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.

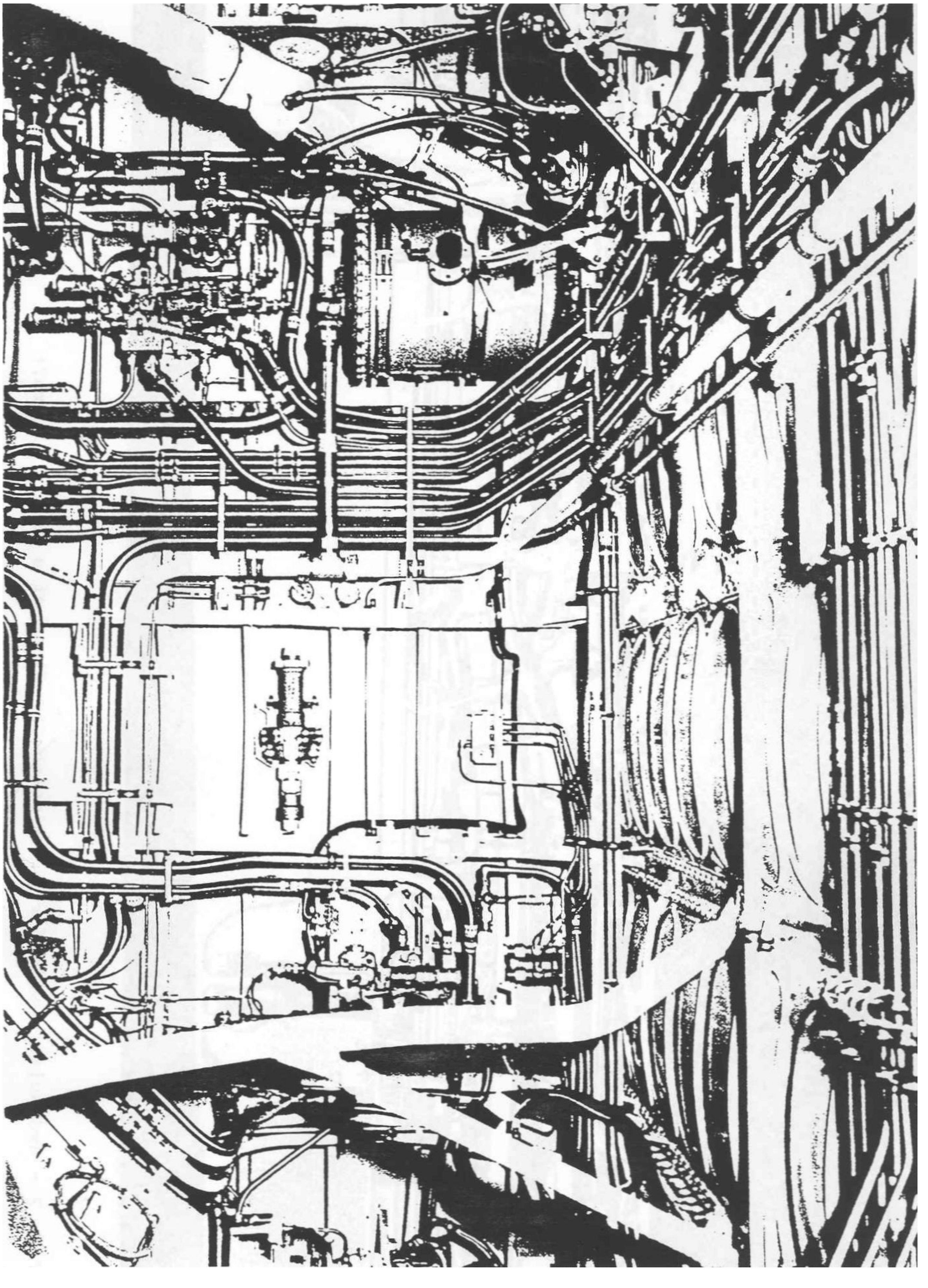


Fig. 1 - View of hydraulic system in a modern aircraft

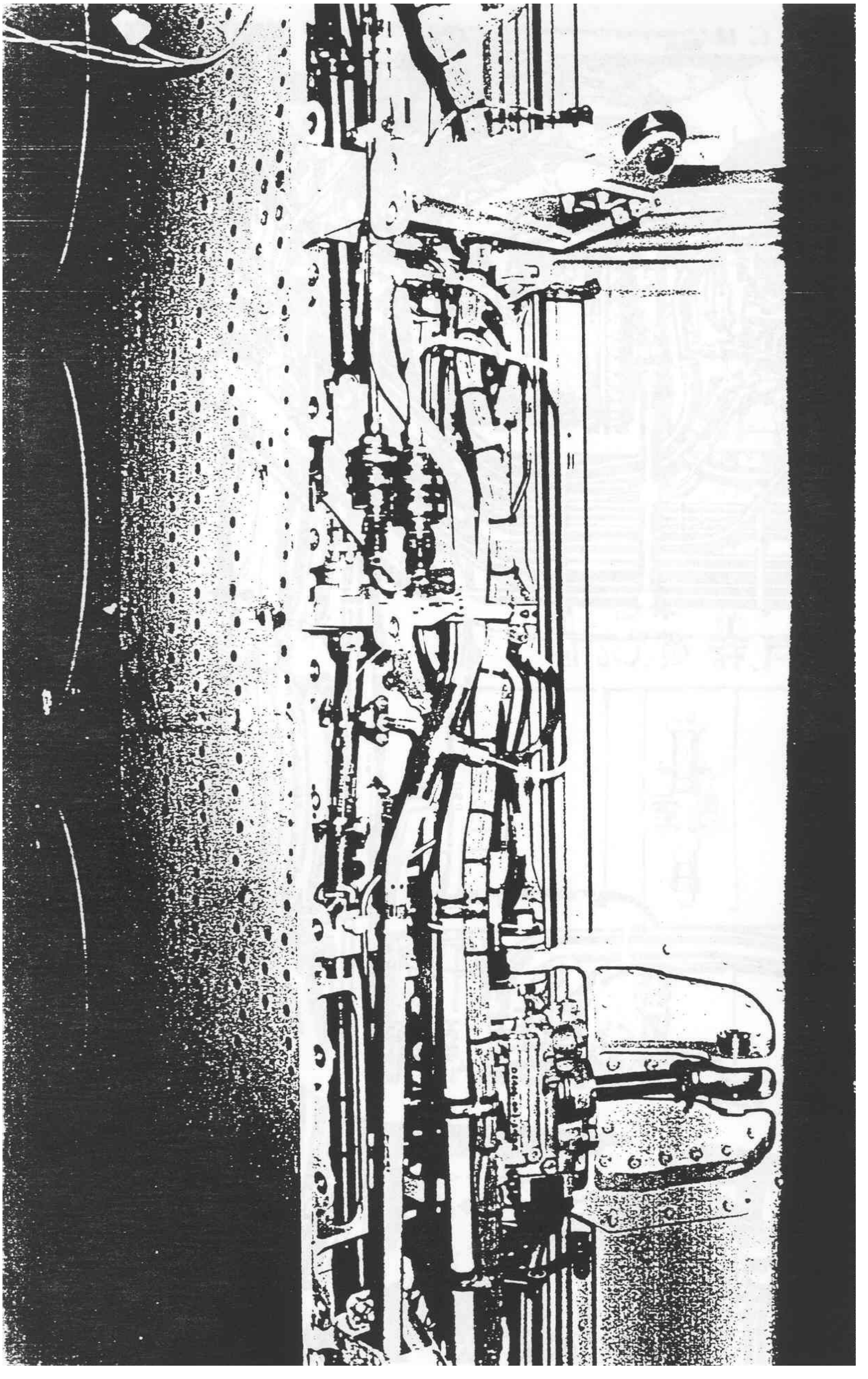


Fig. 2 – Hydraulic system for functioning the flaps of a modern aircraft

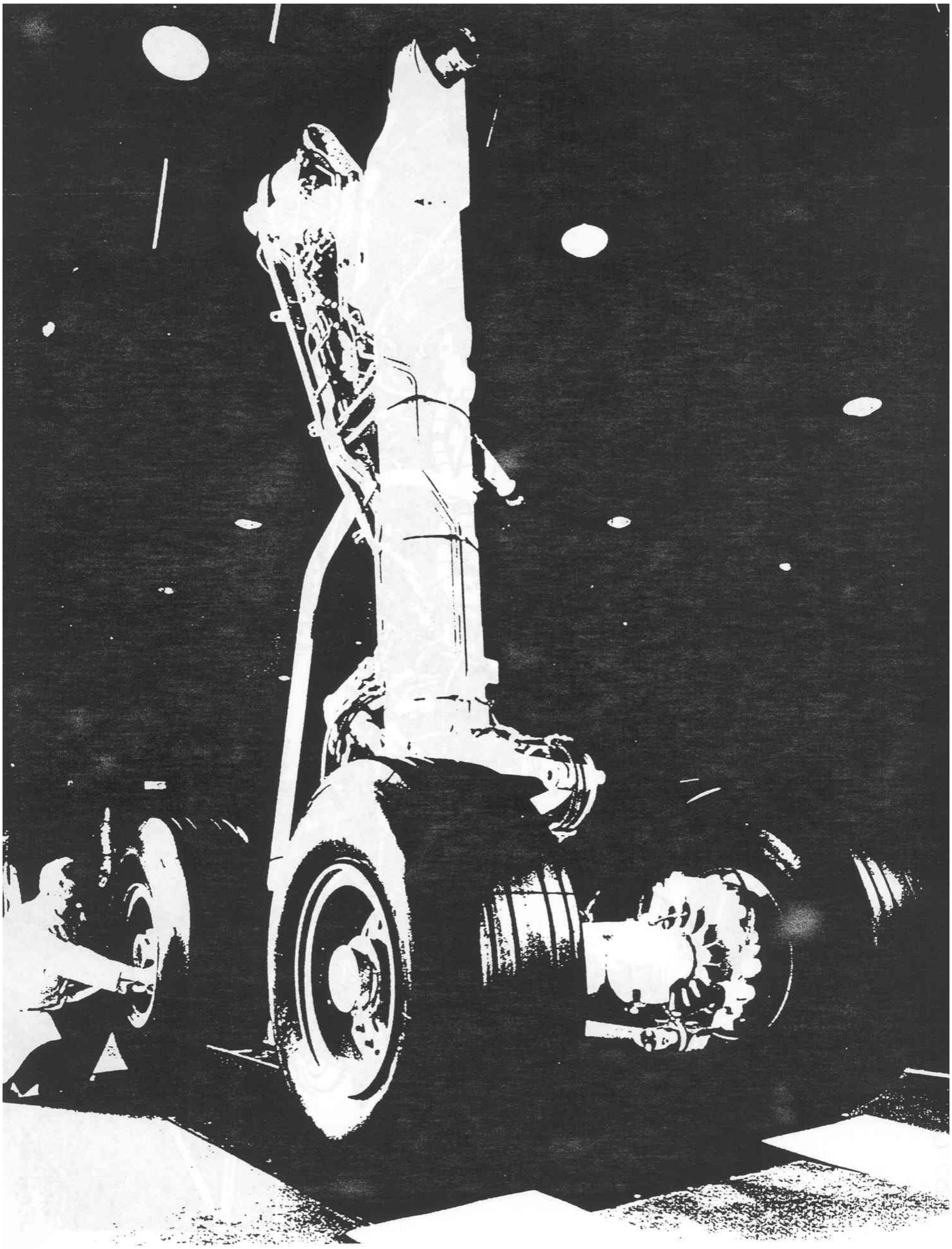


Fig. 3 - Landing gear of a Airbus A-330

