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MECHANICAL PROPERTIES OF HOT ISOSTATIC PRESSED P/M-TITANIUM FOR HELICOPTER COMPONENTS

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Abstract:

Due to generally high machining losses which have to be accepted in the production of titanium components as well as the prices and the increasing shortage in the supply of raw material, industry saw itself compelled to develop alternative technologies like of hot isostatic pressing of powder-metallurgical components.
This technology is applied in the aircraft industry and has been handled for some years mainly in the U.S. and in Germany.

Economy of production and material properties corresponding at least to those obtained with the conventional method constituted two conditions for the introduction of this new technology.

The laboratory scale components, which were manufactures by means of this process, prove that the material properties correspond to those of the conventional forging material.

To provide this evidence, static and dynamic tests were carried out on both individual samples and samples taken from components. The component trials conducted also proved successful. Systematic structure examinations were performed on specimens and components to permit a detailed description of the material.

These acitivities were sponsored by the German Ministry of Defence.

1. Introduction

The widespread use of titanium alloys in the aerospace industry is due primarily to its low density and high strength. The manufactured of intricate shapes is complicated and expensive. Depending on the geometrical complexity of the finished component, up to 90w% (weight per cent) of the forged blank can be lost trough machining. A major reduction in the manufacturing costs can be achieved by the following near net shape processes:

- superplastic forming(1)
- investment casting (2)
- hot isostatic compaction of powder metals.

Titanium powder metallurgy is an interesting alternative. In addition to the above mentioned favomable mechanical properties of titanium alloys, a powder metallurgical approach combines a reduction in the amount of standing material with significantly decreased machining. This results in overall lower manufacturing costs.

Previous work on P/M titanium components manufactured under laboratory conditions has shown that the mechanical properties of the corresponding weight alloy can be obtained.

Hot isostatic pressing was developed approximately 25 years ago almost simultaneously by the Battelle Institute in Columbus/Ohio and ASEA in Sweden(4),(5). Battelle was working on joining and bonding processes whereas ASEA developed out this technique to manufacture artificial diamonds.

The last few years have seen the increasing use of HIP technology (hot isostatic pressing) in powder metallurgy. Its application in aerospace has been directed primarily to the development and manufacture of titanium, nickel base and high strength steels and ceramic components(6).

The technological advantages are:

- a decreased usage of expensive alloying elements
- a reduction in machining
- the manufacture of components from unforgeable or difficult to forge materials
- isotropic properties.

In addition to the cost advantages and improvement in mechanical properties, powder metallurgy opens up the possibility of manufacturing completely new materials with a combination of new hardening mechanisms (precipitation and despersion hardening) not attainable by other processes (7).

2. Process technology

Parts are manufactured by filling powder into preformed metallic or ceramic capsules, which are degassed, evacuated and closed under vacuum. The powder filled capsule is subjected to pressure and temperature applied simultaneously in the HIP unit. This results in a theoretically (w %) dense structural component with near net dimension (Fig 1).

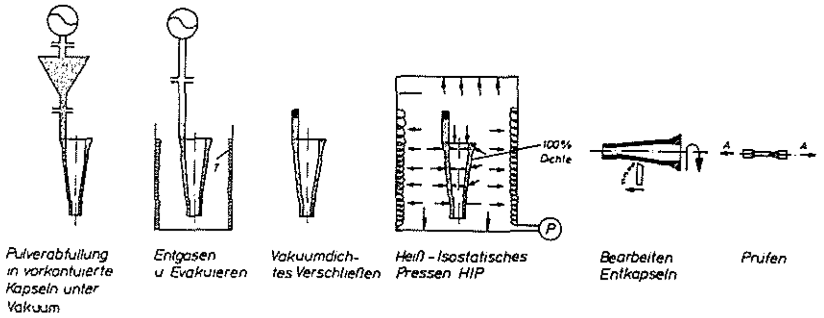


Fig 1

2.1 Powder & powder manufacturing processes

Titanium powder used for the manufacture of heavy duty components must fulfil the following conditions:

- it must be prealloyed with a chemical composition corresponding to that of the finished part
- the particle size should be such that the "tap density" is $\sim$ 60% of the theoretical density
- the powder particles should be primarily spherical
- the powder should be free of foreign particles. Local variation in the chemical composition must be avoided.

The surface morphology as well as a microanalysis composition of a powder particle are reported in Fig 2 and 3.

The chemical composition, particle size analysis and tap densities of a batch of Ti6Al4V powder are included in Fig 4.

Titanium powder cannot be manufactured from an alloy melt using conventional argon or hydrogen atomisation techniques. Due to its highly reactive nature precautions have to be taken to prevent a chemical reaction occurring with oxygen, nitrogen, or the crucible material. As a result, manufacturing processes have been developed to obtain atomised metal free of contaminates.

