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Mechanical Properties of Titanium and Titanium Alloys, Industrial Applications

Thank you very much, Mr. Ginatta, for your introduction.
It will be difficult to give you an overview of titanium production, mechanical properties, new applications, and future aspects in half an hour, but I will try.

This first slide (1) shows you titanium sponge. In this case, it is a magnesium reduced sponge, and the particles have a grain-size of about 1 to 12 millimeters diameter.
In the case of a sodium-reduced sponge the grain-size of the particles lies between 1 - 5 mm.

The titanium sponge is compacted by a large, 7500 ton press (slide 2) and the next slide (3) shows you the product which emerges. These are compacts, about 600 millimeters long and 170 millimeters square. These compacts have to be joined together, and the next slide (4) will show you how this is done. In this apparatus, the compacts are welded together under argon pressure. The next slide (5) shows how the material is melted. The electrode is placed into the vacuum chamber of a vacuum arc furnace with a consumable electrode as you see here.

Now let us come to the next slide (6). Here is the product. These are titanium ingots, and they are between 500 and 1000 millimeters in diameter. Their weight varies between one and ten tons. As you see, titanium is a very common metal. It cannot be termed a precious metal because we melt titanium in large quantities.

Now let us turn to other operations in the processing of titanium ingots.

The next slide (7), will show a normal forging press which we use to forge both steel and titanium. On the next slide (8), you will see a titanium slab which is needed for sheet production. These slabs are about 300 millimeters thick and 1500 millimeters wide. Now let us see the next slide (9). This is a hot rolling mill. Here we break down the slabs and afterwards in this sevenstand mill, we roll this material down to about 3 millimeters in thickness, and a coil is formed. Afterwards the material is cold-rolled to thicknesses down to 0.4 millimeters with widths up to 1500 millimeters.

[Slide (10)]. Now I would like to say a few words about chemical compositions. As Dr. Rüdinger pointed out we have different grades of commercially pure Titanium. Grade I is the material with the lowest oxygen content. The maximum oxygen content according to the general specifications is 0.10 percent. But, normally, the oxygen contents are in the region of 0.005 to 0.08 percent. The mechanical properties of the commercially-pure grades are influenced by oxygen content and not so much by the iron content, because the iron is normally not added. The oxygen is added to the melt in the form of titanium-oxide. Oxygen levels up to 0.30 percent can be reached with the difficult grades.

Now we come to the next slide (11). Don't let the large number of alloys alarm you. I'm taking out one or two examples, e.g. the 6-4 alloy with 6 percent aluminium and 4 percent vanadium or the 6-2-4-2 alloy with 6 percent aluminium, 2 percent tin, 4 percent zirconium, 2 percent molybdenum and a addition of silicon to improve the creep properties.

Now let me mention mechanical properties. [Slide (12)] The minimum yield strength of the grade one commercially pure titanium is 180 N/mm^2. Normally there are different values according to the direction e.g. 140 up to 220 N/mm^2. If you want to make heat exchanger plates, you need a material with high ductility and lower strength, because of a good formability of these plates. On the other hand for the aircraft industry, the grade one has a little more oxygen and therefore a little higher strength.

Now let us go on the next slide (13) showing the mechanical properties of the alloys. You shouldn't be worried, I'm taking out e.g. the alloy 6-4. Its minimum yield-strength is 830 N/mm^2. Normal values are between 900 and 950 N/mm^2. Tensile strength is in the region of 900 to 1000, and if the alloy is aged, up to 1140 N/mm^2. If we speak of alloys for engines, we need good high temperature properties. That means we can't use the 6-4 alloy, and therefore we have special alloys, as Dr. Seagle has pointed out, which have higher contents e.g. of zirconium, tin, molybdenum, and silicon.

The next slide (14) will show you the influence of temperature on the tensile strength. If you look at the

6-4 alloy you will see that the tensile strength falls to very low values at high temperatures. So you see that normally the 6-4 alloy will break down in the region of 300°C; therefore we need other alloys with higher hot strengths.

The next slide (15) will show you that another very important property to look at is creep strength. In turbine engines the discs have temperatures in the region of about 500 to 600°C and we need good creep properties at this temperature.

Now we come to applications. I will start with the aircraft industry. What you see in the next slide (16) are rings and casings. These have been forged in to rings and afterwards machined. Another example - the next slide (17), shows a plate, which is machined. It is used in the wing box of the Tornado. These plates are normally delivered with a thickness of about 60 to 80 millimeters, and they are machined down to about 70 percents of their original thickness.
[Next slide (18)] shows another application of commercially pure titanium. These are heat exchanger plates, made of commercially pure titanium of grade I, the only grade capable of such high deformation.

In the slide (19) we see pump casing and an impeller which have been cast in a rammed graphite mould.

In slide (20) you see a valve for the chemical industry made of titanium because of its high corrosion resistance. Slide (21) shows a big column for the chemical process industry, made of commercially pure titanium of grade II.

Another field of application of titanium alloys is the medical industry. You see in the slide (22) a new alloy of the type TiAl5Fe2,5 for the fabrication of endo-prosthesis. The material has outstanding corrosion resistance and bio-compatibility. The mechanical properties shown here are the minimum values to the specifications. This alloy has mechanical properties comparable to the 6-4 alloy, but it has been chosen because vanadium as an element is toxic in the human body. Therefore the vanadium was replaced by iron. Possible applications are complete artificial hips, spinal implants, and permanent surgical implants of every kind, as well as narrow pins, bones, screws, nuts, and plates.

In slide 23 you will see a very common application - a watch made fully of titanium. The casing is hot forged. There are many people who can't wear stainless steels, so titanium is a metal which has bio-compatibility, and for some people it is necessary to use such a metal. Next slide (24) shows scissors made by hot forging the 6-4 titanium alloy. For hardness reasons it has been plated with titanium-nitride.

I would like to point out some future techniques, in particular powder metallurgy. Normally, titanium is melted, and then forged, or it is cast. In this case, we are taking the powder metallurgy route. We use forged bars. These bars are rotated, and we get a very fine powder in the region of 100 to 500 Microns. These powders are filled into capsules and hot isostatically-pressed.

A comparison of material requirements for forgings and powder-metallurgical parts is shown in slide (25). In the case of forgings you have to machine away a lot of material - 66 percent or more, as I pointed out with the plate, and in some cases as much as 80 percent.

In the case of a part made by the powder metallurgy route, the machining is only 20 percent. Testing of the material is more expensive, however. Additionally the fabrication by the powder metallurgy route is more expensive. So on the whole, you must decide part by part, if powder metallurgy is worthwhile. The chance for powder metallurgy will be that you have the possibility to make new alloys, which you can't melt and forge.

Next slide (26) shows a procedure of superplastic forming and diffusion bonding. Here titanium sheets are blown up together by high argon pressure of about 20 bar. Complex structures can be produced, and I think that is the latest trend in the aircraft industry.

Now ladies and gentlemen I will come to the end and I hope that I've shown you some new aspects of making titanium.

Thank you.

Krupp-Marke TIKRUTAN	Werkstoff-Nummer		Normen		Chemische Zusammensetzung in Gew.-% (Rest: Titan)					
	DIN	Luftfahrt	Vd TÜV	AECMA	Eisen max.	Sauer-stoff ca.	Stick-stoff max.	Kohlen-stoff max.	Wasser-stoff max.	(Palladium)
RT 12 (Pd)	3.7025	3.7024	Gruppe I	Ti-P01	0,20	0,10	0,05	0,08	0,013 1)	(0,15-0,25)
RT 15 (Pd)	3.7035	3.7034	Gruppe II	Ti-P02	0,25	0,20	0,06	0,08	0,013 1)	(0,15-0,25)
RT 18 (Pd)	3.7055	—	Gruppe III	—	0,30	0,25	0,06	0,10	0,013 1)	(0,15-0,25)
RT 20	3.7065	3.7064	Gruppe IV	Ti-P04	0,35	0,30	0,07	0,10	0,013 1)	-

1) Bei Blechen <2 mm Dicke und anderem Halbzeug <2 mm ⌀ oder vergleichbarem Querschnitt sind Wasserstoffgehalte bis zu 0,015 % zulässig.