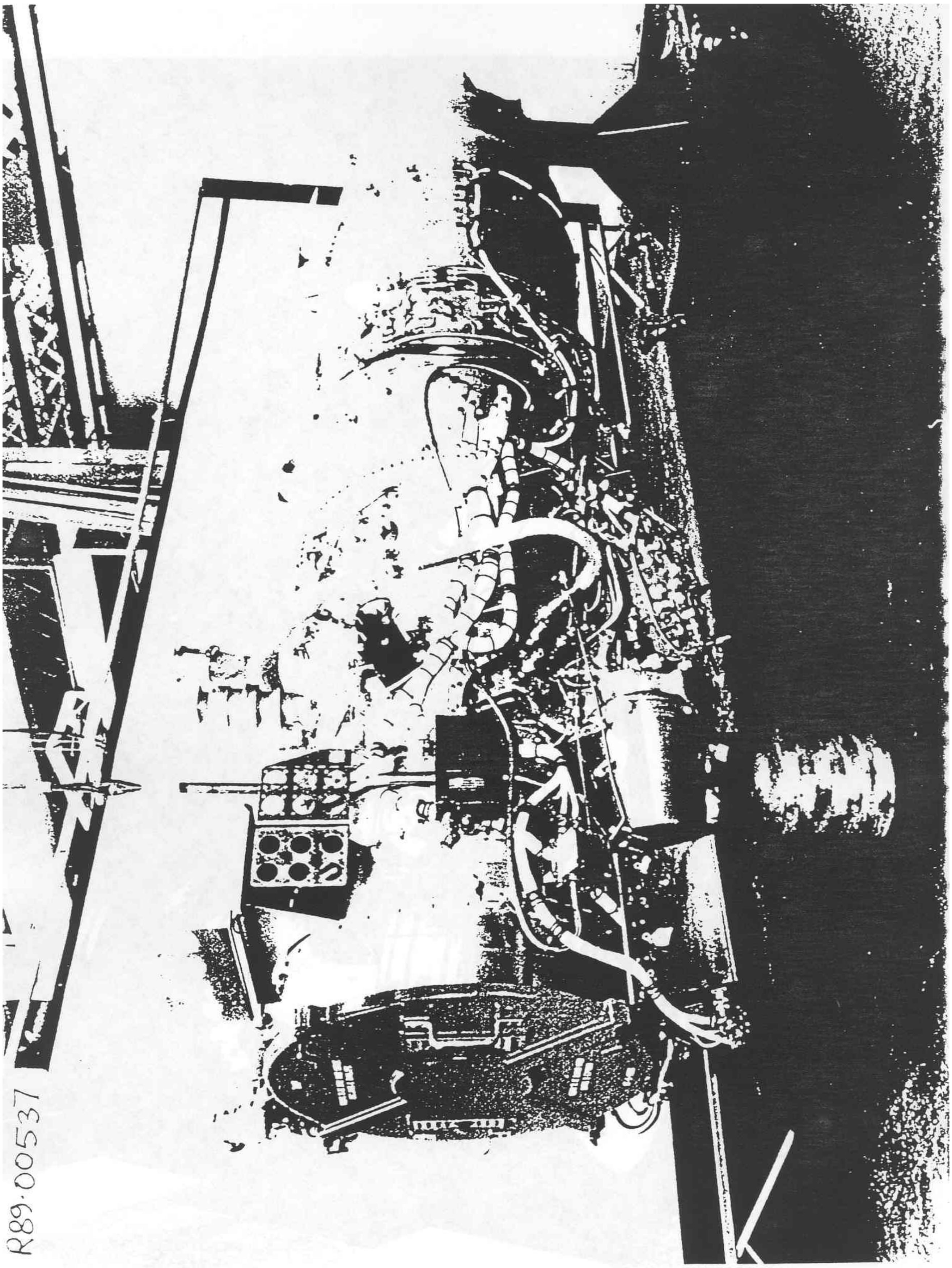


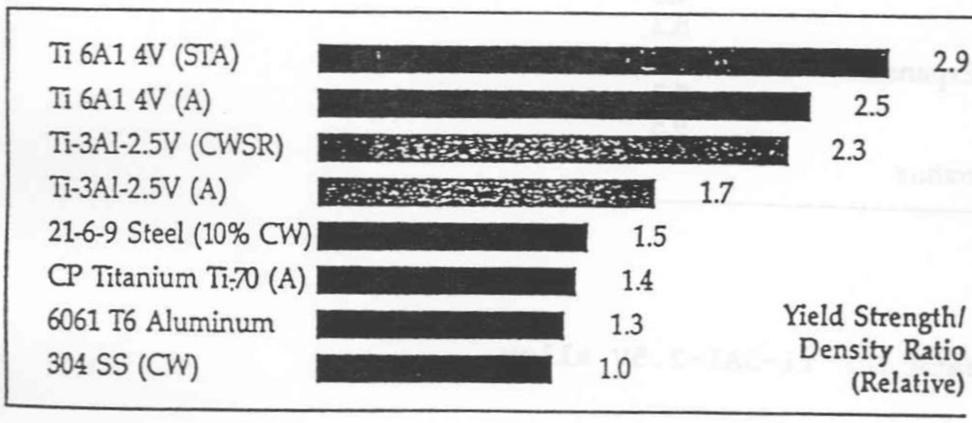
Fig. 4 - V-2500 engine assembly

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	
$\times 10^6$ psi	15.0
$\times 10^4$ MPa	10.3
Modulus of Rigidity	
$\times 10^6$ psi	6.5
$\times 10^4$ 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

