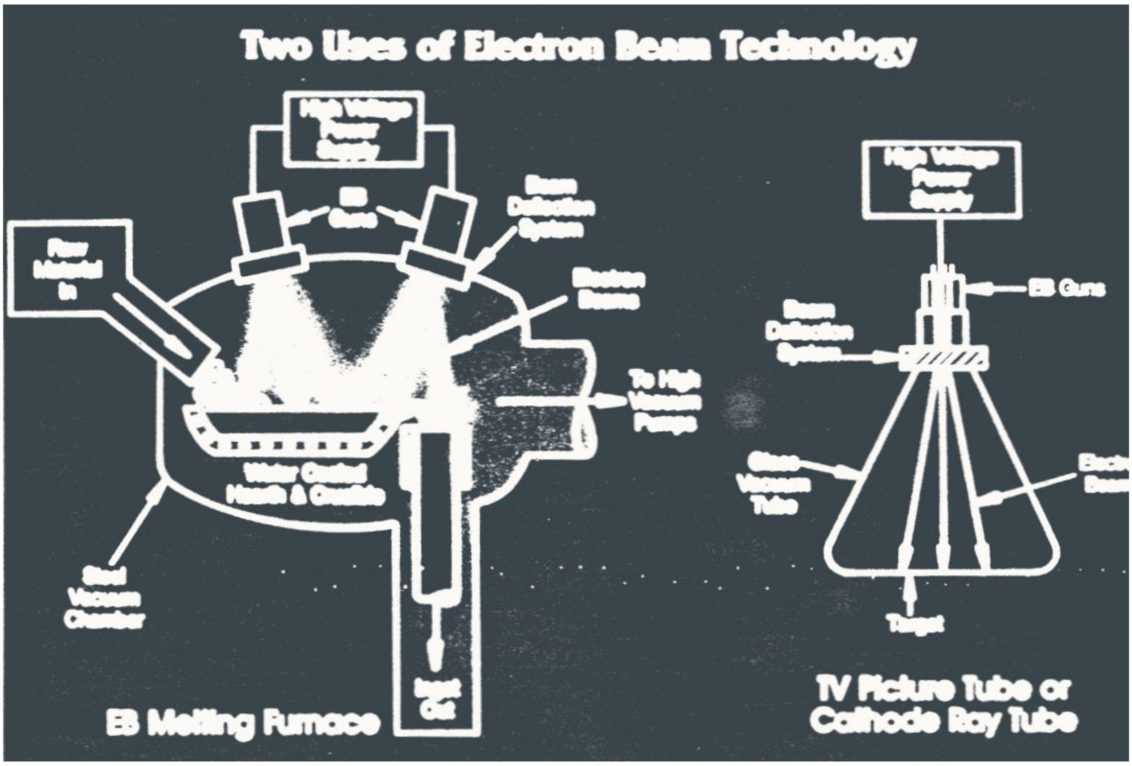


Fig. 8 - Electron beam processes

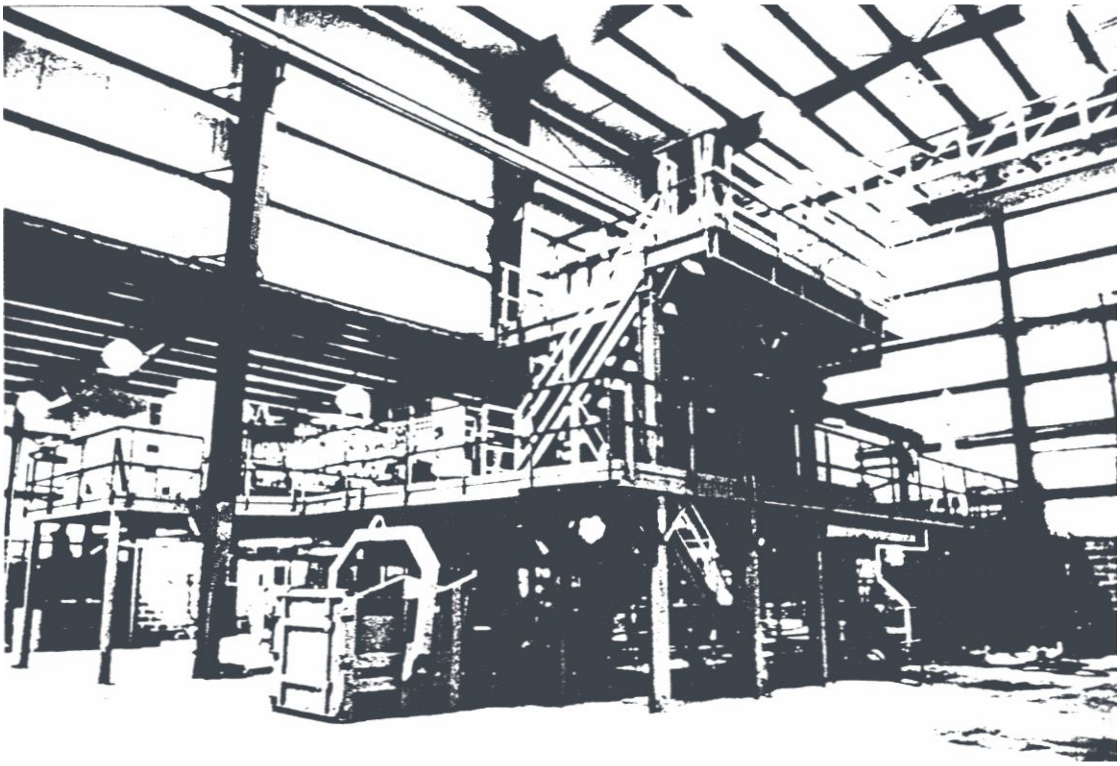
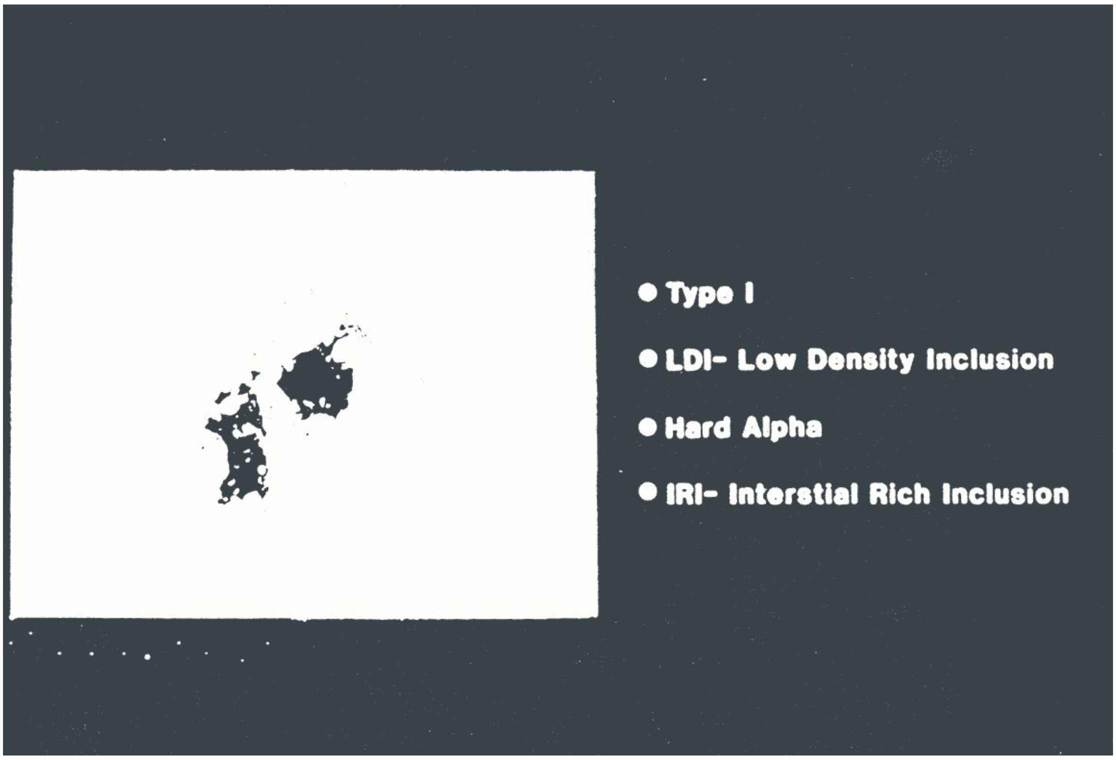


Fig. 9 - Electron beam installation

Fig. 10 - Molten metal flow in the electron beam cold earth



- Type I
- LDI- Low Density Inclusion
- Hard Alpha
- IRI- Interstial Rich Inclusion