Fig. 10: Chemical composition of commercially Pure titanium grades

Krupp Marke TIKRUTAN	Kurz-bezeichnung	Legie-rungs-typ	Chemische Zusammensetzung in Gew.-%										
			Legierungselemente						Begleitelemente				
			Al	V	Mo	Sn	Zr	Cu	Fe (max)	O (max)	H (max)	N (max)	C (max)
LT 21 [1]	TiAl5Sn2,5	α	4,0-6,0	–	–	1,5-3,0	–	–	0,25	0,20	0,020	0,07	0,08
LT 22	TiAl8Mo1V1	$\alpha(+\beta)$	7,5-8,5	0,75-1,25	0,75-1,25	–	–	–	0,30	0,15	0,015	0,05	0,08
LT 24	TiAl6Sn2Zr4Mo2	$\alpha(+\beta)$	5,5-6,5	–	1,8-2,2	1,8-2,2	3,6-4,4	–	0,25	0,12	0,015	0,05	0,05
LT 25	TiCu2	α	–	–	–	–	–	2-3	0,20	(0,20)	0,010	0,05	0,1
LT 31 [1]	TiAl6V4	$\alpha+\beta$	5,5-6,5	3,5-4,5	–	–	–	–	0,25	0,20	0,013	0,07	0,08
LT 33	TiAlV6Sn2	$\alpha+\beta$	5,0-6,0	5,0-6,0	–	1,5-2,5	–	–	0,35 1,0	0,20	0,015	0,04	0,05
LT 34	TiAl4Mo4Sn2Si [2]	$\alpha+\beta$	3,5	–	3-5	1,5-2,5	–	–	0,2	–	0,015	–	0,08

[1]) Für spezielle Anwendungsfälle bei tiefen Temperaturen können diese Legierungen mit niedrigen Gehalten an Begleitelementen hergestellt werden.

[2]) Si 0,3-0,7 Gew.-%

Fig. 11: Chemical composition of titanium alloys

Krupp-Marke TIKRUTAN	Werkstoff-Nummer DIN	Werkstoff-Nummer Luftfahrt	Normen VdTÜV	Normen AECMA	Zustand
RT 12 (Pd)	3.7025.10	3.7024	Gruppe I	Ti-PO1	geglüht, zunder-frei
RT 15 (Pd)	3.7035.10	3.7034	Gruppe II	Ti-PO2	
RT 18 (Pd)	3.7055.10	–	Gruppe III	–	
RT 20	3.7065.10	3.7064	Gruppe IV	Ti-PO4	

Krupp-Marke TIKRUTAN	0,2-Grenze min. N/mm^2	Zugfestigkeit N/mm^2	Bruchdehnung min. % [1])	Bruchdehnung min. % [2])	Brucheinschnürung min. % [2])	Kerbschlagarbeit (DVM-Probe[3]) min. J	Biegeradius (105 °C Biegewinkel für Blechdicke $\le$ 2 mm	Biegeradius $>$ 2–5 mm[3])s
RT 12 (Pd)	180	290–410	30	25	35	60	1s	1,5s
RT 15 (Pd)	250	390–540	22	20	30	35	1,5s	2s
RT 18 (Pd)	320	460–590	18	16	30	25	2s	2,5s
RT 20	390	540–740	16	15	25	20	2,5s	3s

[1]) Bleche und Bänder sowie [2]) Schmiedestücke und Stäbe: > 80 mm ∅ bzw. Dicke: Proben in Querrichtung

[3]) Bei Blechdicken über 5 mm

Fig. 12: Mechanical properties of commercially pure titanium grades

Krupp-Marke	Flieg-werk-stoff-Nr.	Zustand	Abmes-sungen mm	0,2 %-Grenze min. N/mm²	Zugfestigkeit min. N/mm²	Zugfestigkeit max. N/mm²	Bruch-dehnung min. %	Bruch-ein-schnü-rung min. %
TIKRUTAN LT 21[1]) (TiAl5Sn2,5)	3.7114	geglüht	0,4–5,0	780	830	–	10	–
		geglüht	< 100	760	790	–	10	25
TIKRUTAN LT 22 (TiAl8Mo1V1)	3.7134	geglüht	0,6–5,0	860	930	–	10	–
		geglüht	< 65	820	890	–	10	20
TIKRUTAN LT 24[1]) (TiAl6Sn2Zr4Mo2)	3.7144	ausgehärt.	< 80	830	900	–	8	25
TIKRUTAN LT 25 (TiCu2)	3.7124	geglüht	0,4–5,0	460	540	–	15	–
		geglüht	< 80	400	540	–	16	35
		ausgehärt.	0,4–5,0	550	690	–	10	–
		ausgehärt.	< 80	540	650	–	10	30
TIKRUTAN LT 31 (TiAl6V4)	3.7164	geglüht	0,6–2,0	870	930	–	8	–
		geglüht	2,0–5,0	870	930	–	10	–
		geglüht	< 80	830	900	–	10	25
		geglüht	< 160	830	900	–	8	20
		ausgehärt.	< 12,5	1070	1140	–	8	20
TIKRUTAN LT 33 (TiAl6V6Sn2)	3.7174	geglüht	0,6–5,0	1000	1070	–	8	10
		geglüht	< 100	930	1000	–	8	–
		ausgehärt.	< 25	1170	1240	–	6	15
TIKRUTAN LT 34 (TiAl4Mo4Sn2Si)	3.7184	ausgehärt.	< 25	960	1100	1280	9	20
		ausgehärt.	25–100	920	1050	1220	9	20
		ausgehärt.	100–150	870	1000	1200	9	20