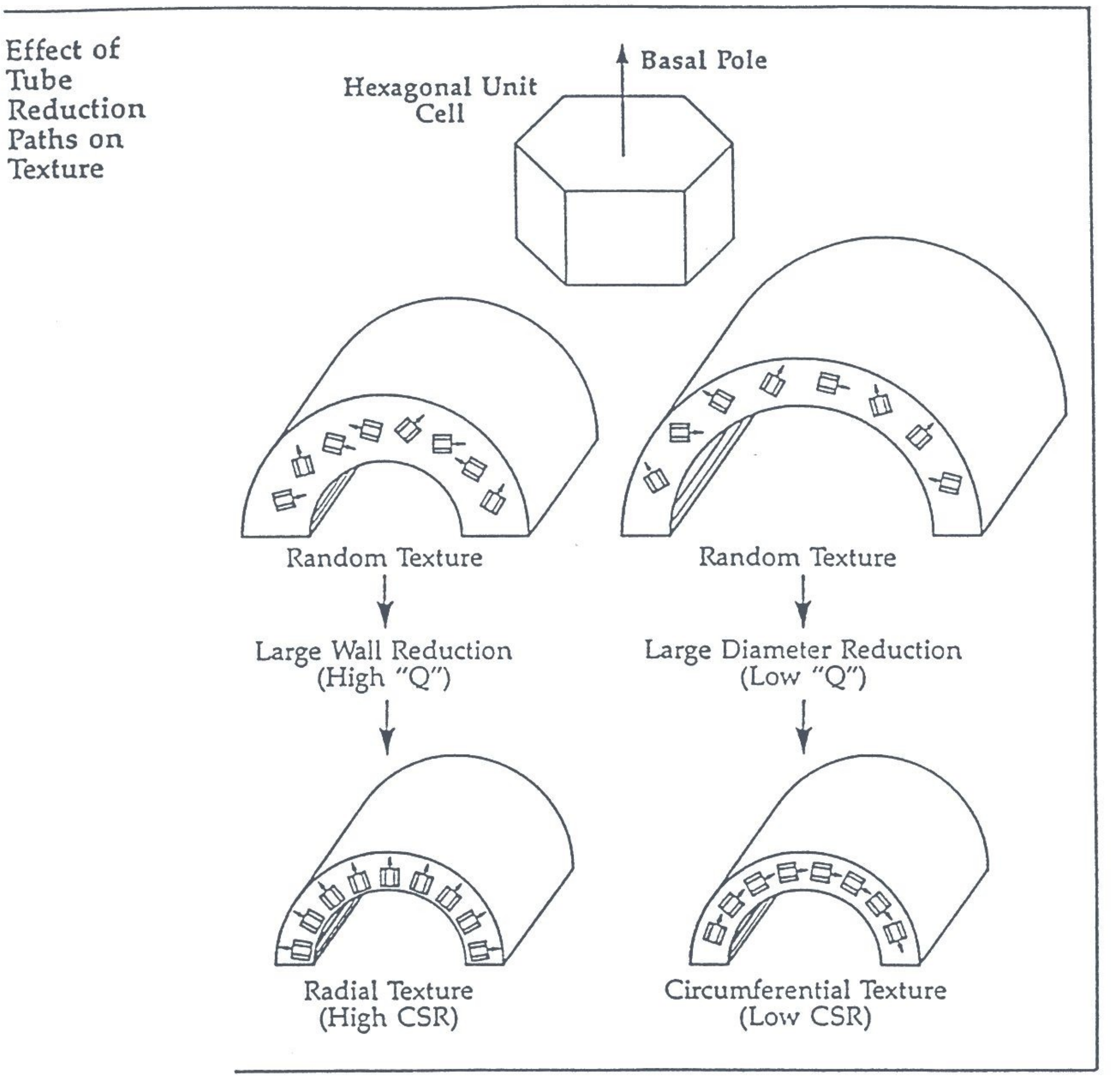


Fig. 7 - Effect of the tube reduction path on texture

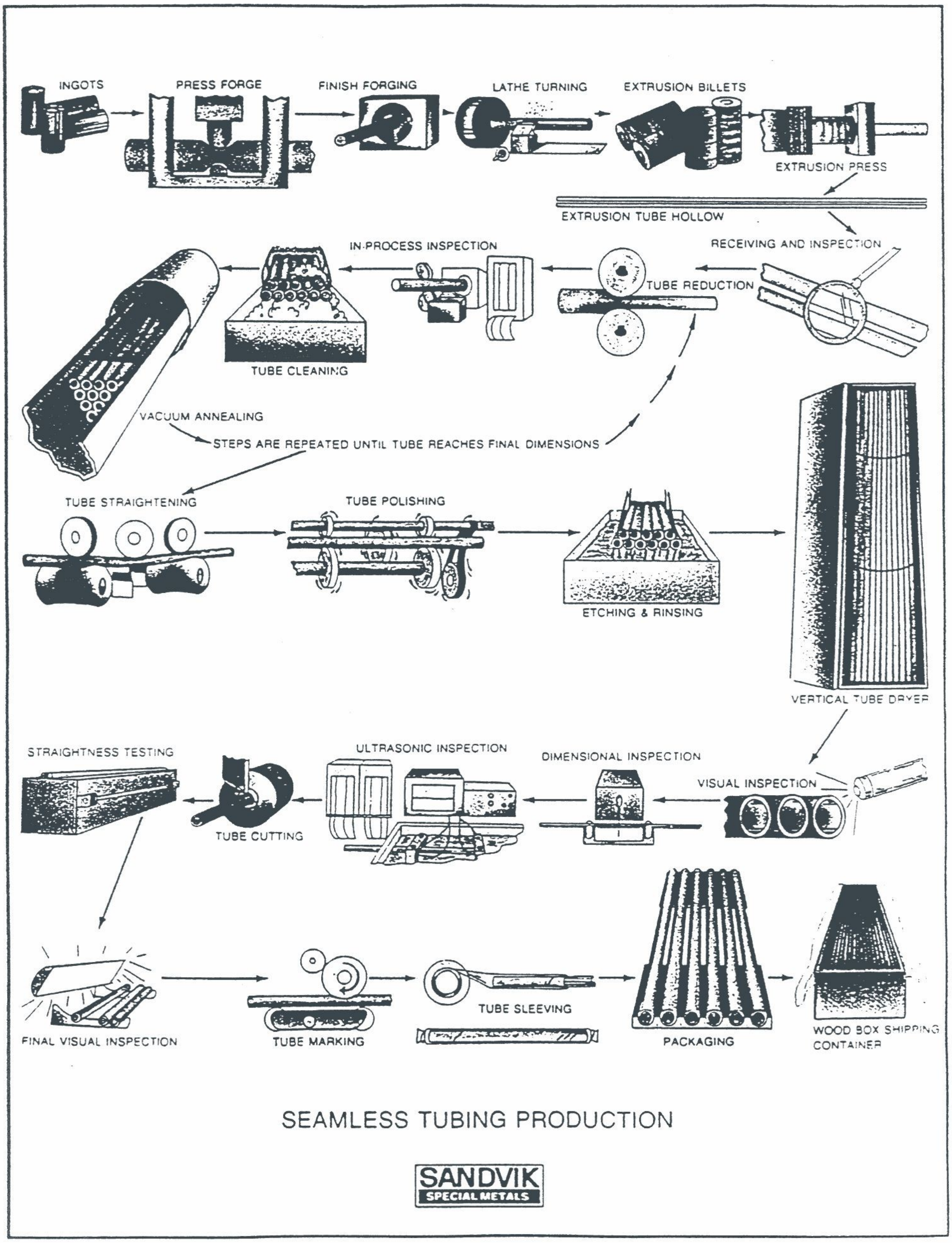