Fig. 11 - Type I defect in titanium

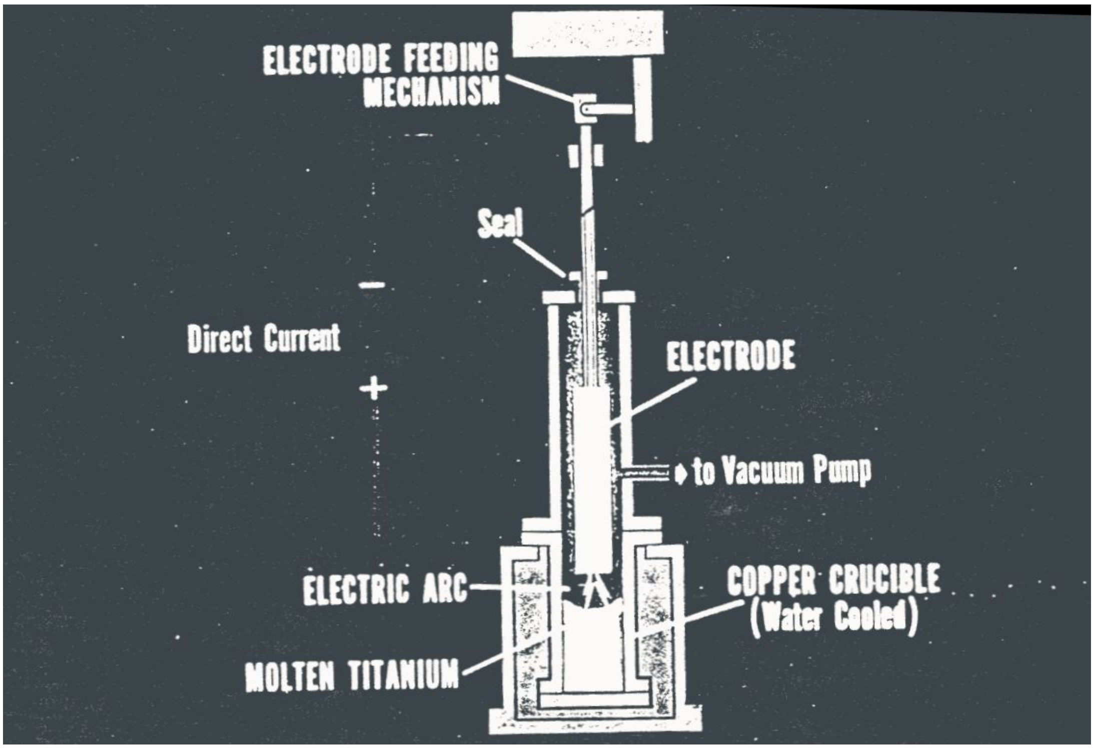


Fig. 12 - Consumable electrode vacuum arc melting (CEVAM) furnace diagram

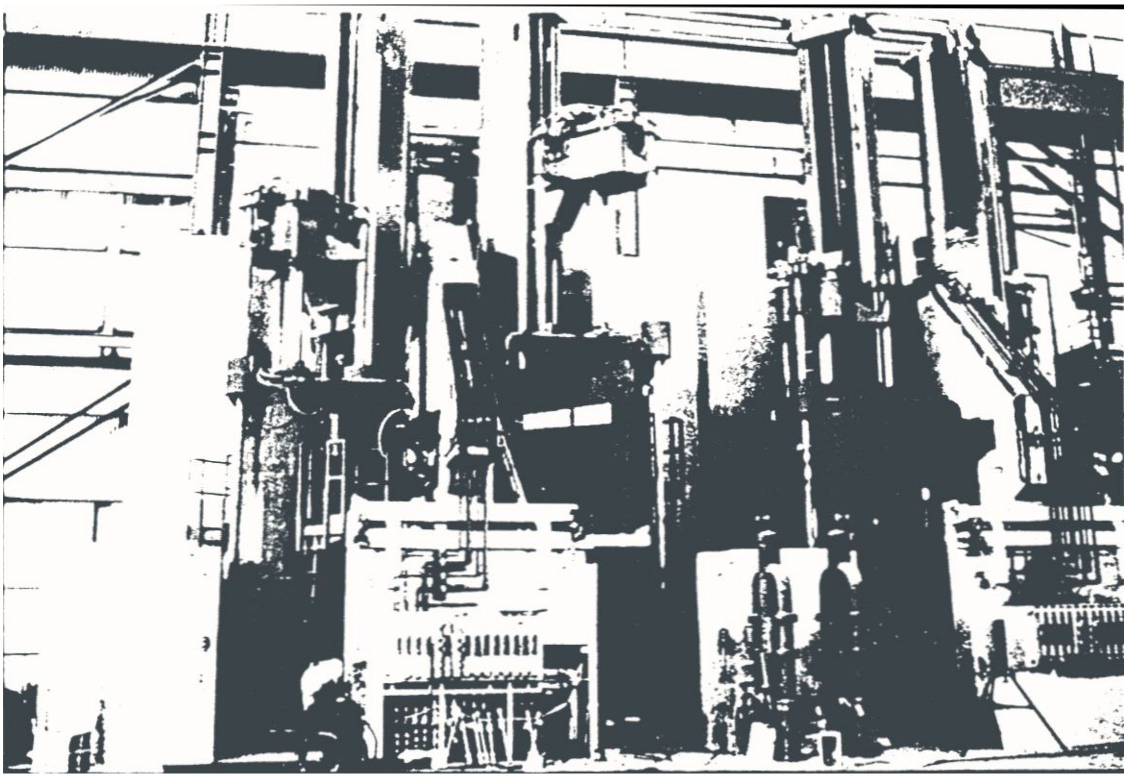


Fig. 13 - CEVAM furnace at RMI

Fig. 14 - Compressed sponge electrodes

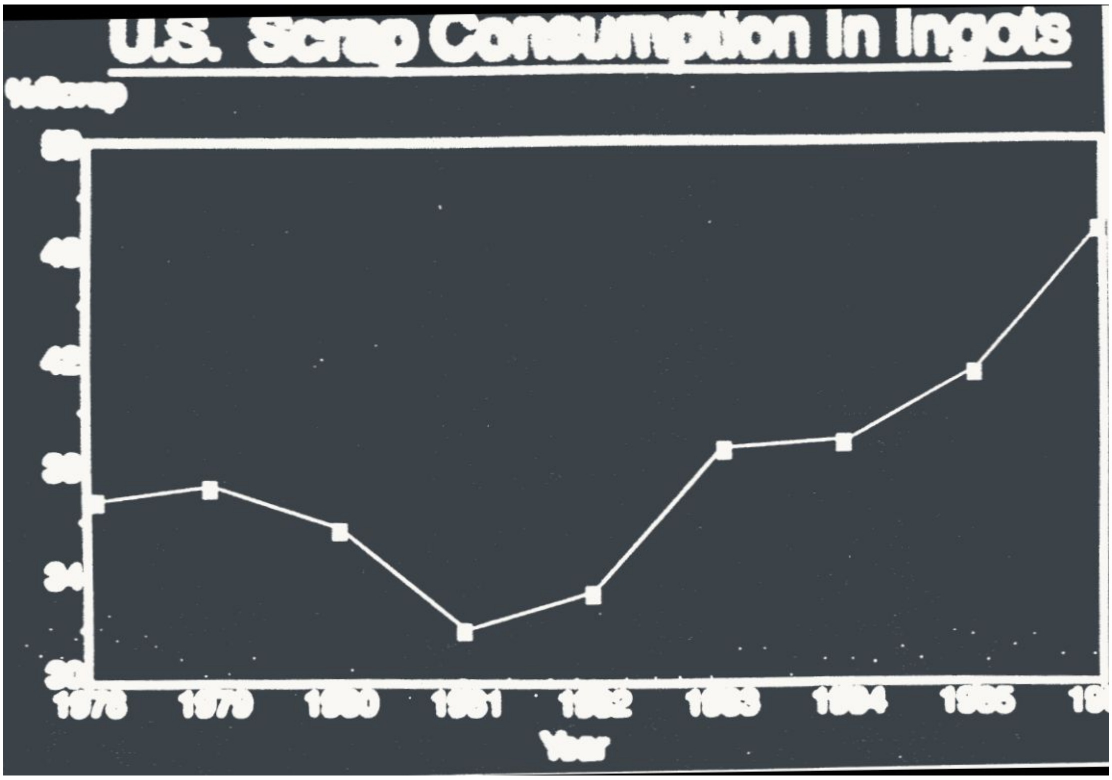
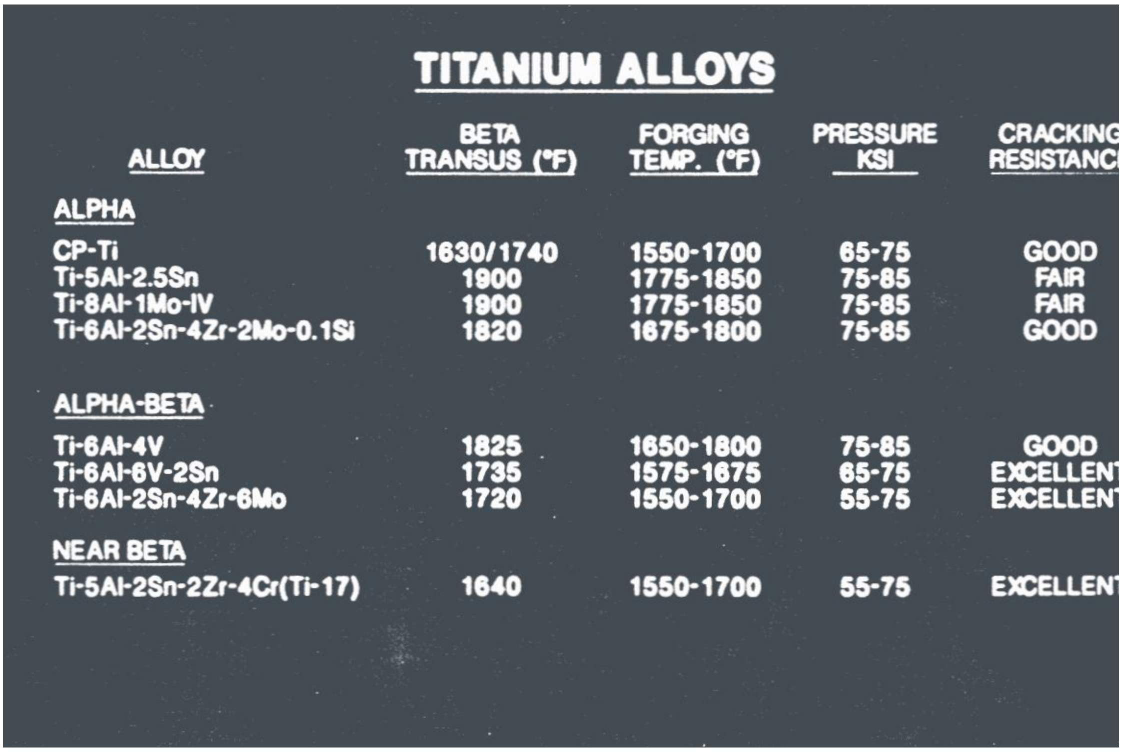


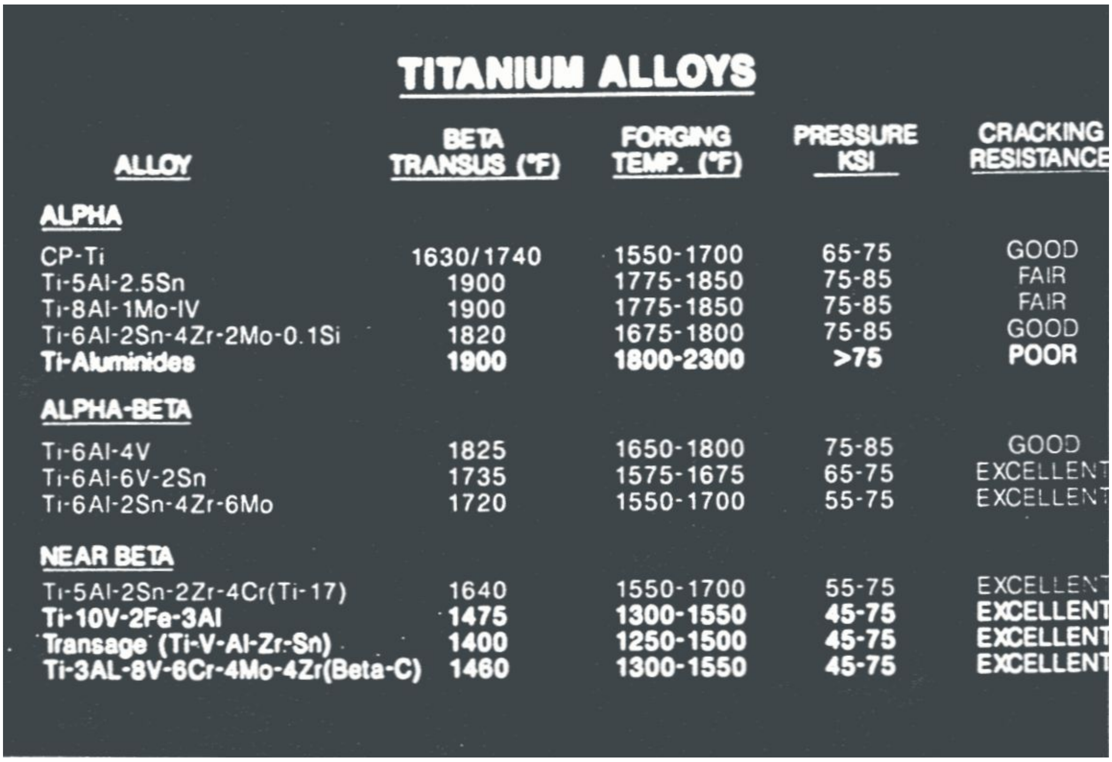
Fig. 15 - U.S. scrap consumption trend



TITANIUM ALLOYS

ALLOY	BETA TRANSUS (°F)	FORGING TEMP. (°F)	PRESSURE KSI	CRACKING RESISTANC
ALPHA				
CP-Ti	1630/1740	1550-1700	65-75	GOOD
Ti-5Al-2.5Sn	1900	1775-1850	75-85	FAIR
Ti-8Al-1Mo-IV	1900	1775-1850	75-85	FAIR
Ti-6Al-2Sn-4Zr-2Mo-0.1Si	1820	1675-1800	75-85	GOOD
ALPHA-BETA				
Ti-6Al-4V	1825	1650-1800	75-85	GOOD
Ti-6Al-6V-2Sn	1735	1575-1675	65-75	EXCELLEN
Ti-6Al-2Sn-4Zr-6Mo	1720	1550-1700	55-75	EXCELLEN
NEAR BETA				
Ti-5Al-2Sn-2Zr-4Cr(Ti-17)	1640	1550-1700	55-75	EXCELLEN