Fig. 13: Mechanical properties of titanium alloys

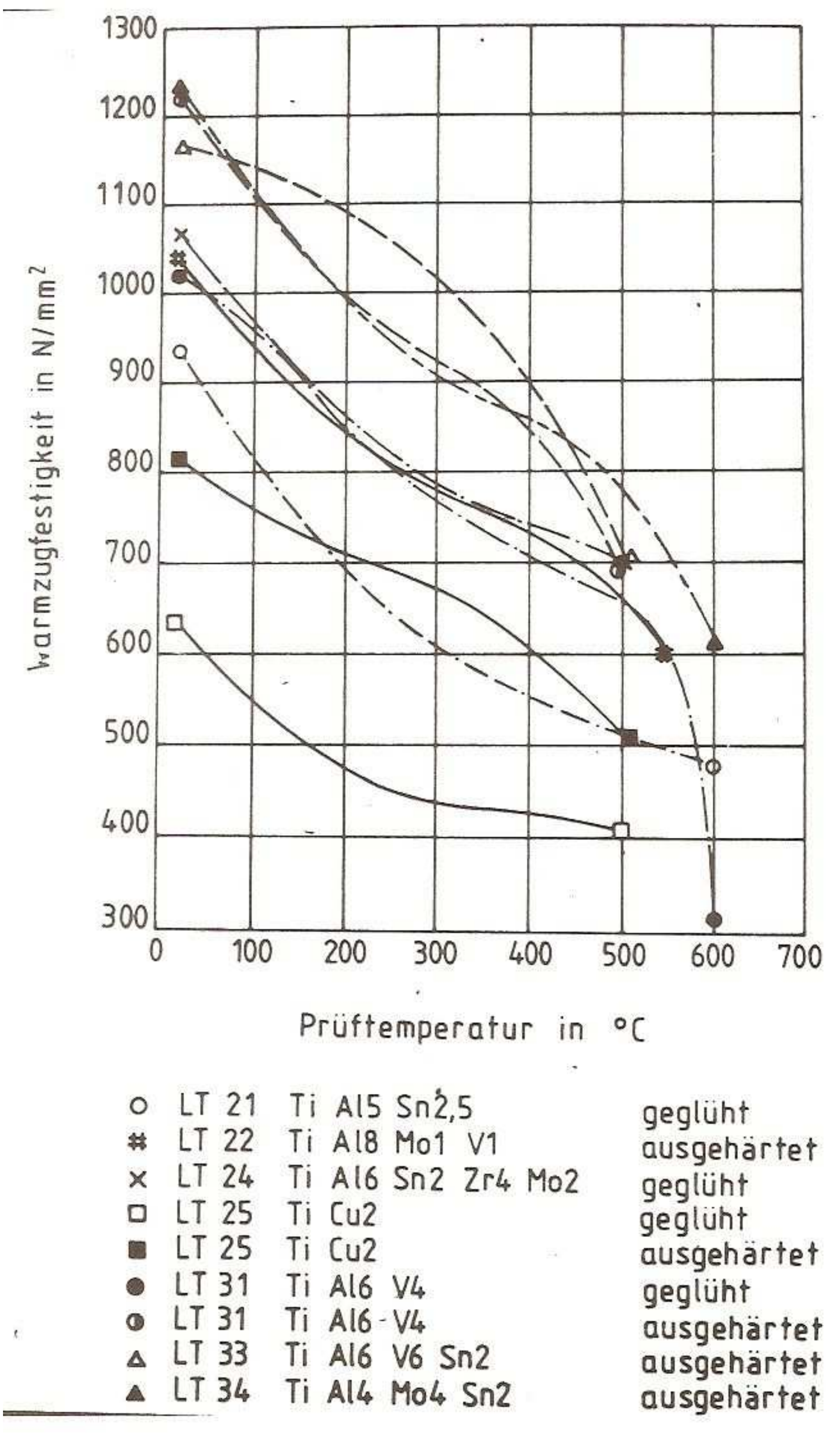

Fig. 14: Warm strength of titanium alloys

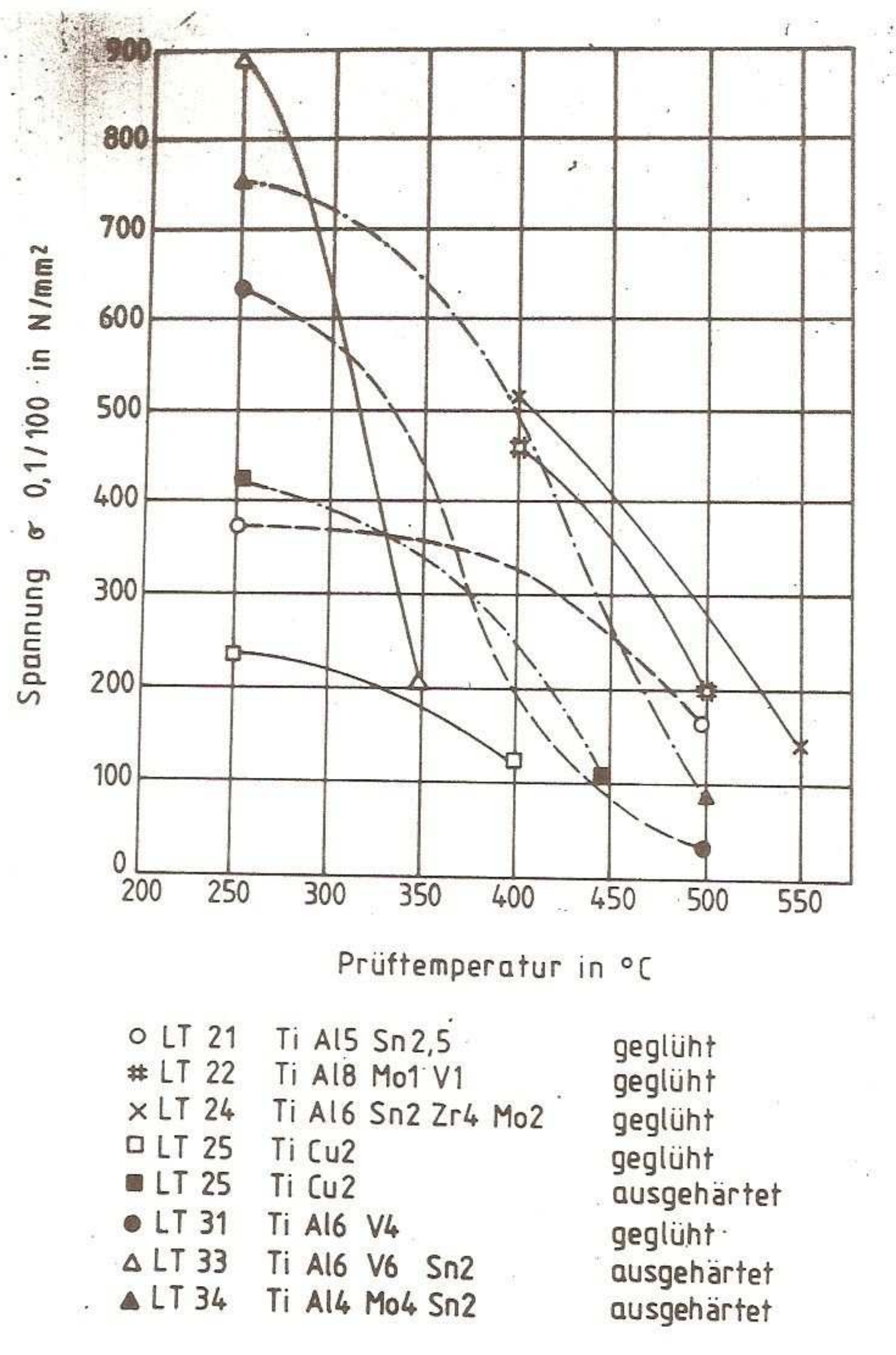