Fig. 8 – Ti-3Al-2.5V seamless titanium tubing production cycle

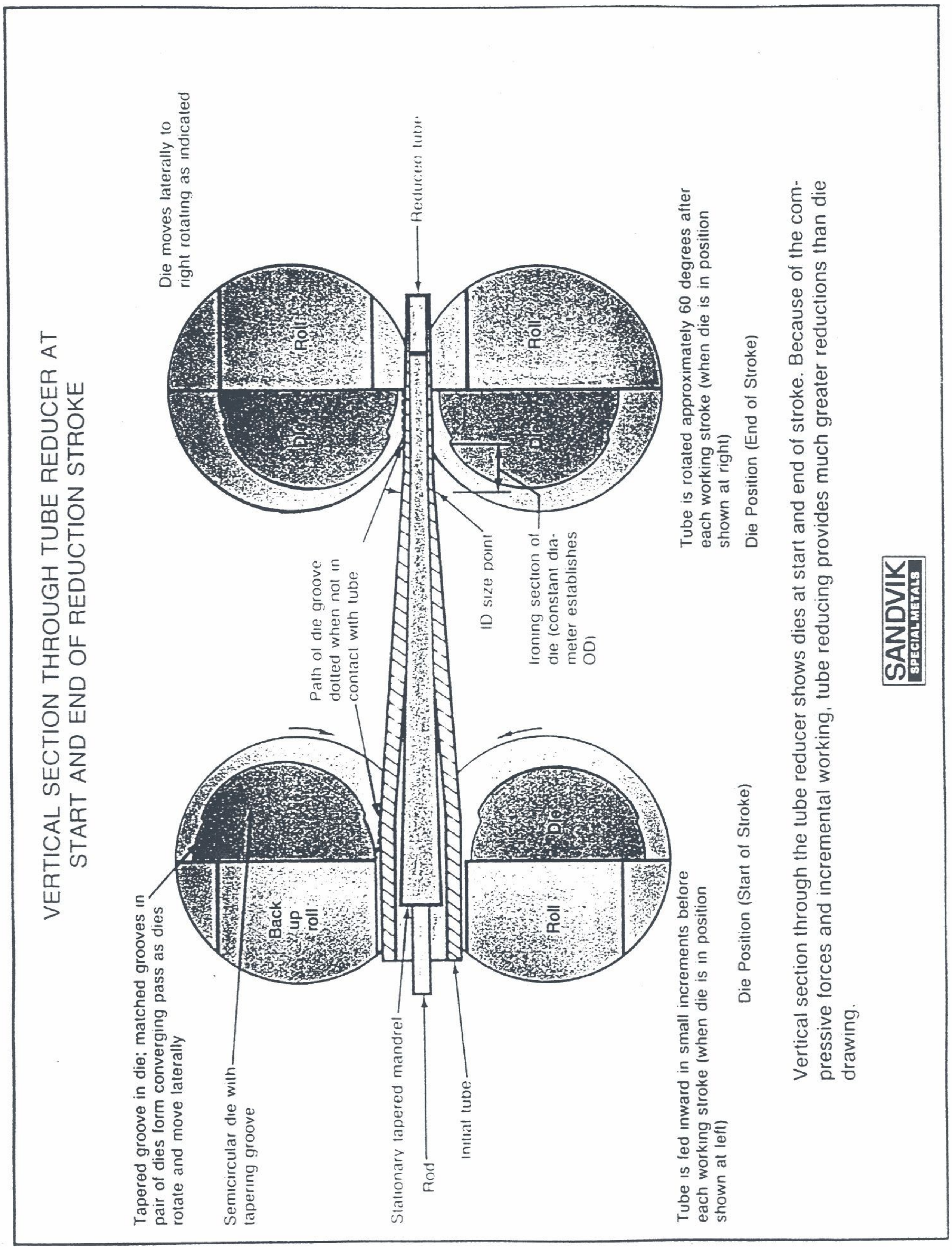
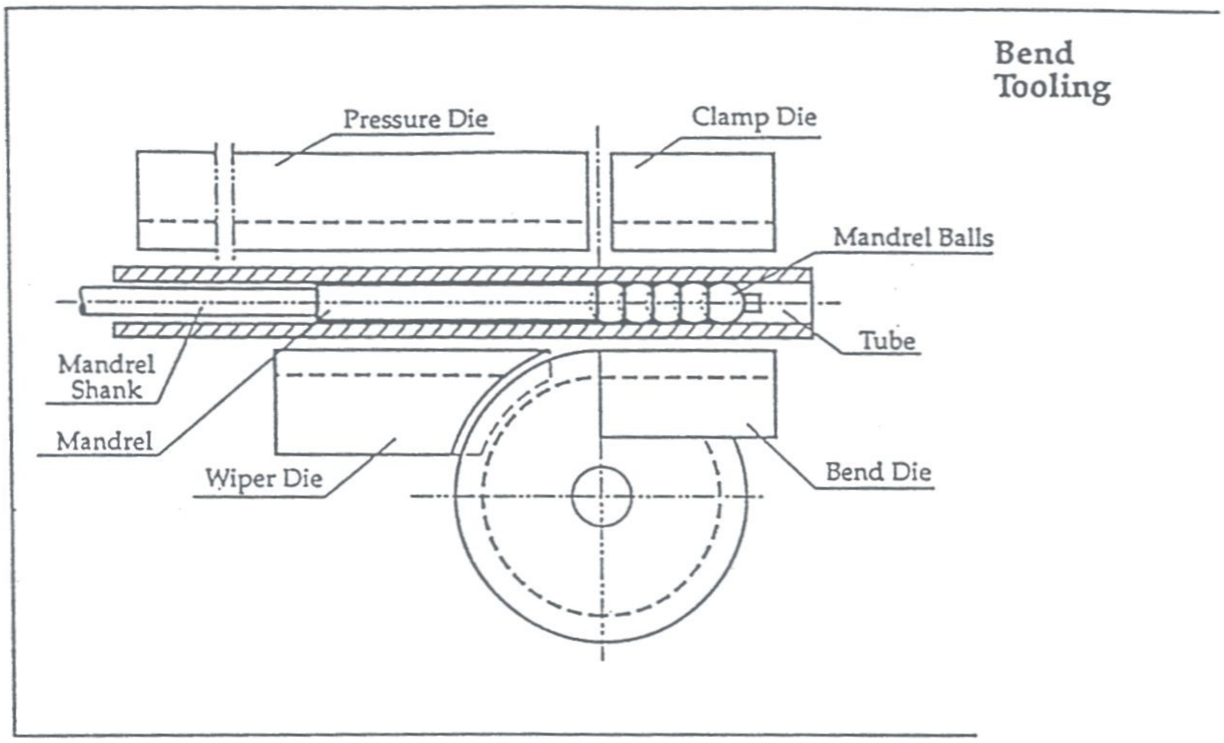