Fig. 16 - Forging for titanium alloys



TITANIUM ALLOYS

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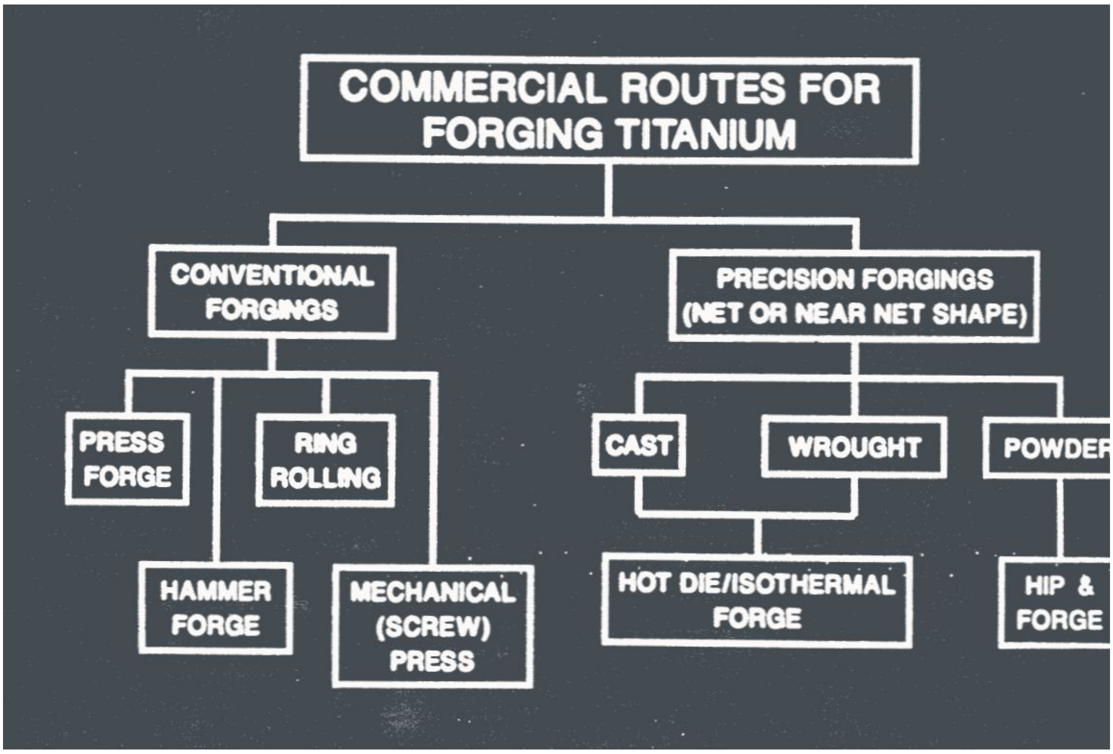
ALPHA				
CP-Ti	1630/1740	1550-1700	65-75	GOOD
Ti-5Al-2.5Sn	1900	1775-1850	75-85	FAIR
Ti-8Al-1Mo-IV	1900	1775-1850	75-85	FAIR
Ti-6Al-2Sn-4Zr-2Mo-0.1Si	1820	1675-1800	75-85	GOOD
Ti-Aluminides	**1900**	**1800-2300**	**>75**	**POOR**
ALPHA-BETA				
Ti-6Al-4V	1825	1650-1800	75-85	GOOD
Ti-6Al-6V-2Sn	1735	1575-1675	65-75	EXCELLENT
Ti-6Al-2Sn-4Zr-6Mo	1720	1550-1700	55-75	EXCELLENT
NEAR BETA				
Ti-5Al-2Sn-2Zr-4Cr(Ti-17)	1640	1550-1700	55-75	EXCELLENT
Ti-10V-2Fe-3Al	**1475**	**1300-1550**	**45-75**	**EXCELLENT**
Transage (Ti-V-Al-Zr-Sn)	**1400**	**1250-1500**	**45-75**	**EXCELLENT**
Ti-3AL-8V-6Cr-4Mo-4Zr(Beta-C)	**1460**	**1300-1550**	**45-75**	**EXCELLENT**

Fig. 17 - Forging conditions for titanium alloys



COMMERCIAL ROUTES FOR FORGING TITANIUM

CONVENTIONAL FORGINGS

PRESS FORGE

RING ROLLING

HAMMER FORGE

MECHANICAL (SCREW) PRESS

PRECISION FORGINGS (NET OR NEAR NET SHAPE)

CAST

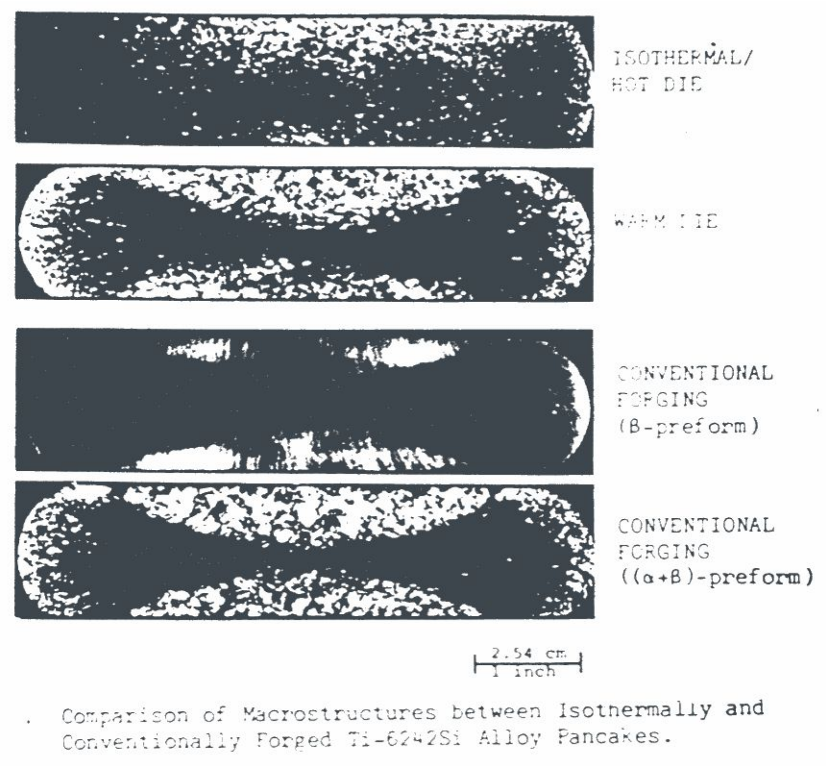
WROUGHT

POWDER

HOT DIE/ISOTHERMAL FORGE

HIP & FORGE

Fig. 18 - Commercial techniques for forging titanium



. Comparison of Macrostructures between Isothermally and Conventionally Forged Ti-6242Si Alloy Pancakes.