Fig. 15: Creep properties of titanium alloys

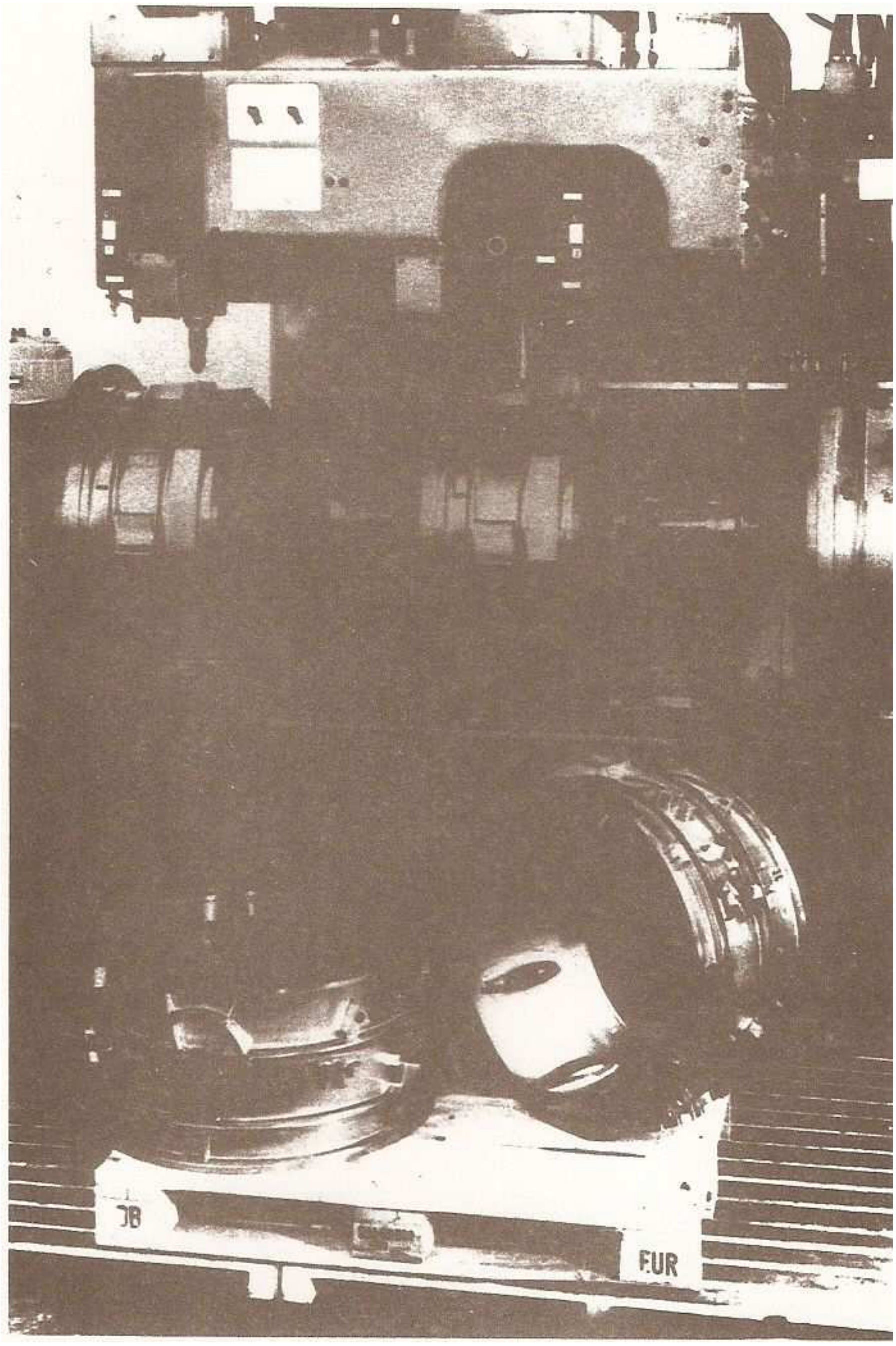

Fig. 16: Outer casings for the Tornado engine

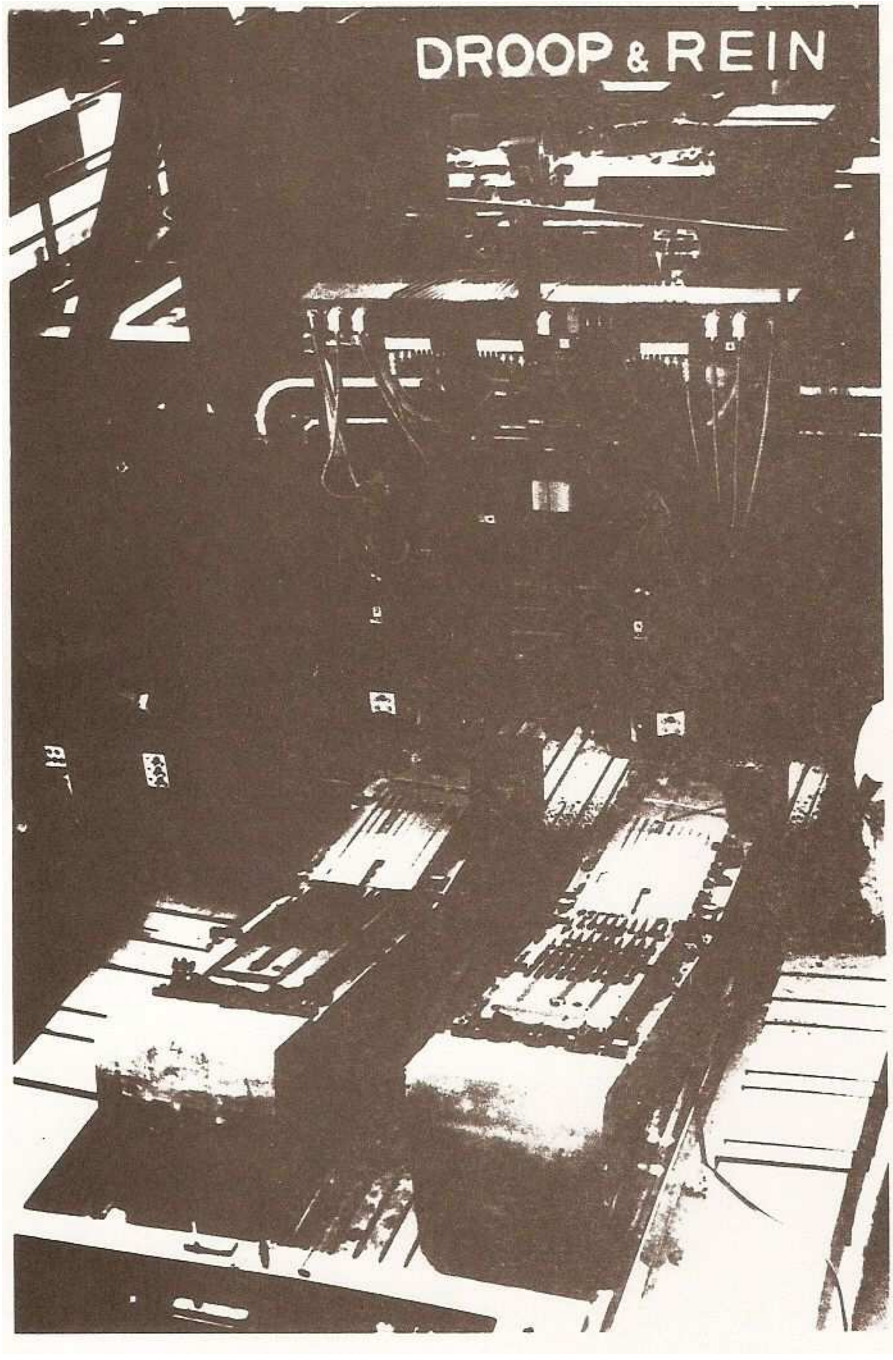

Fig. 17: Machining of plates for the wing box