Fig. 9 - Tube reduction cycle: diagram of the cold pilgering



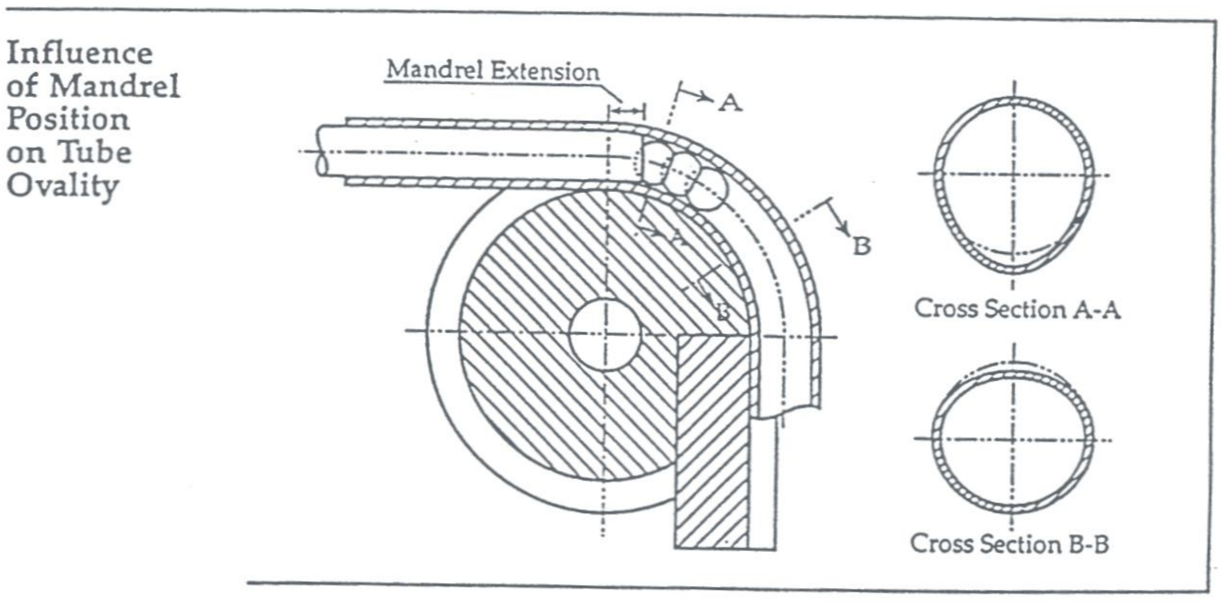


Fig. 10 – Titanium tube bending tools

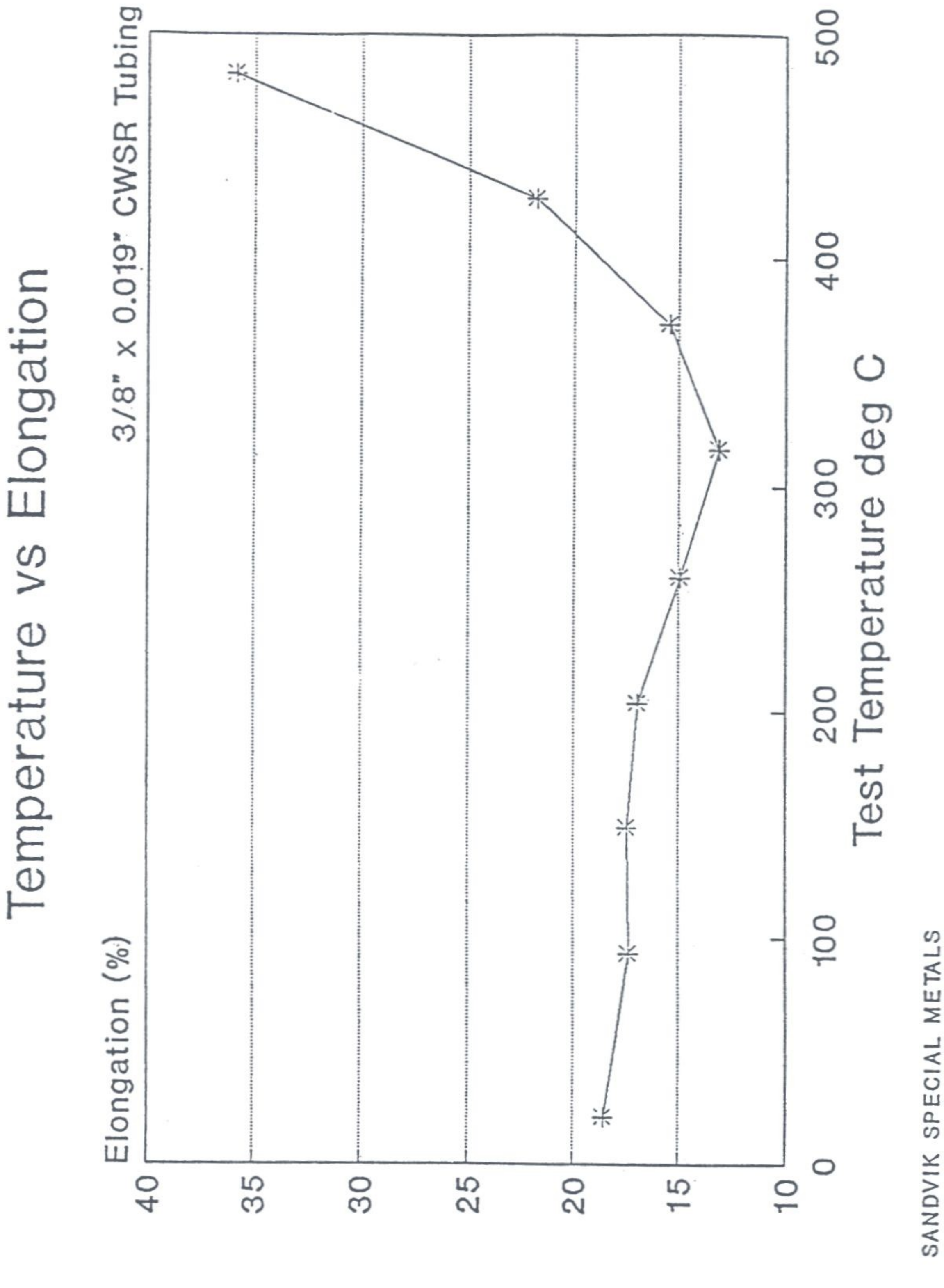


Fig. 11 - The effect of temperature on ductility of Ti-3Al-2.5V tubing

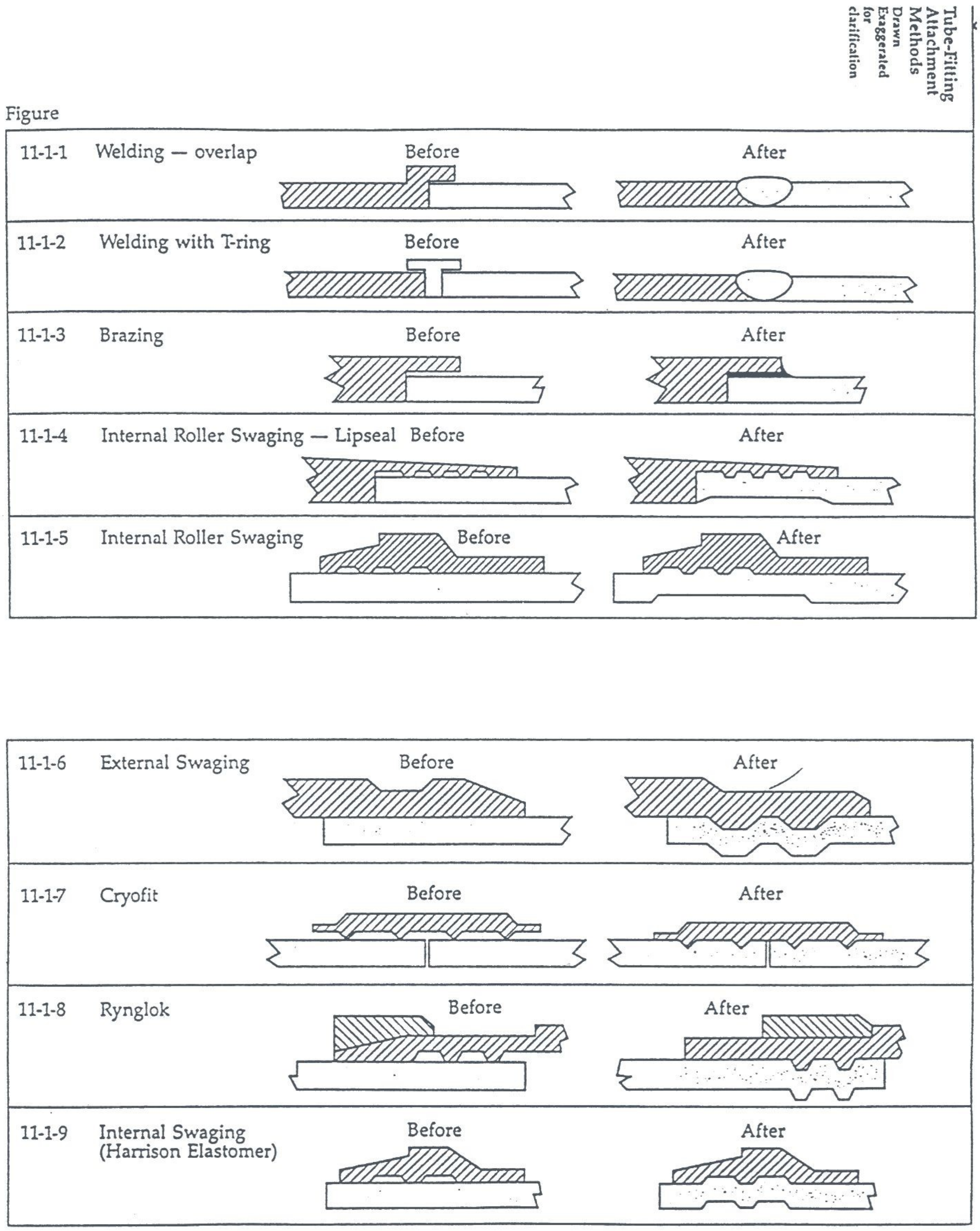


Fig. 12 - Tube-fitting attachment method

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).