Fig. 19 - Macrostructure comparison in different Ti-6242Si forgings

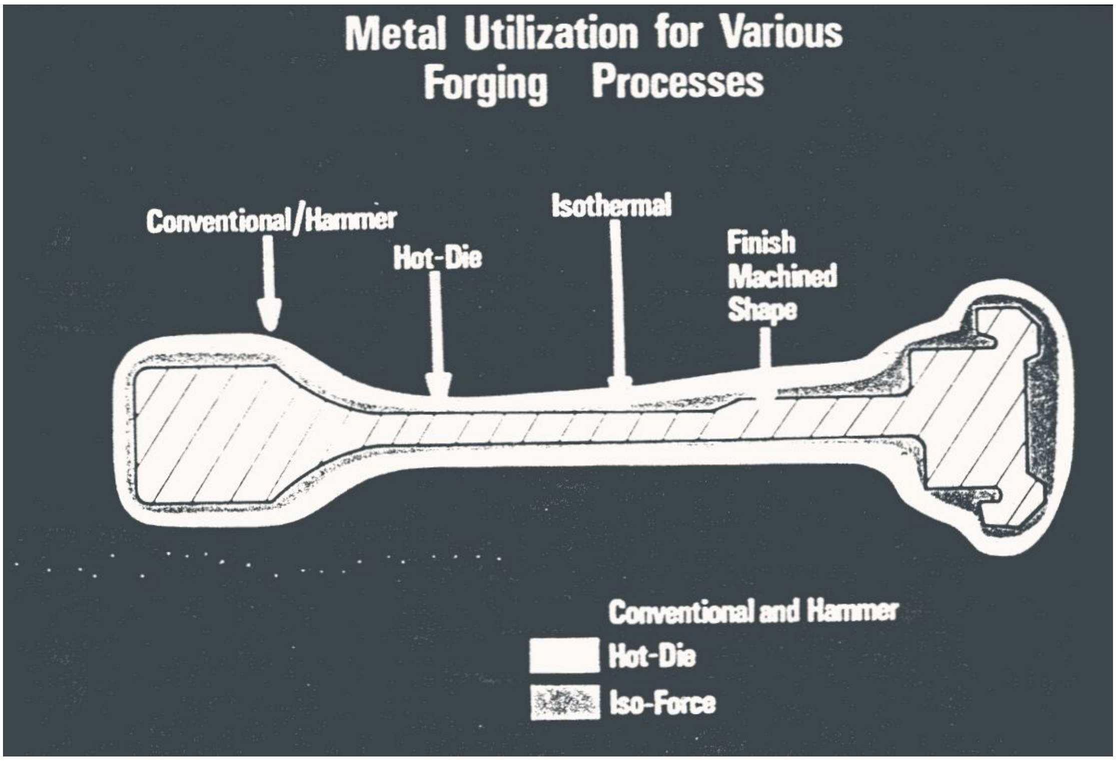


Fig. 20 - Metal utilisation for various forging processes

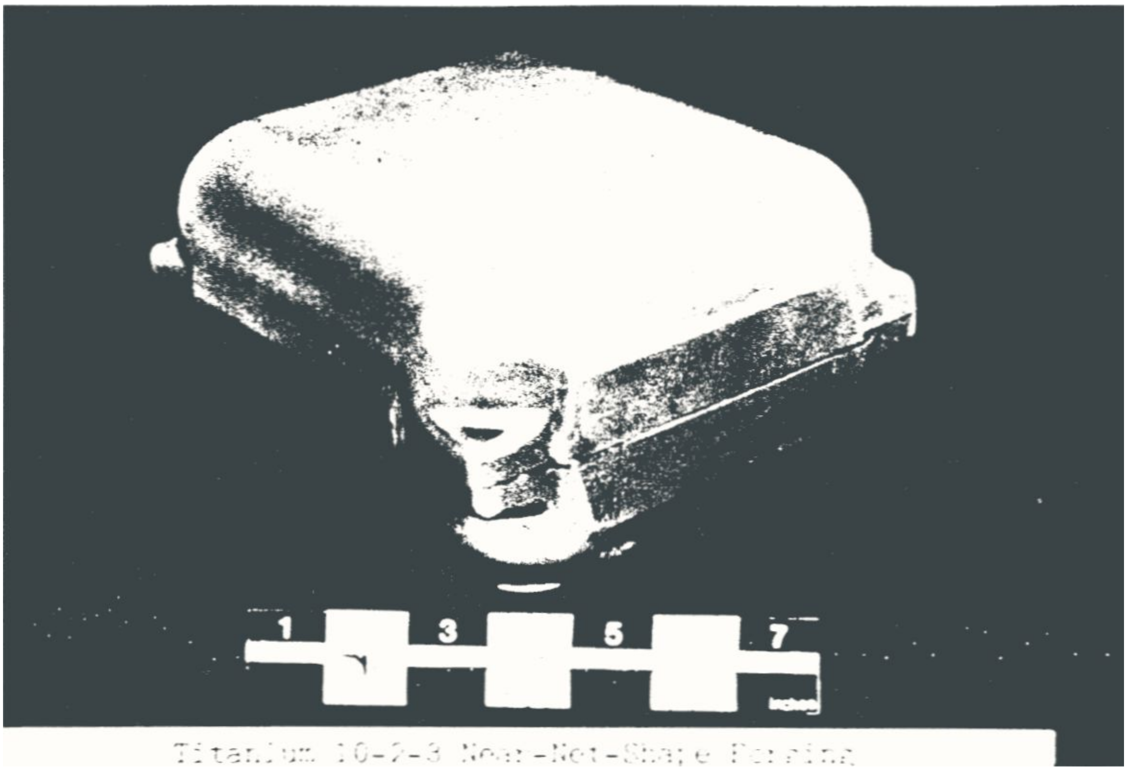


Fig. 21 - 10-2-3 near net shape instrument housing

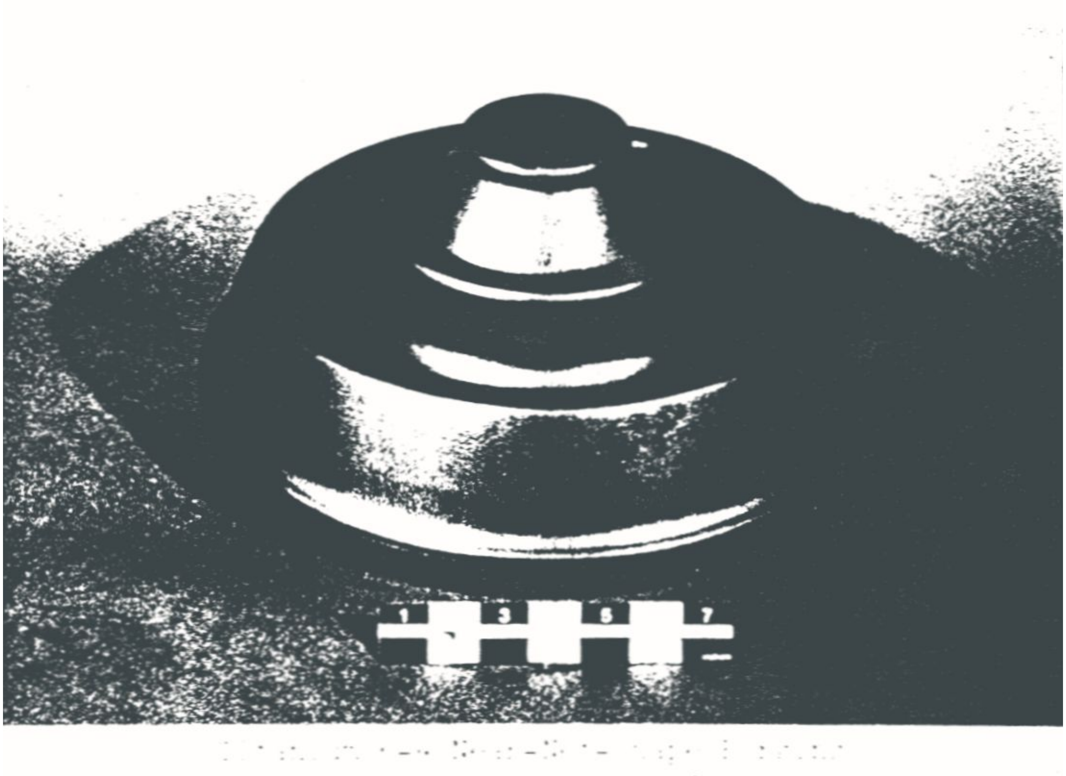
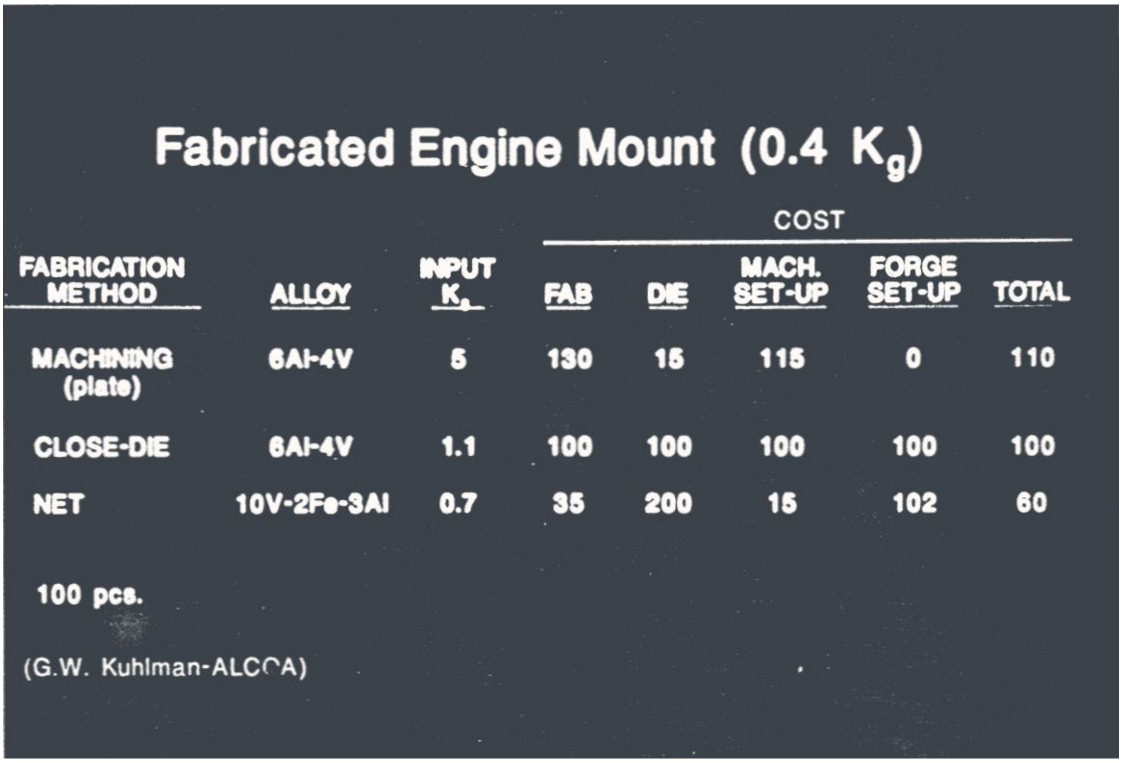


Fig. 22 - Near net shape disc

Fig. 23 - Transage alloy isothermal forging



Fabricated Engine Mount (0.4 K_g)

FABRICATION METHOD	ALLOY	INPUT K_g	COST FAB	DIE	MACH. SET-UP	FORGE SET-UP	TOTAL
MACHINING (plate)	6Al-4V	5	130	15	115	0	110
CLOSE-DIE	6Al-4V	1.1	100	100	100	100	100
NET	10V-2Fe-3Al	0.7	35	200	15	102	60

100 pcs.

(G.W. Kuhlman-ALCOA)