Of the Tornado

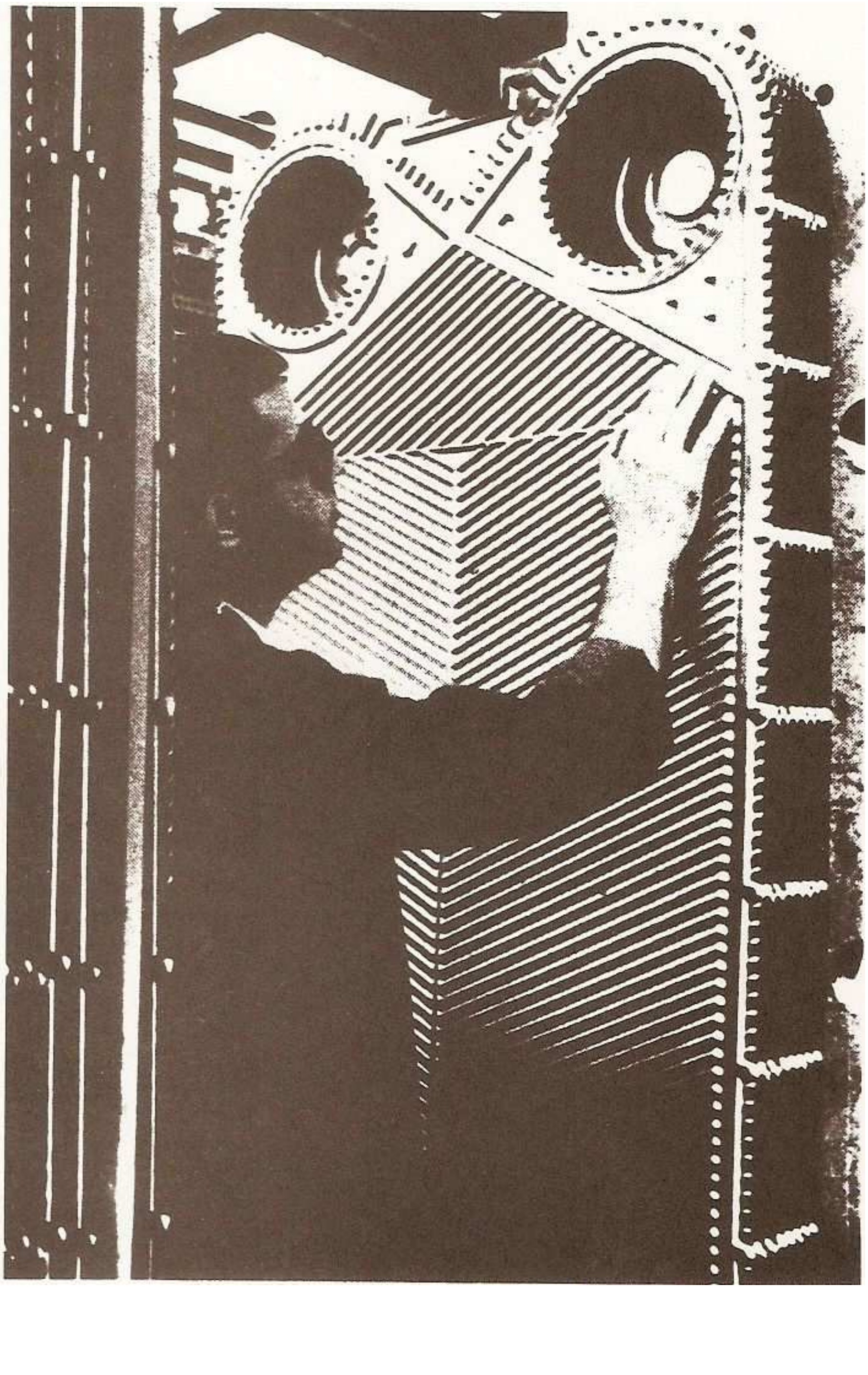

Fig. 18: Heat exchanger plates

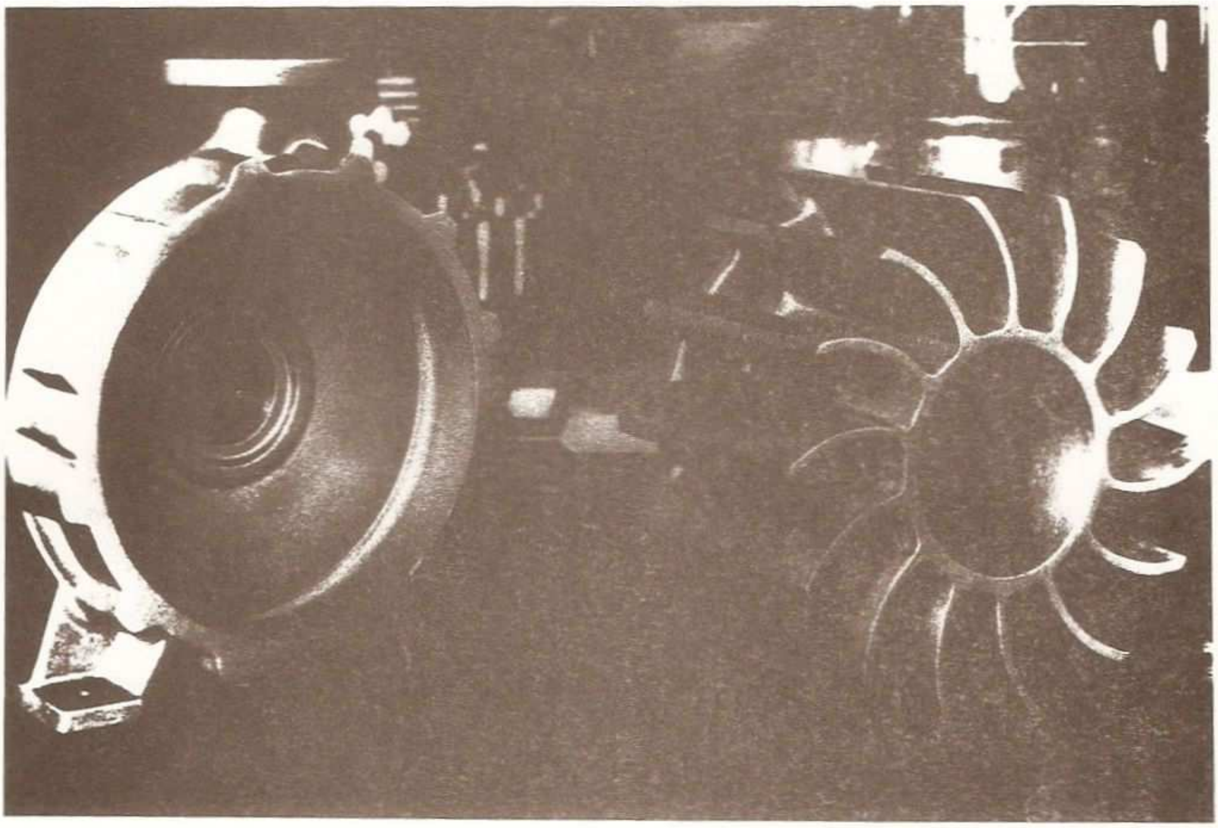

Fig. 19: Pump casing and impeller