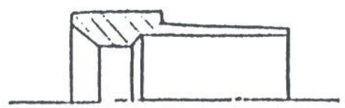
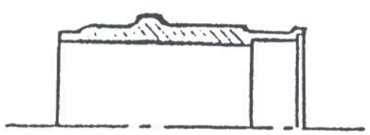
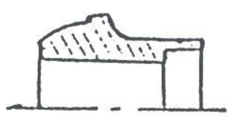
Fitting type	User P/N	Interface	Pressure level	Applications
	P + W/JAEC MS 9483 (Sierracin interchange EP0038T)	37°	engine	F100, V-2500
	General Electric	60°	engine	GE 404
	Boeing AS 1581 (Sierracin interchange 35211)	24°	3000 psi	Boeing 757/767
	Aerospatiale BAE	45°	4000 psi	Concord

Fig. 13 - Actual fittings used

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

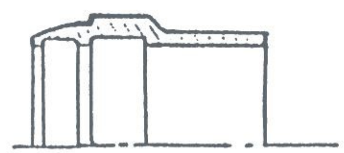
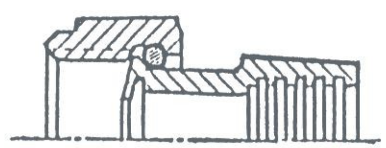
Fitting type	User P/N	Interface	Pressure level	Applications
	Boeing BACS13BX (Sierracin 35235VXX)	24°	3000 psi	Repair, Production back-up
	Airbus 35211/12 ASNA 3759	24°	3000 psi	A-320 A-330 A-340
	Resistoflex Aeroquip Sierracin/Harrison 35247	8 1/2°	3000 psi 4000 psi	F-15, F-18, B1, B2 Space Shuttle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

Fig. 14 - Actual fittings used

AIRCRAFT FITTINGS FOR 3AL-2.5V TUBING

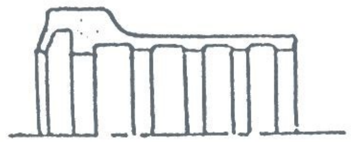
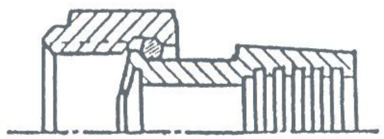
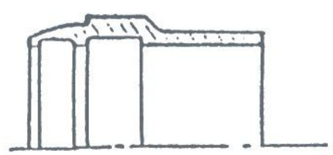
Fitting type	User P/N	Interface	Pressure level	Applications
		-- Metric fittings rolled		
	Sierracin P/N 38536	8 1/2°	4000 psi	(adapted to MBBN-EN-specifications)
	Aeroquip Resistoflex	8 1/2°	4000 psi	
	Sierracin P/N 58512	24°	5000 psi	possibly repair
		-- Metric fitting - expander swaged - Tube T40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

Fig. 15 - Actual fittings used

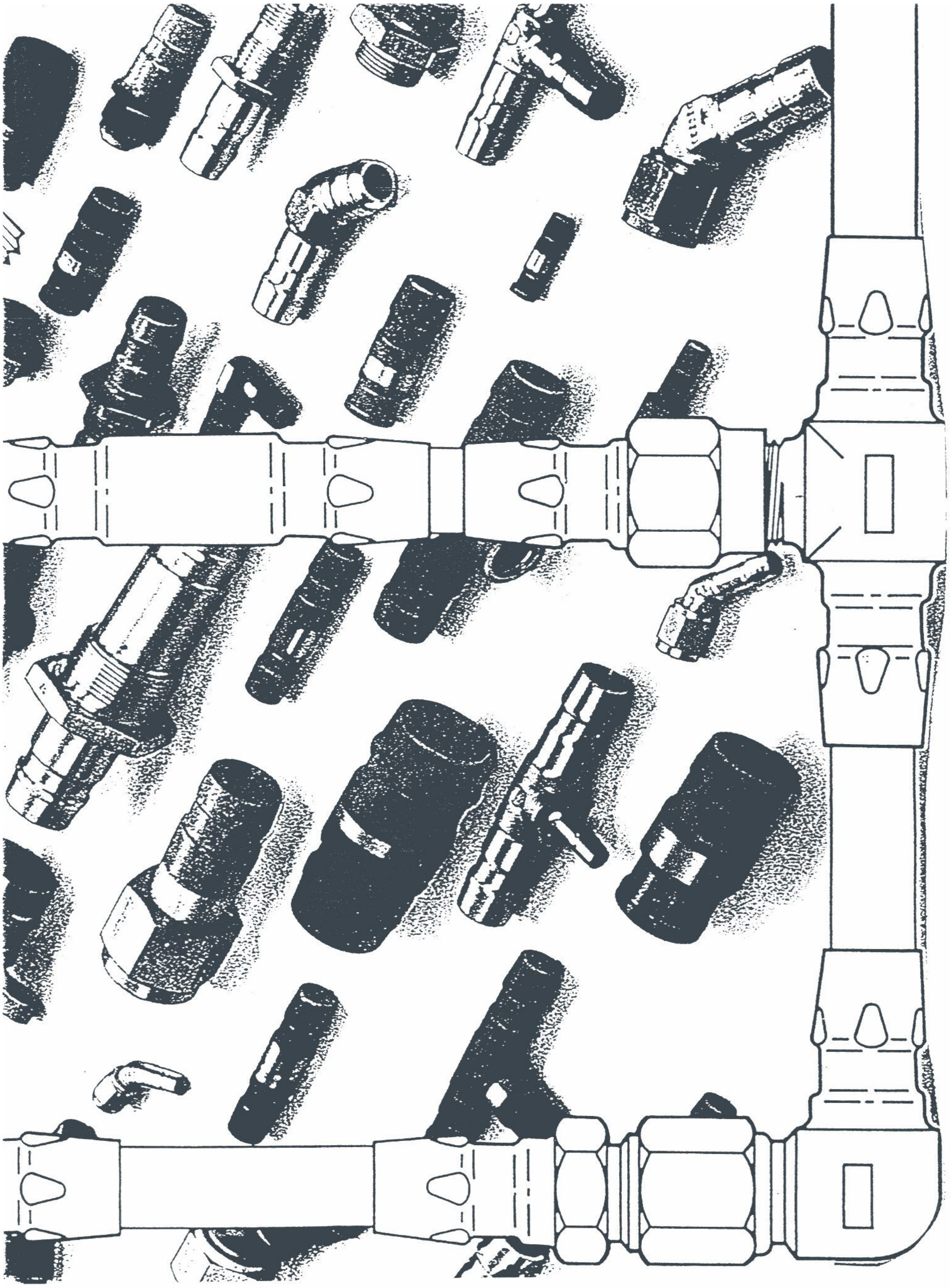
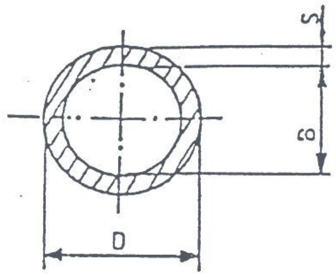


Fig. 16 - Permanent fittings for titanium tubing



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)		.0304 (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)