Fig. 24 - Cost comparison in various fabrication methods

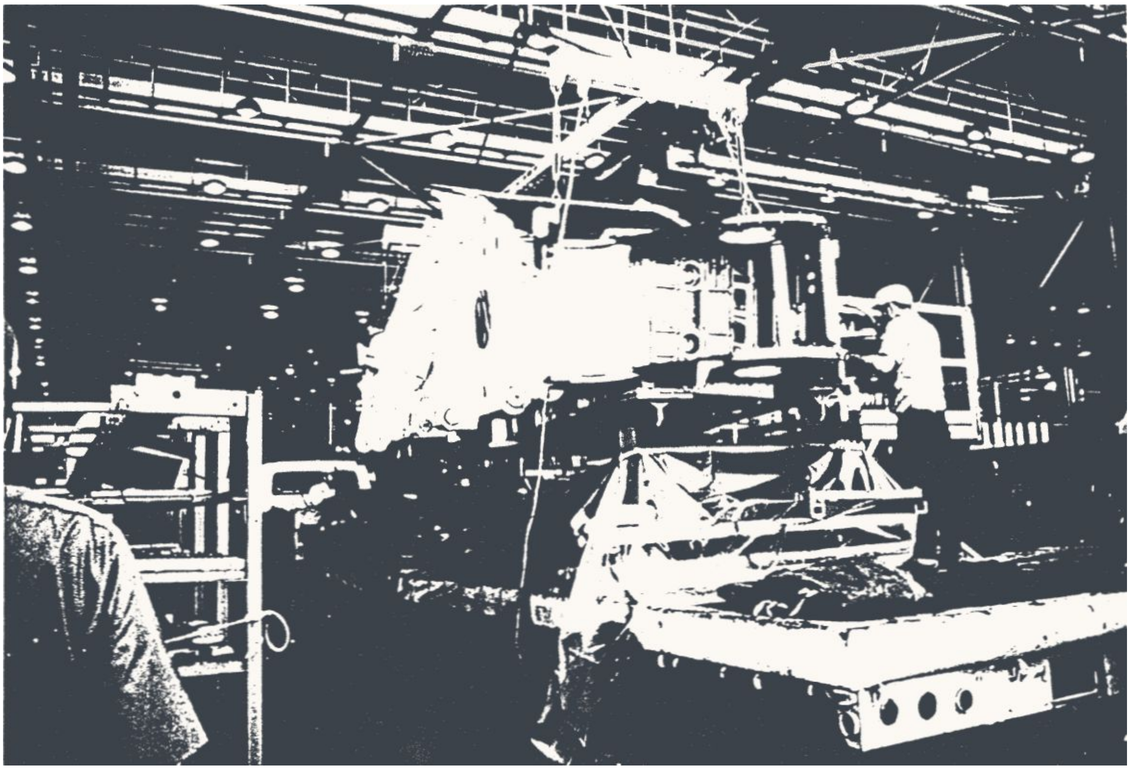
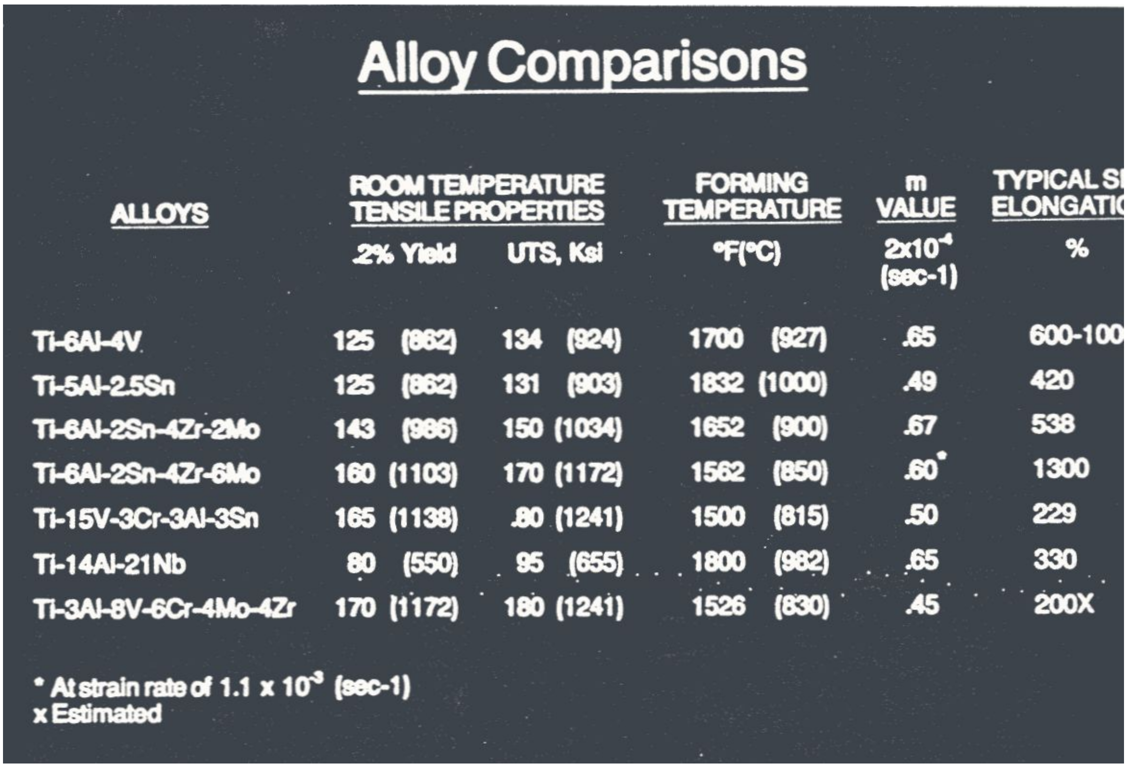


Fig. 25 - Wing carry through structure fabricated by diffusion bonding

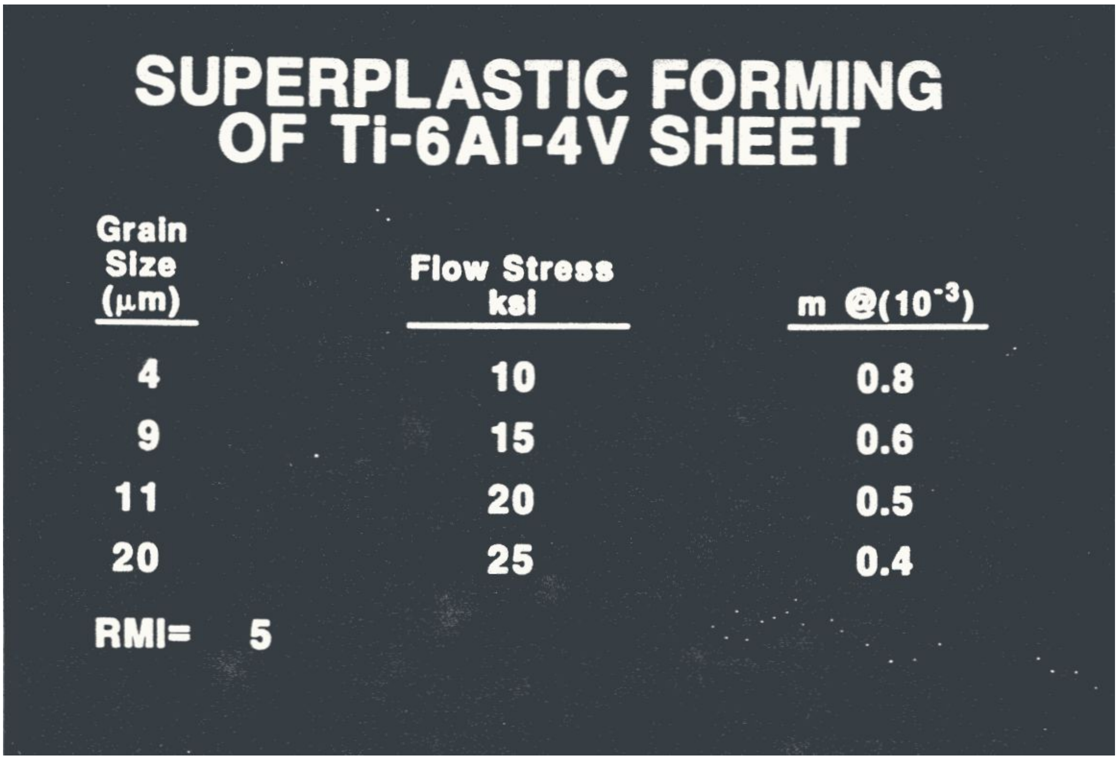


Alloy Comparisons

ALLOYS	ROOM TEMPERATURE TENSILE PROPERTIES		FORMING TEMPERATURE	m VALUE	TYPICAL S ELONGATI
	.2% Yield	UTS, Ksi	°F(°C)	$2x10^{-4}$ (sec-1)	%
Ti-6Al-4V	125 (862)	134 (924)	1700 (927)	.65	600-100
Ti-5Al-2.5Sn	125 (862)	131 (903)	1832 (1000)	.49	420
Ti-6Al-2Sn-4Zr-2Mo	143 (986)	150 (1034)	1652 (900)	.67	538
Ti-6Al-2Sn-4Zr-6Mo	160 (1103)	170 (1172)	1562 (850)	.60*	1300
Ti-15V-3Cr-3Al-3Sn	165 (1138)	.80 (1241)	1500 (815)	.50	229
Ti-14Al-21Nb	80 (550)	95 (655)	1800 (982)	.65	330
Ti-3Al-8V-6Cr-4Mo-4Zr	170 (1172)	180 (1241)	1526 (830)	.45	200X

* At strain rate of 1.1×10^{-3} (sec-1)
x Estimated

Fig. 26 - SPF characteristics for various Ti alloys



SUPERPLASTIC FORMING OF Ti-6Al-4V SHEET

Grain Size (μm)	Flow Stress ksi	m @(10^{-3})
4	10	0.8
9	15	0.6
11	20	0.5
20	25	0.4