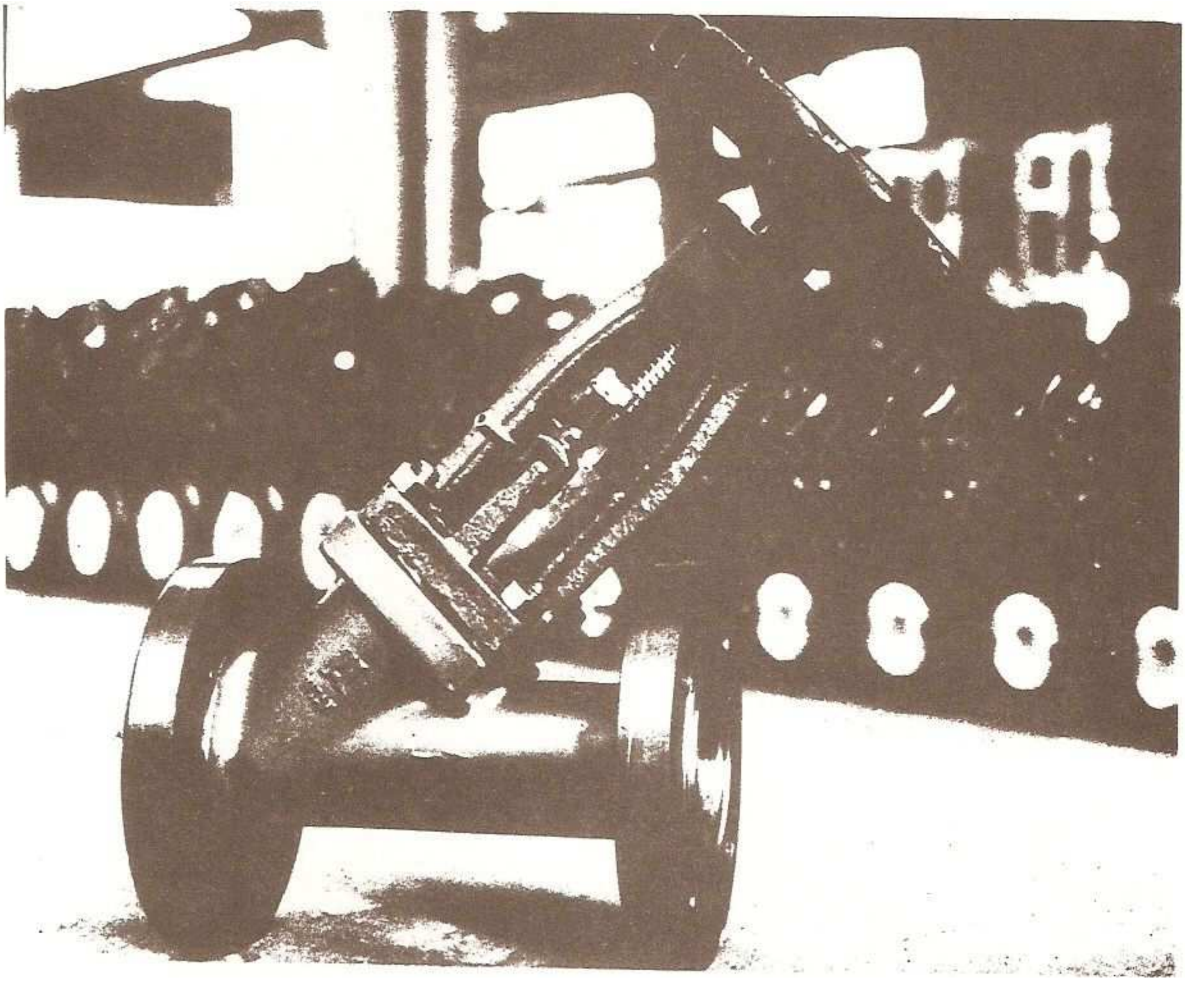

Fig. 20: Valve

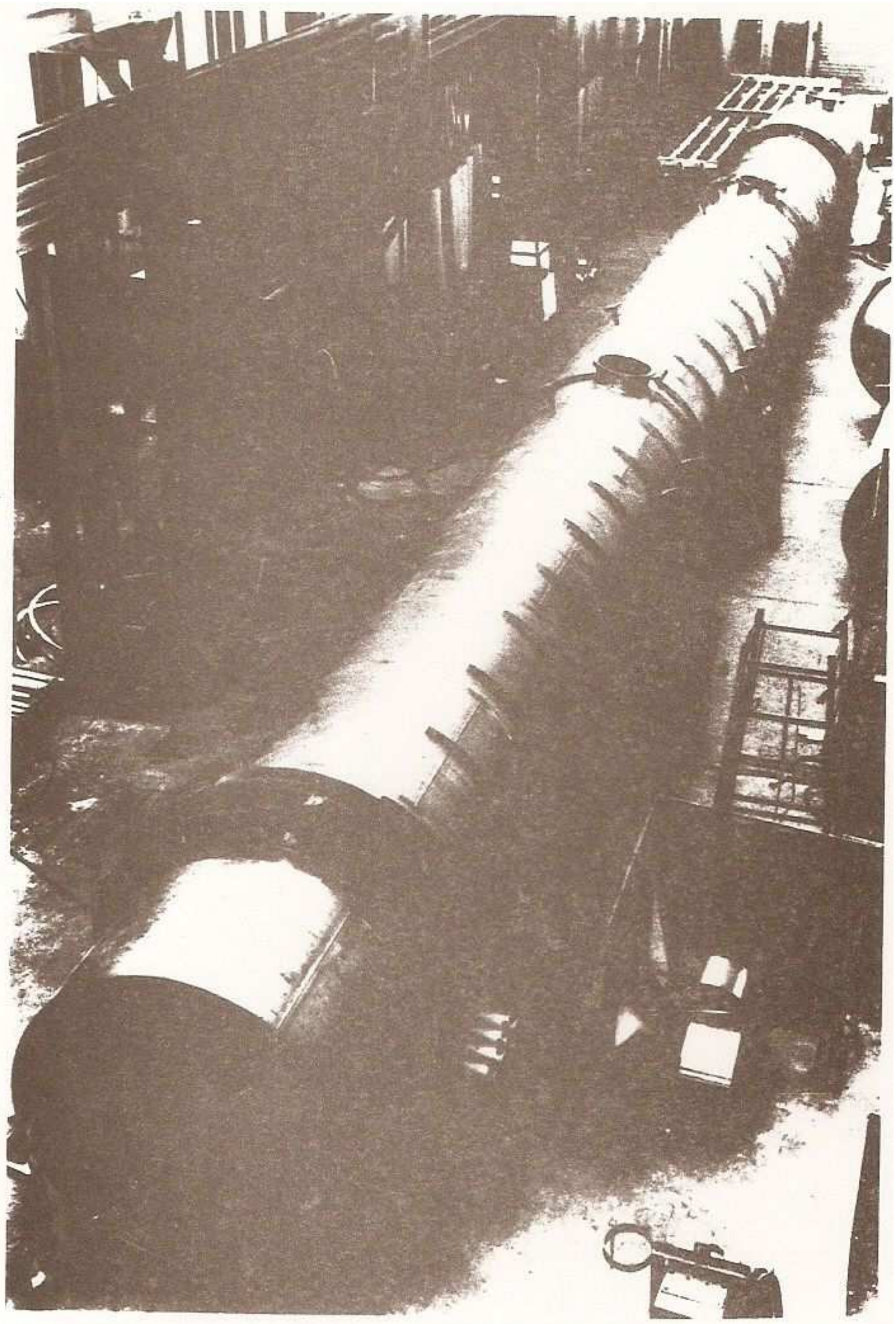

Fig. 21: Reaction vessel

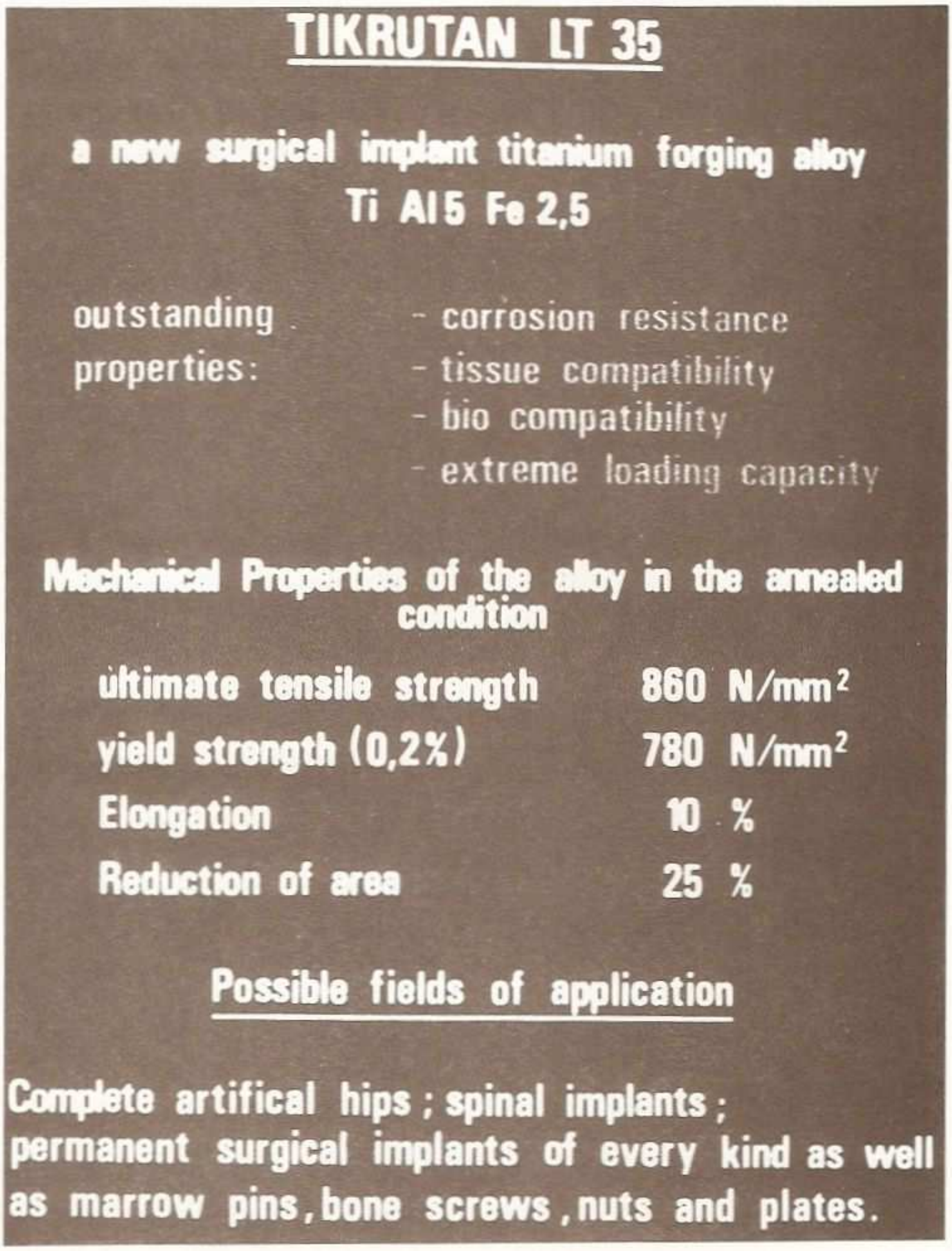

Fig. 22: Titanium forging alloy for surgical implants