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

Form: AIF 8001

Published and distributed by: AIRBUS-INDUSTRIE
31700 BLAGNAC
FRANCE

133203

Fig. 17 - Airbus Industrie specification for titanium tubing

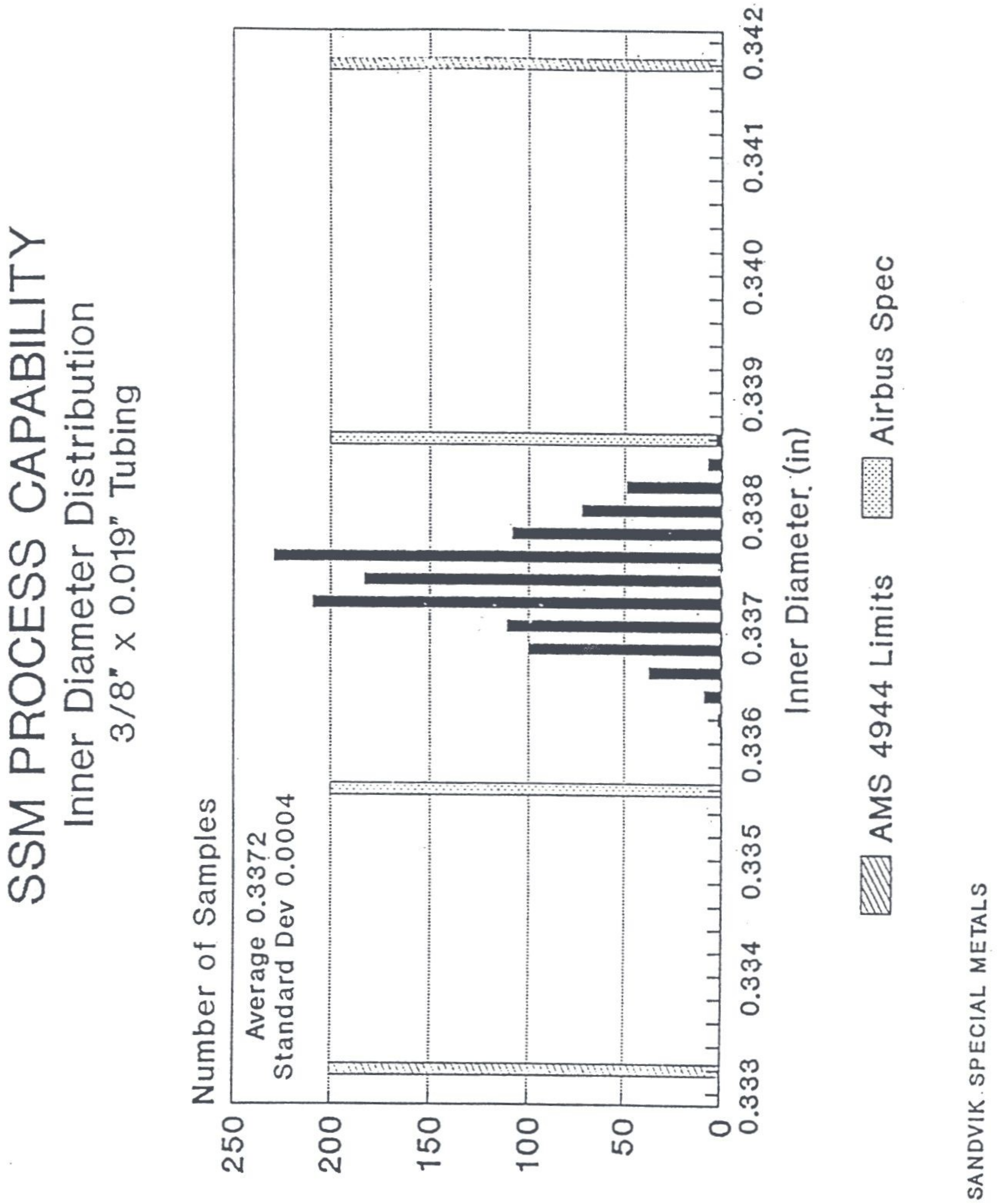
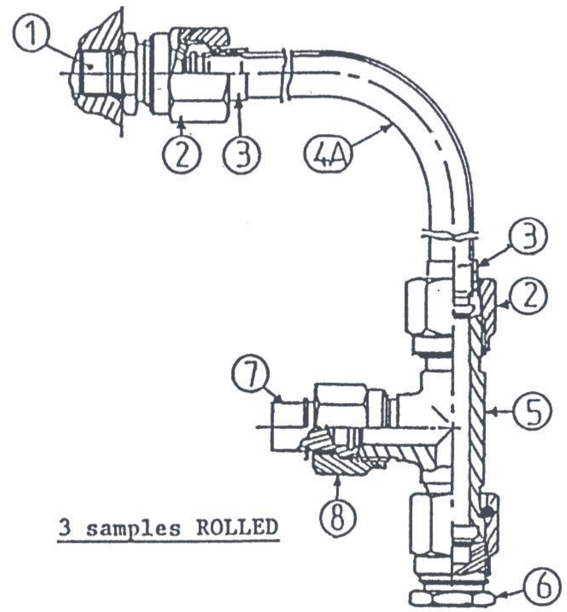
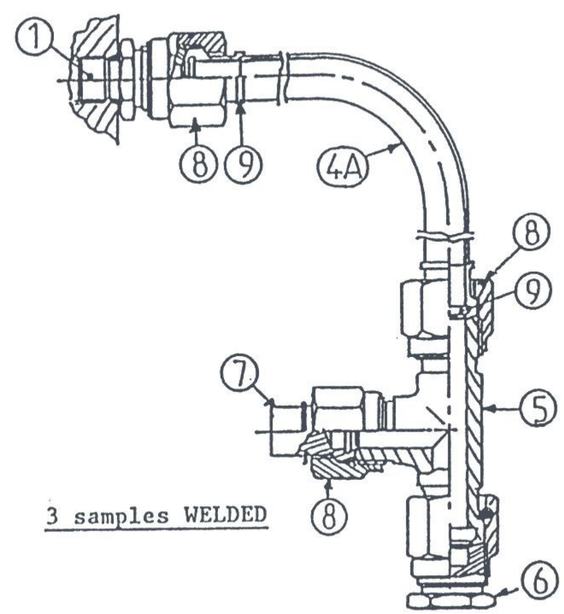


Fig. 18 - Comparison between AMS 4944 limits, Airbus specification and SSM process capability

HARDWARE FO[illegible] EN 3275 TESTING - (SIZES 6mm to 28 [illegible] -(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 (EN 3265)	6 (38536T)	6	6	6	6	12	6
08mm	6	6 (EN 3265)	6 (38536T)	6	6	6	6	12	6
10mm	6	6 (EN 3265)	6 (38536T)	6	6	6	6	12	6
12mm	6	6 (EN 3265)	6 (38536T)	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	38543T	38535T	6	6	6	6	18	12
28mm	6	38543T	38535T	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

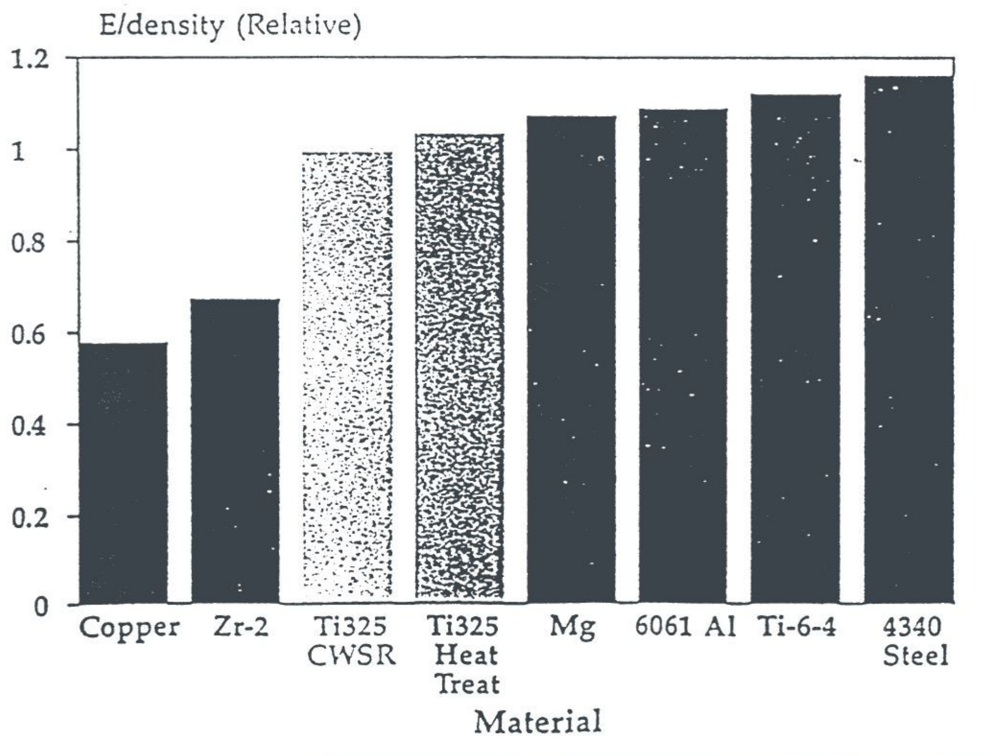


Fig. 20 – Ti-3AL-2.5V golf shaft and comparison of elastic modulus in different materials