RMI= 5

Fig. 27 - Influence of grain size on flow stress

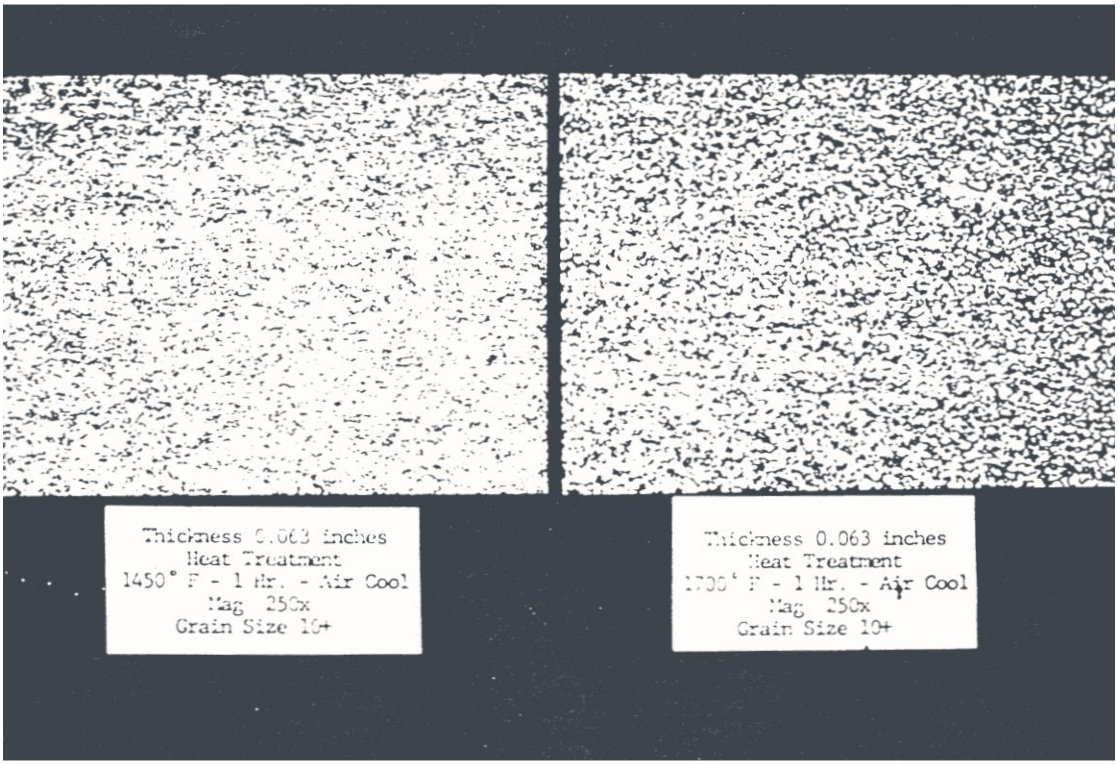


Fig. 28 - Typical microstructure of RMI sheet

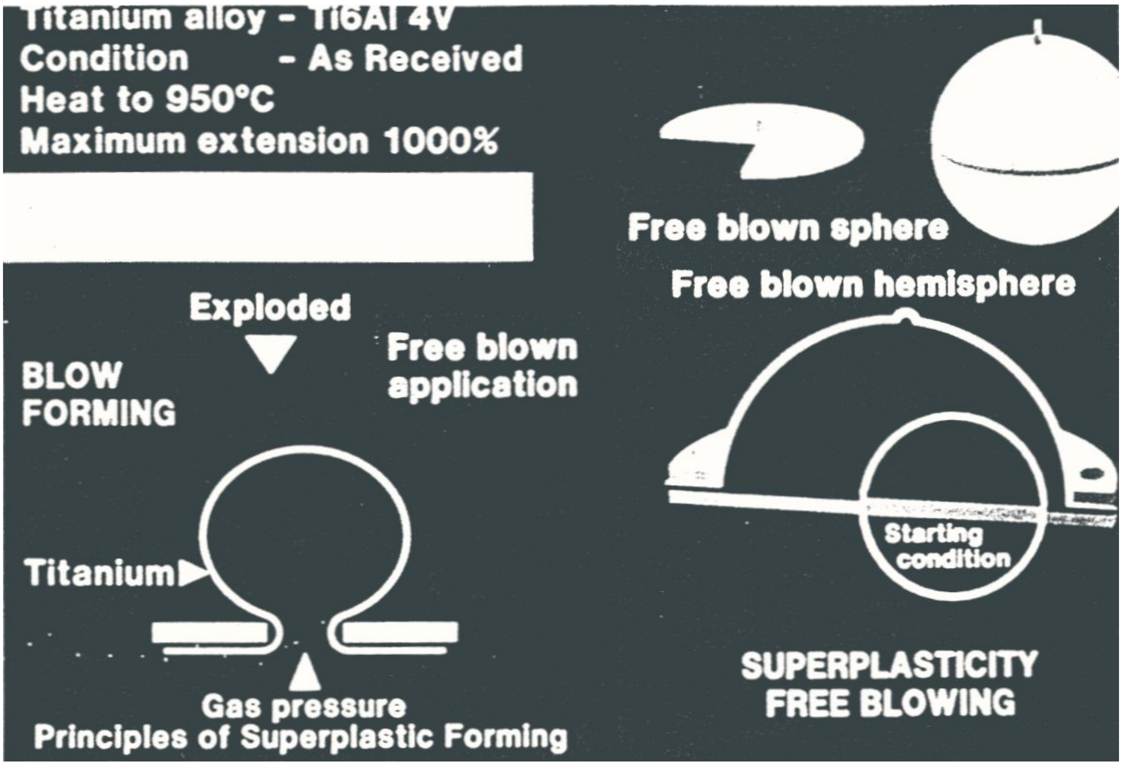


Fig. 29 - Examples of SPF processes

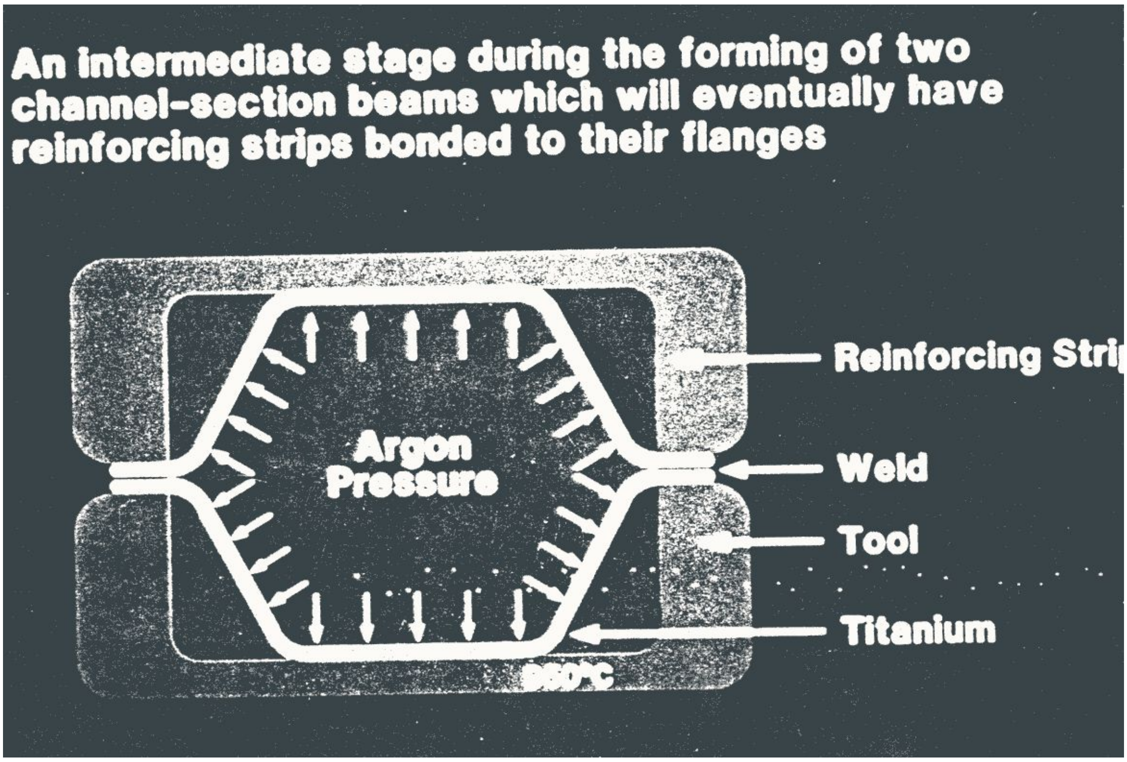


Fig. 30 - A SPF/DB process example

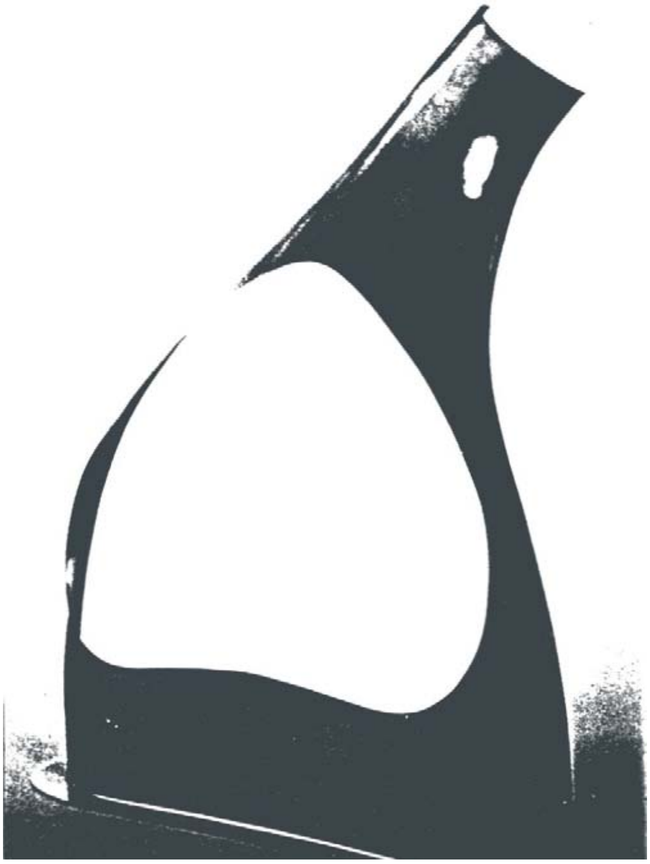


Fig. 31 - SPF part

Fig. 32 - SPF part

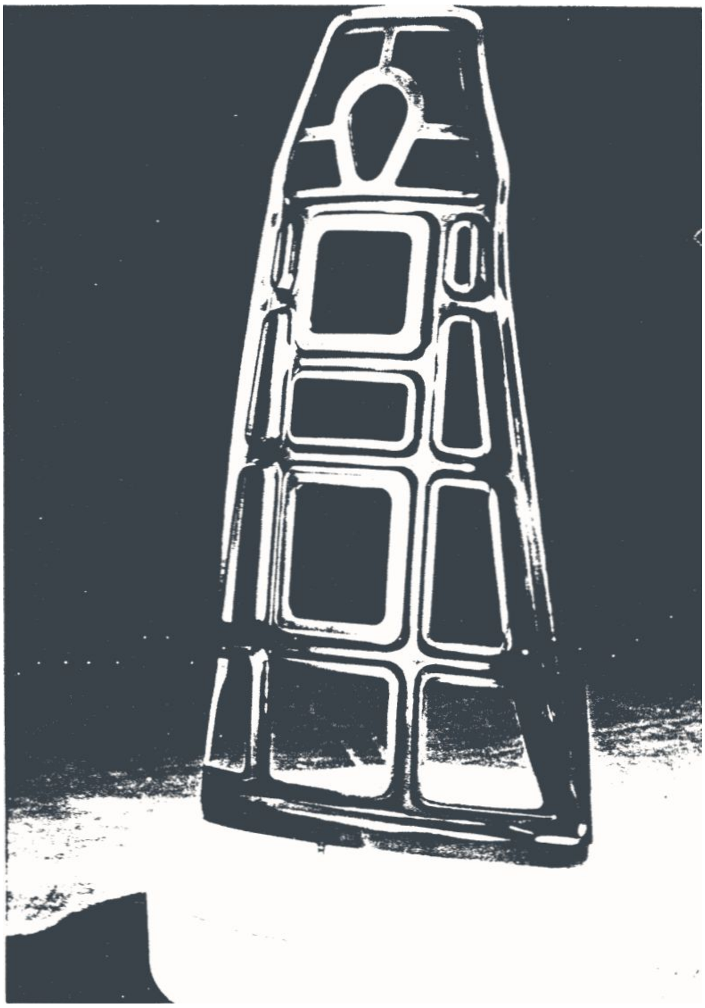


Fig. 33 - SPF part

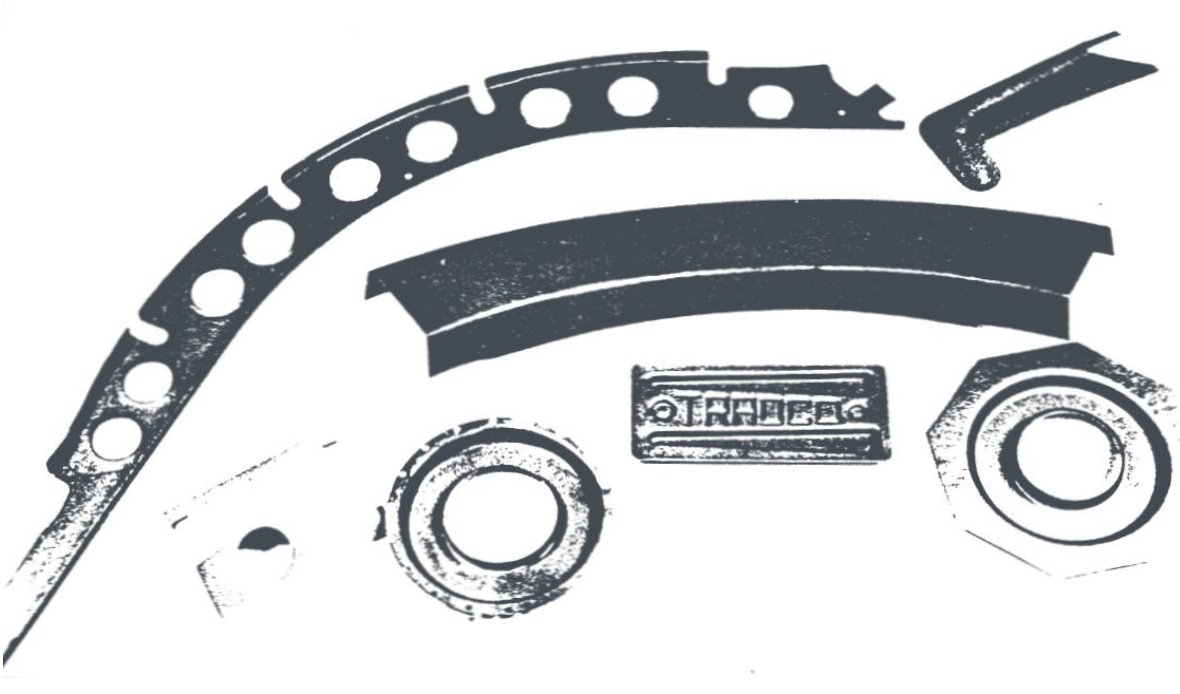
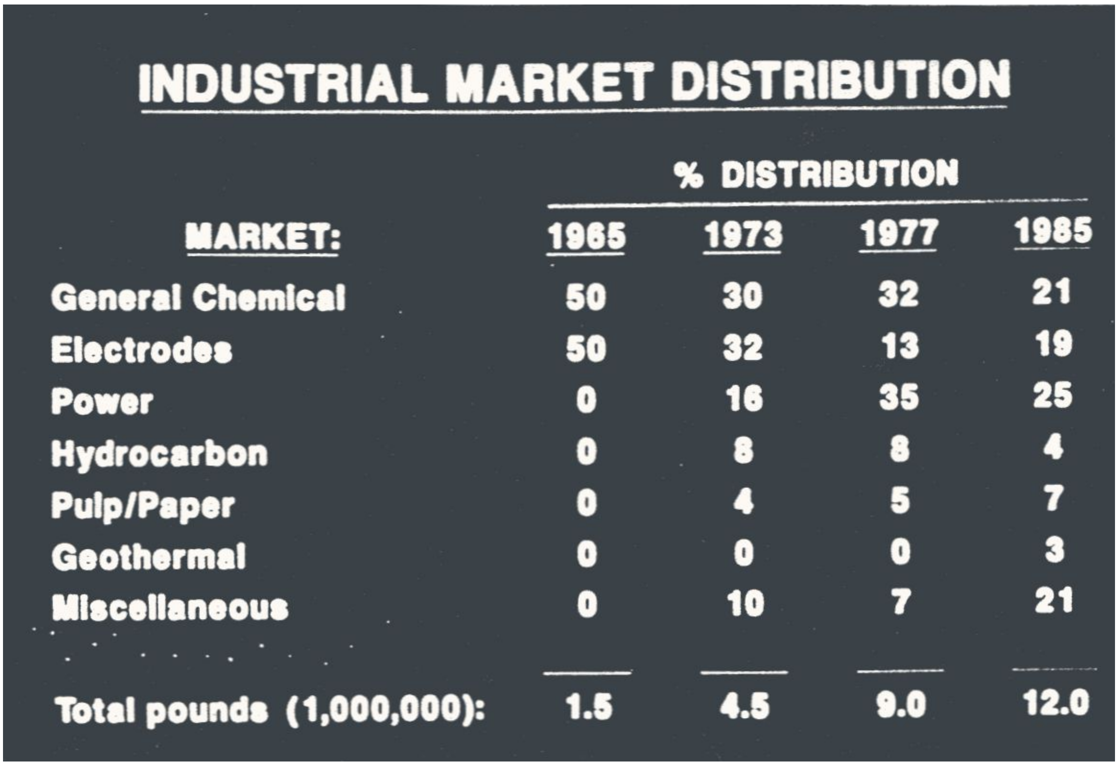


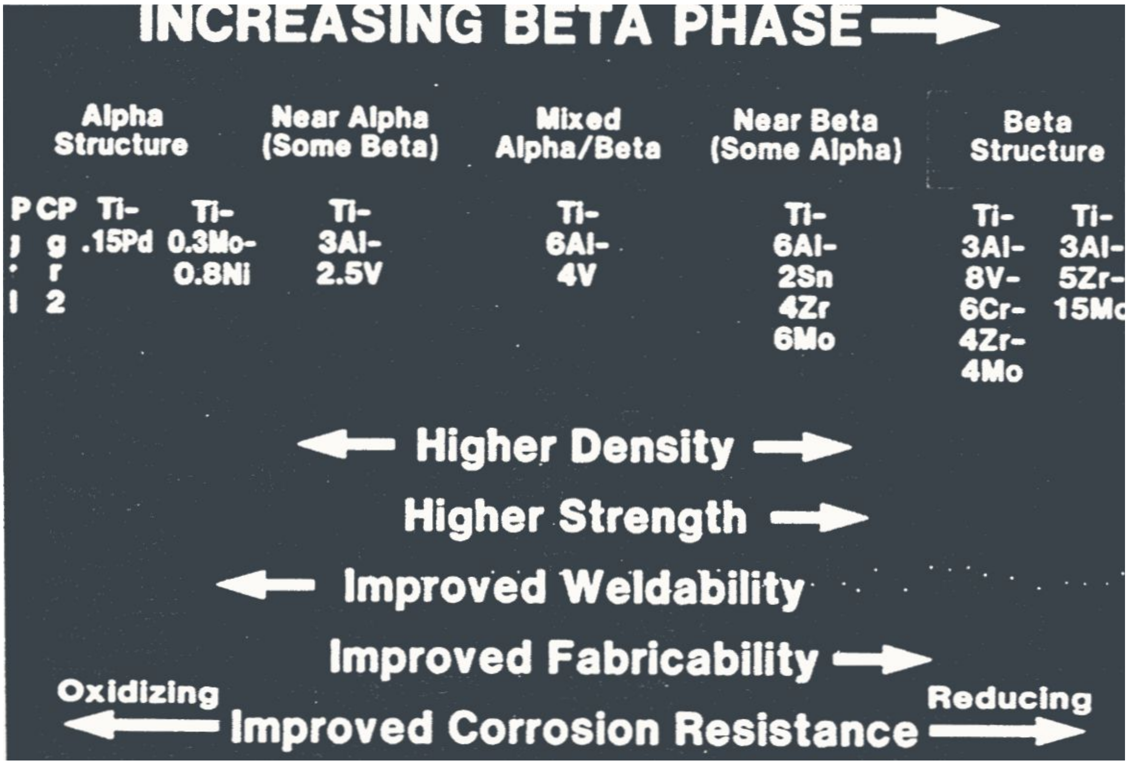
Fig. 34 - Conventional hot formed parts



INDUSTRIAL MARKET DISTRIBUTION

MARKET:	1965	1973	1977	1985
	% DISTRIBUTION			
General Chemical	50	30	32	21