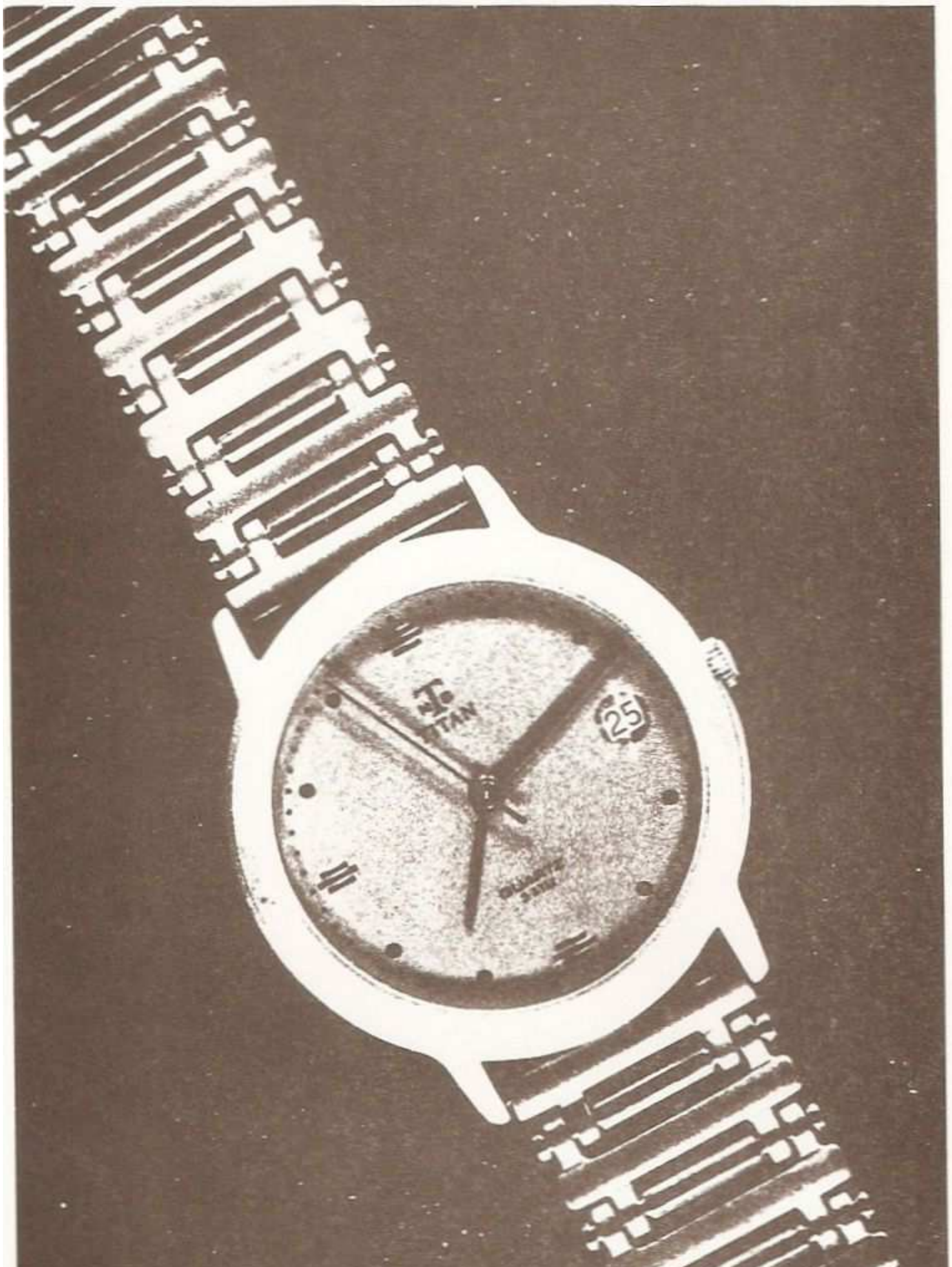

Fig. 23: Watch with bracelet

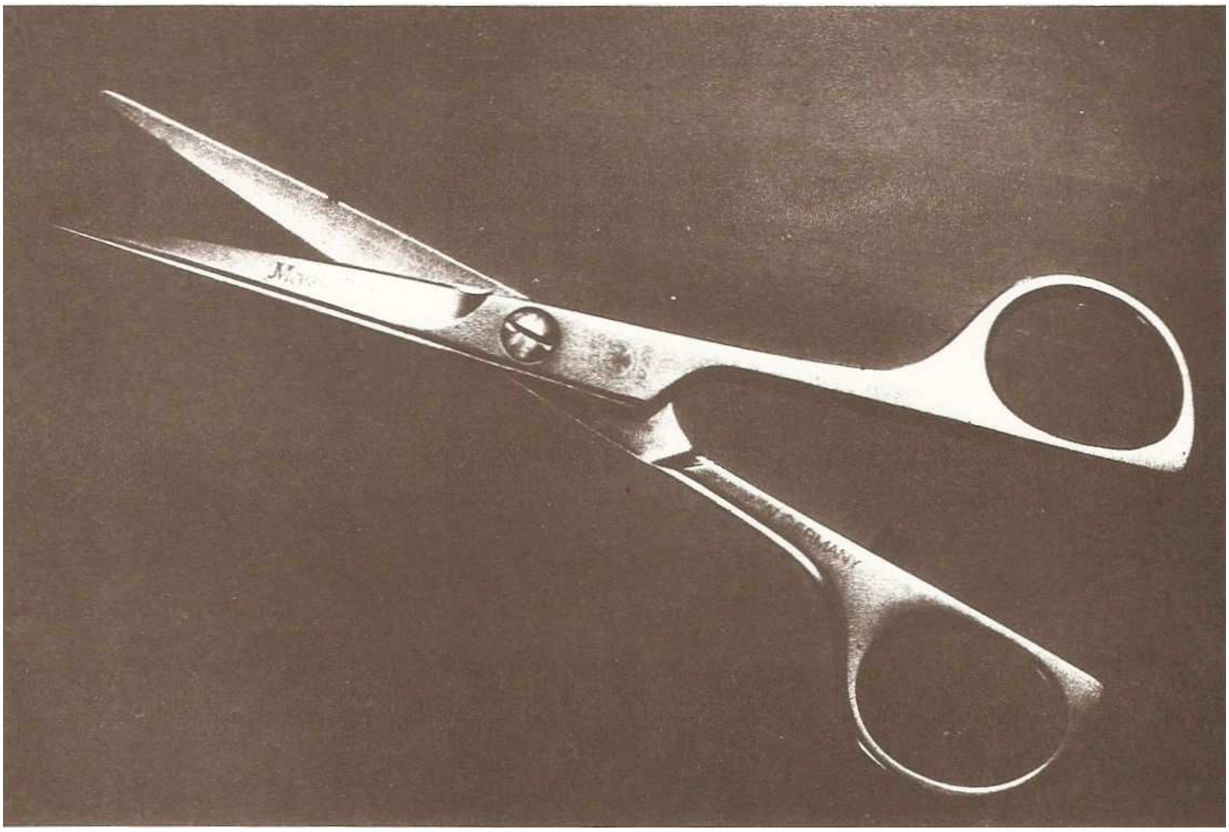

Fig. 24: Scissors with hard titanium nitride layer