Figure 14-4

Ti-3-2.5
Rackets

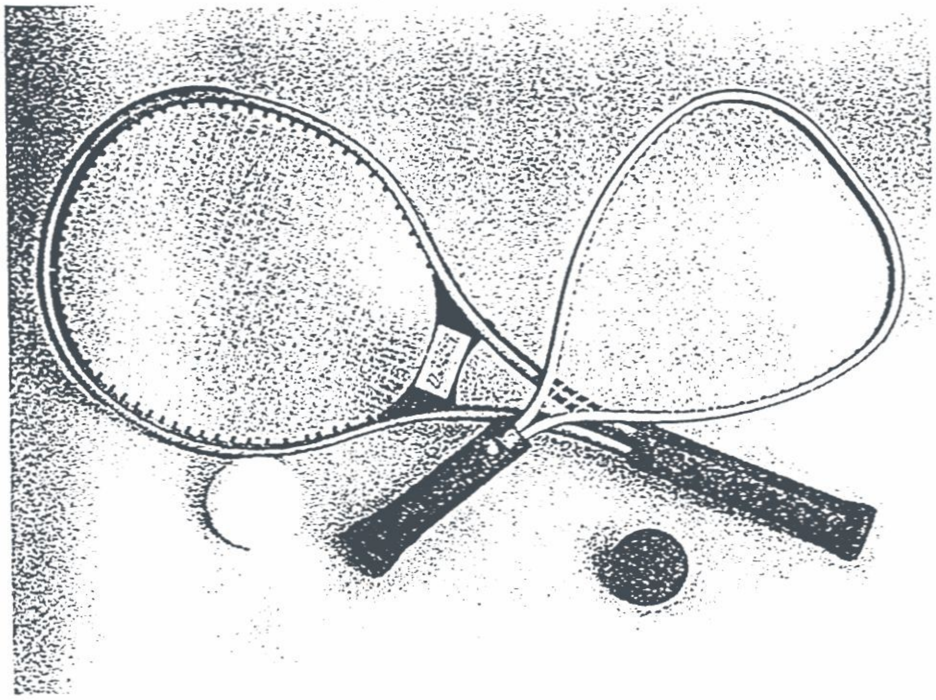


Figure 14-5

Ti-3-2.5
Mountain
Bike Frame

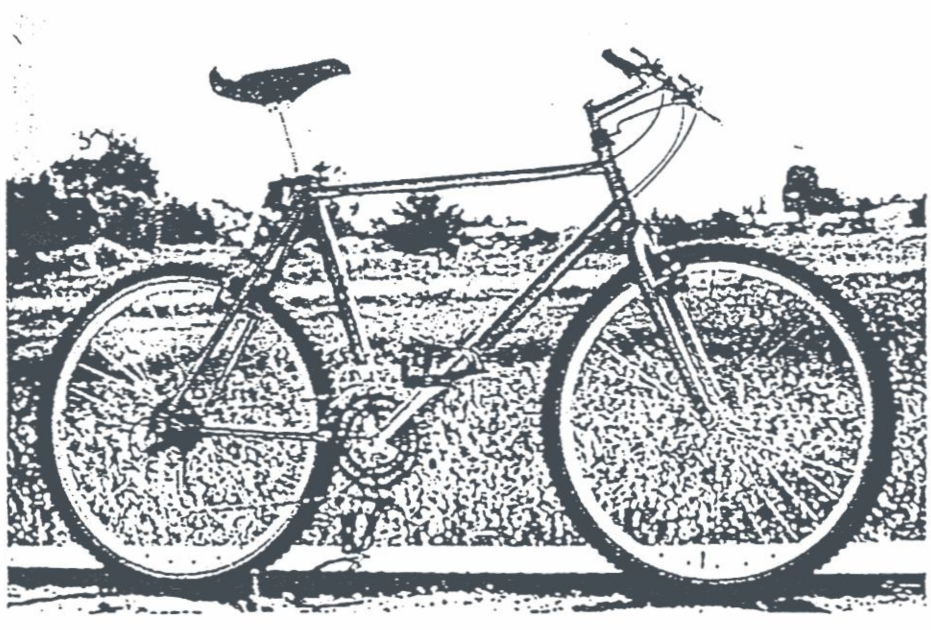


Fig. 21 – Ti-3Al-2.5V tennis rackets and mountain bike frame

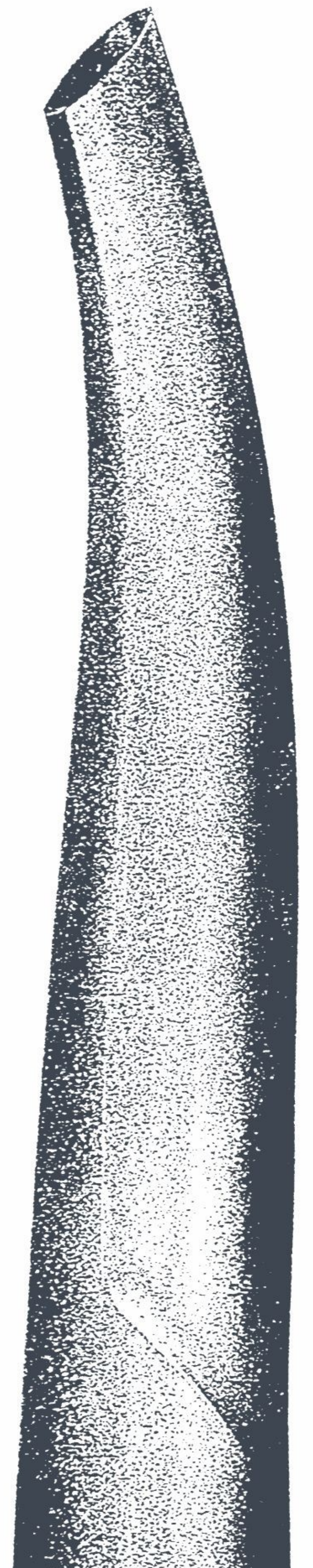


Fig. 22 – Ti-3Al-2.5V tooth drill structure, superplasticity formed

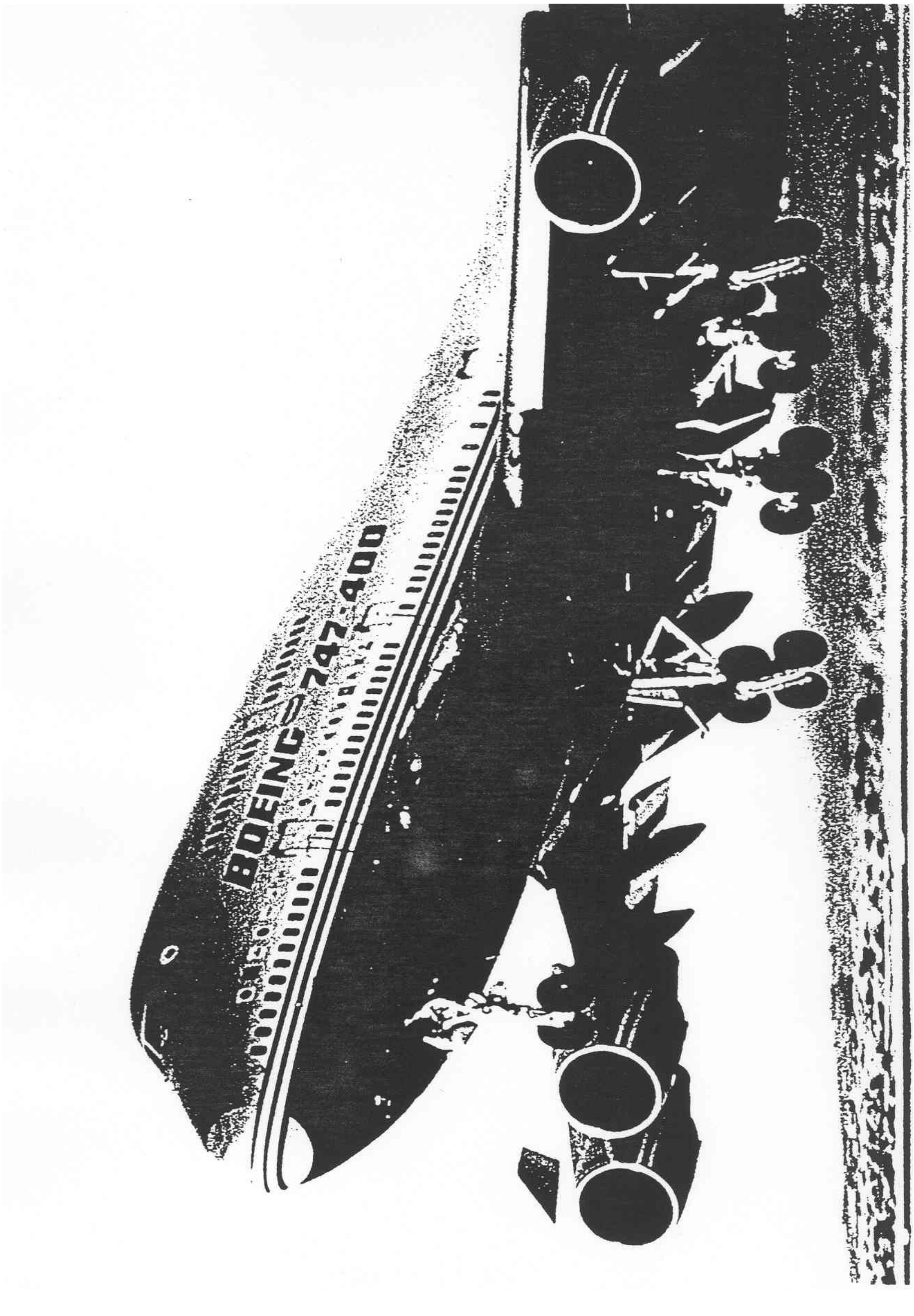


Fig. 23 - The Boeing 747-400 aircraft with Ti-3Al-2.5V hydraulic tubing