Electrodes	50	32	13	19
Power	0	16	35	25
Hydrocarbon	0	8	8	4
Pulp/Paper	0	4	5	7
Geothermal	0	0	0	3
Miscellaneous	0	10	7	21
Total pounds (1,000,000):	1.5	4.5	9.0	12.0

Fig. 35 - Distribution and growth of titanium Industrial markets



INCREASING BETA PHASE →

Alpha Structure
P
CP gr 2
Ti-.15Pd
Ti-0.3Mo-0.8Ni

Near Alpha (Some Beta)
Ti-3Al-2.5V

Mixed Alpha/Beta
Ti-6Al-4V

Near Beta (Some Alpha)
Ti-6Al-2Sn 4Zr 6Mo

Beta Structure
Ti-3Al-8V-6Cr-4Zr-4Mo
Ti-3Al-5Zr-15M

← Higher Density →

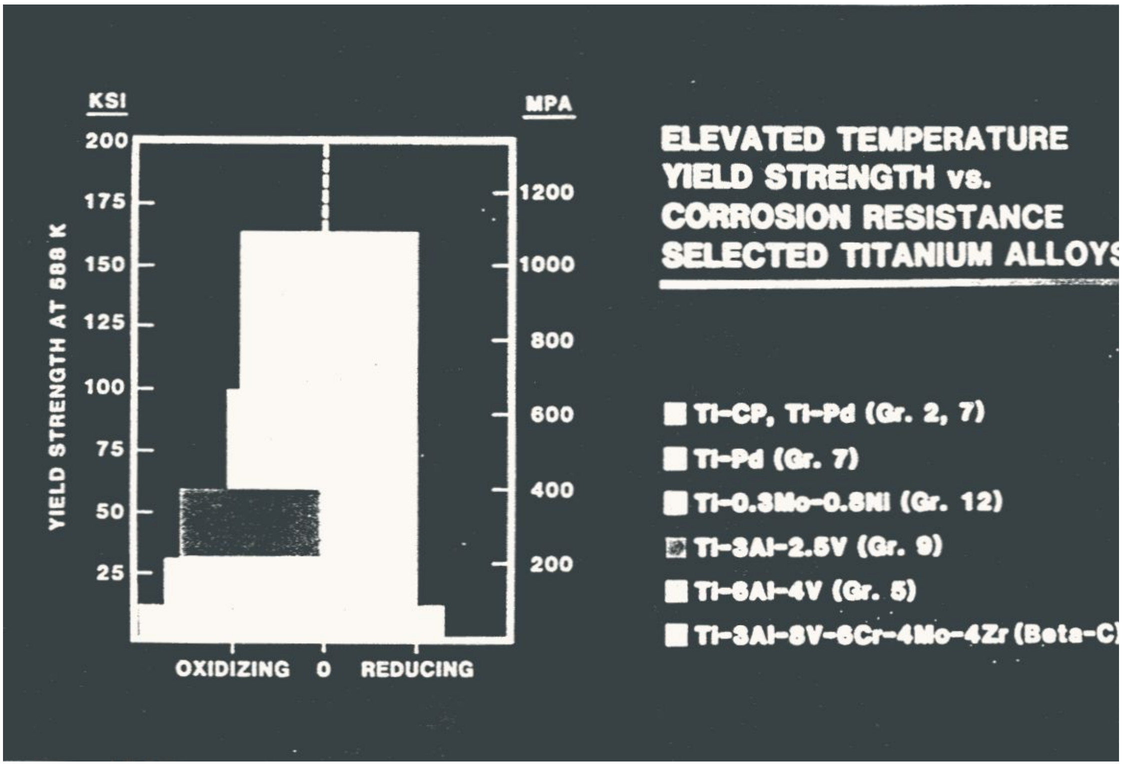
Higher Strength →

← Improved Weldability

Improved Fabricability →

Oxidizing ← Improved Corrosion Resistance → Reducing

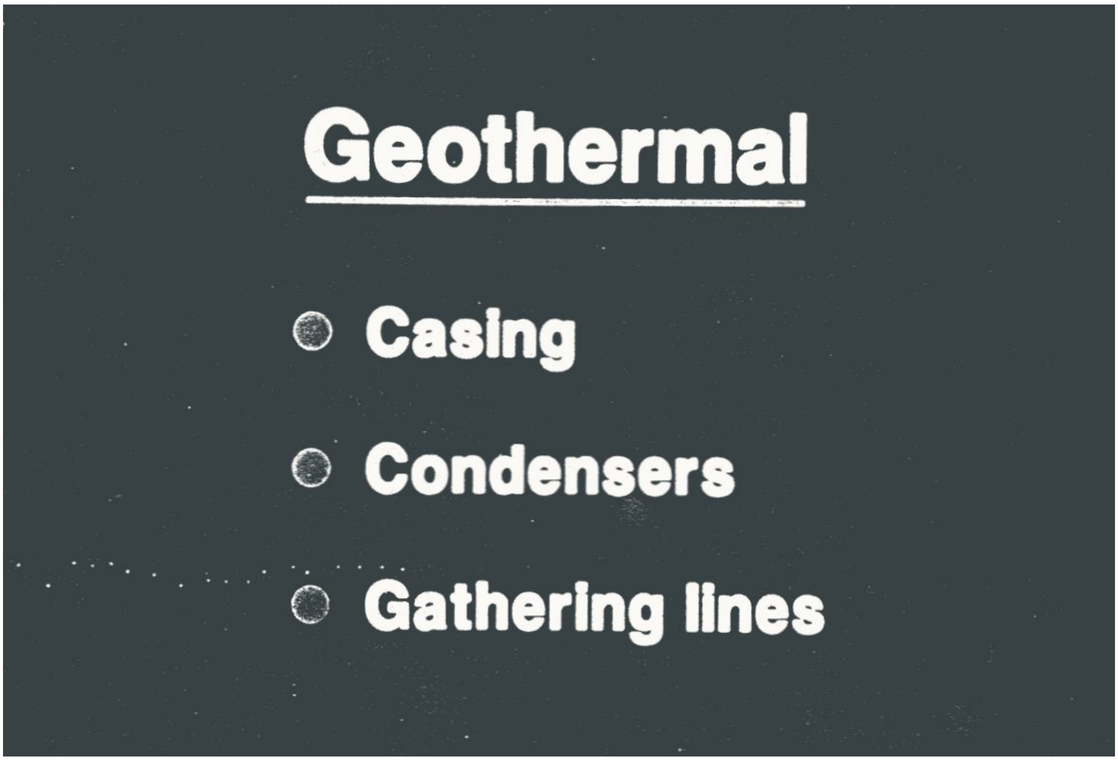
Fig. 36 - General properties of titanium alloys