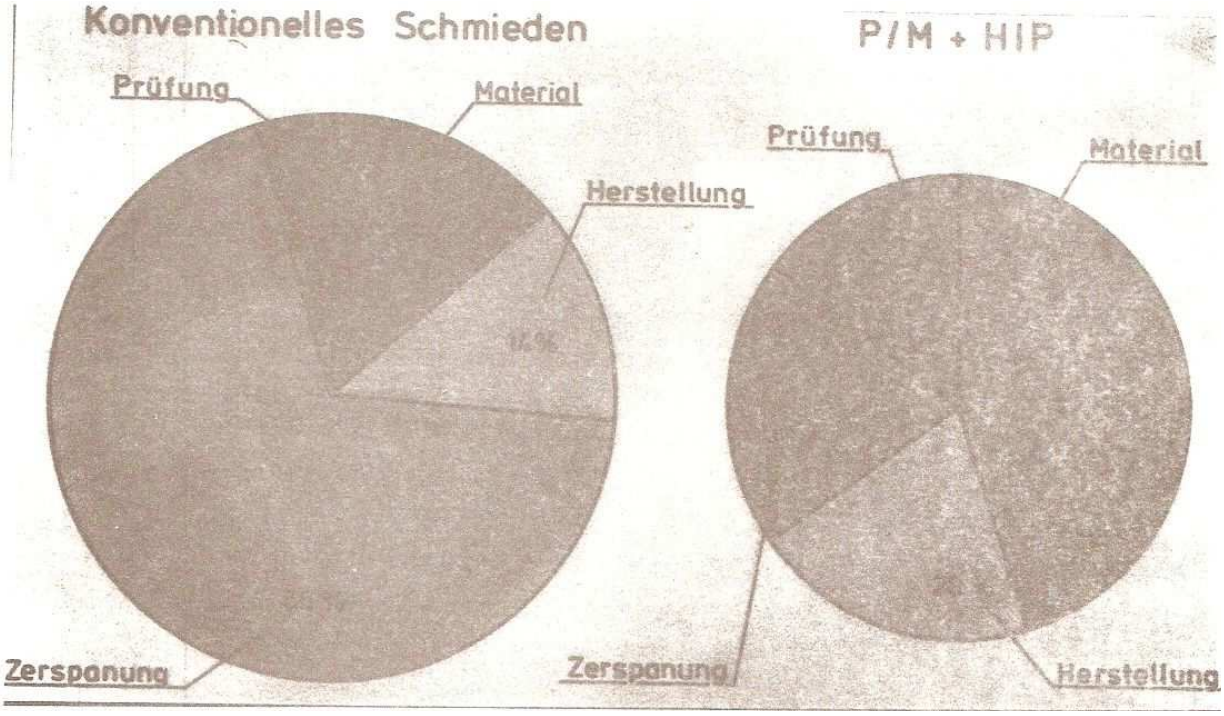

Fig. 25: Cost comparison of production steps
For forged and P/M material

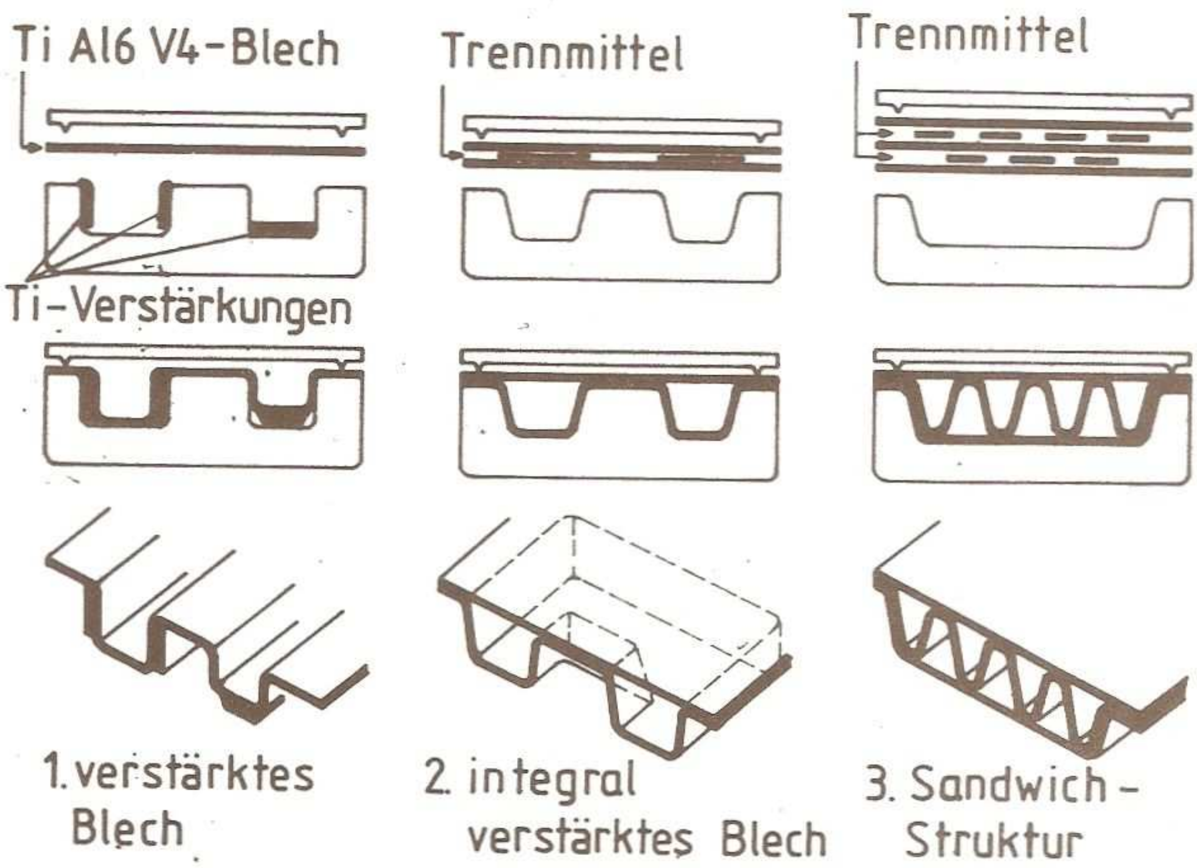

Fig. 26: Superplastic forming and diffusion bonding