ELEVATED TEMPERATURE YIELD STRENGTH vs. CORROSION RESISTANCE SELECTED TITANIUM ALLOY

- ■ Ti-CP, Ti-Pd (Gr. 2, 7)
- ■ Ti-Pd (Gr. 7)
- ■ Ti-0.3Mo-0.8Ni (Gr. 12)
- ▨ Ti-3Al-2.5V (Gr. 9)
- ■ Ti-6Al-4V (Gr. 5)
- ■ Ti-3Al-8V-6Cr-4Mo-4Zr (Beta-C

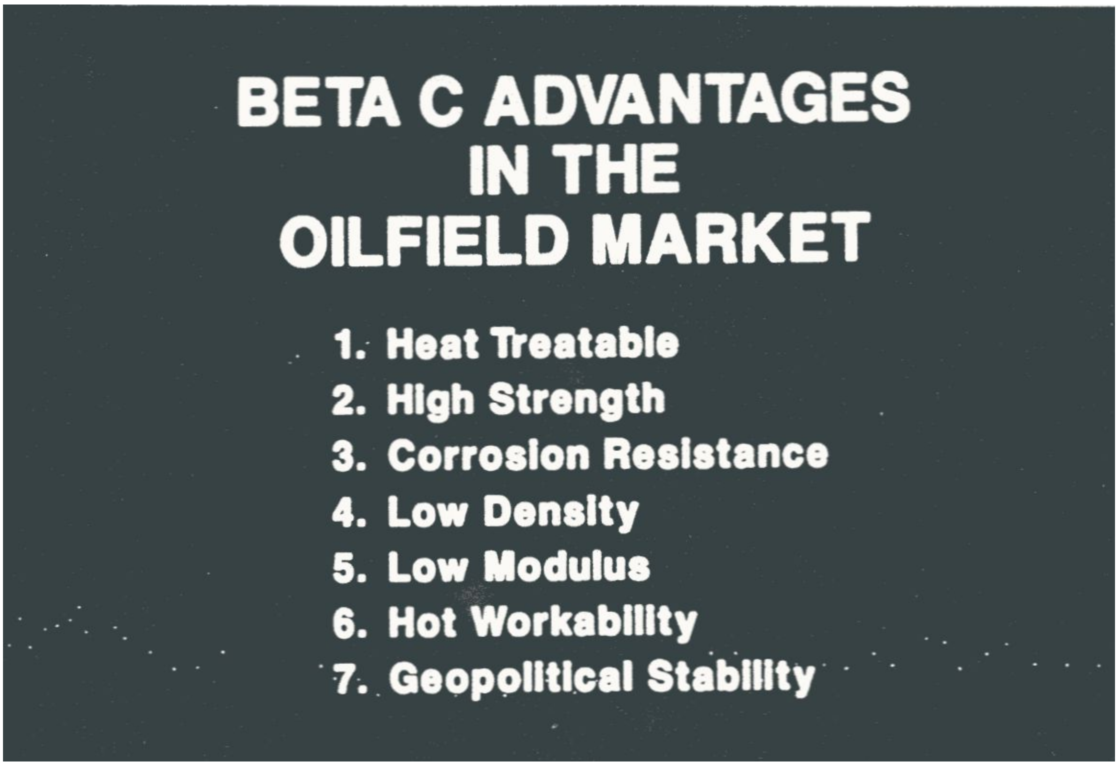
Fig. 37 - Elevated temperature yield strength vs. Corrosion resistance for various titanium Alloys



Geothermal

- Casing
- Condensers
- Gathering lines

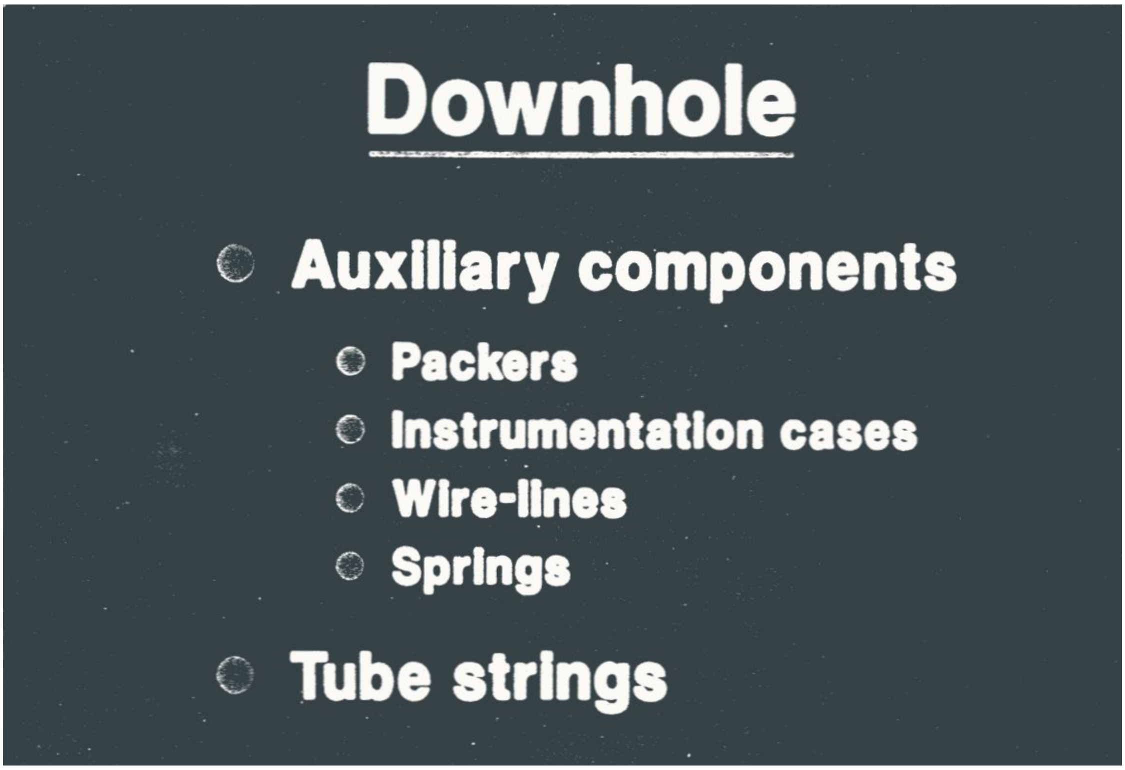
Fig. 38 - Geothermal applications of titanium alloys



BETA C ADVANTAGES
IN THE
OILFIELD MARKET

1. Heat Treatable
2. High Strength
3. Corrosion Resistance
4. Low Density
5. Low Modulus
6. Hot Workability
7. Geopolitical Stability

Fig. 39 - Beta C advantages in the oil field market



Downhole

- Auxiliary components
  - Packers
  - Instrumentation cases
  - Wire-lines
  - Springs
- Tube strings

Fig. 40 - Examples of downhole applications for Beta C alloy

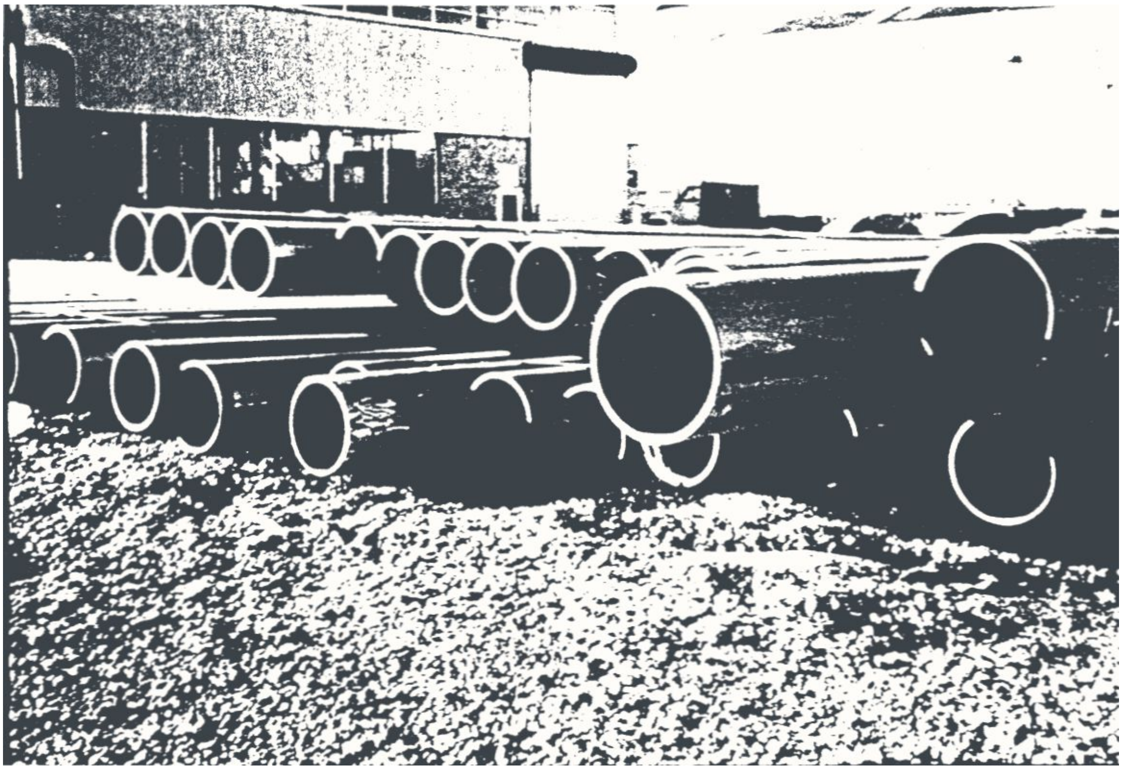


Fig. 41 - Beta C downhole piping

Fig. 42 - Beta C downhole piping