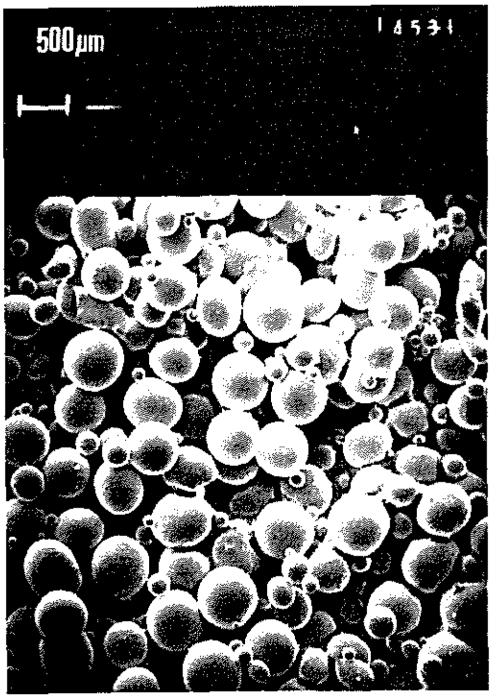


Fig 2

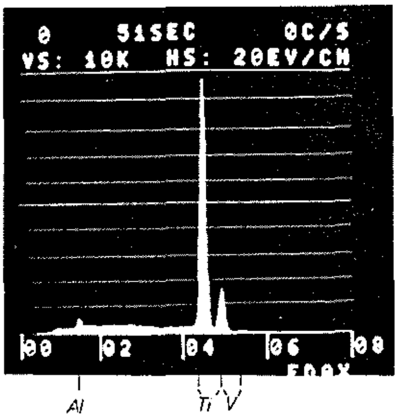


Fig 3

The following two technically viable processes are used for manufacturing titanium powder:

- REP Rotating Electrode Process (Are or Plasma process)8)
- REP Electron beam melting in vacuum9).

Recently developed processes, which are not yet in use, can lead to a further improvement in powder properties and a reduction in manufacturing costs10),11).

Powder Ti6Al4V Size 1250 µm

Chem. Analysis	Sieve Analysis		Tap Density	
	µm	w %	Powder	Density
Al : 5,9 %	1000	1,2		
	1000 - 710	8,1	1250 µm	65 %
V : 4,1 %	710 - 500	17,6		
	500 - 355	18,7	710 µm	68 %
Fe : 0,17 %	355 - 200	29,4		
	250 - 180	14,7		
Cr : 0,02 %	180 - 125	7,8	500 µm	68 %
	125 - 90			
O : 0,18 %	90 - 63	0,8		
	63			
H : 0,001 %				
C : 0,03 %	analog Stahl-Eisen Prüfblatt		Stahl-Eisen Prüfblatt	
Ti : Bal.	81 - 69		83 - 69	

Fig 4

2.2 Capsule technology

In order to manufacture parts with near net dimensions, the powder is poured into metallic or ceramic capsules. Basically, three processes are currently used:

- plain carbon steel or stainles steel capsules are used for axially symmetrical components. These capsules can be cold formed into the required shape without any machining (Fig 5)
- galvanoplastic electrolytic nickel (Fig 6). A wax core with an electrically conductive surface layer acts as a substrate.
- ceramic capsule

An investment cast, thin walled ceramic container (capsule) is filled with powder[12]. This is placed in a simple steel capsule, which is topped up with loosely filled ceramic.

Galvanoplastic nickel and ceramic capsules were used for the development of the helicopter components described here. The electrolytic nickel capsules were prepared at MBB's Central Laboratories, the ceramic capsules at the Krupp Research Institute as a part of a Ferderal Defence Ministry (BMVg) sponsored ZTL-programme.

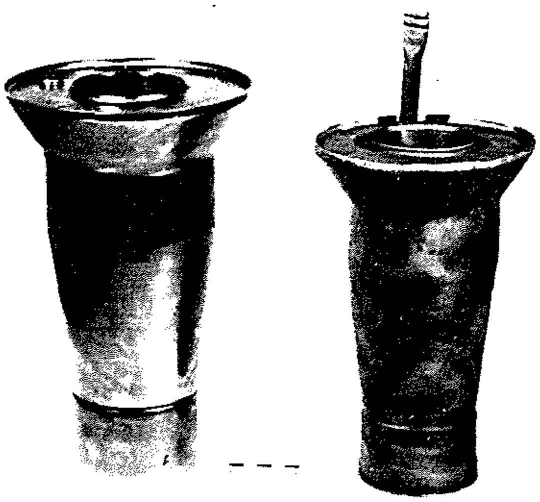


Fig 5

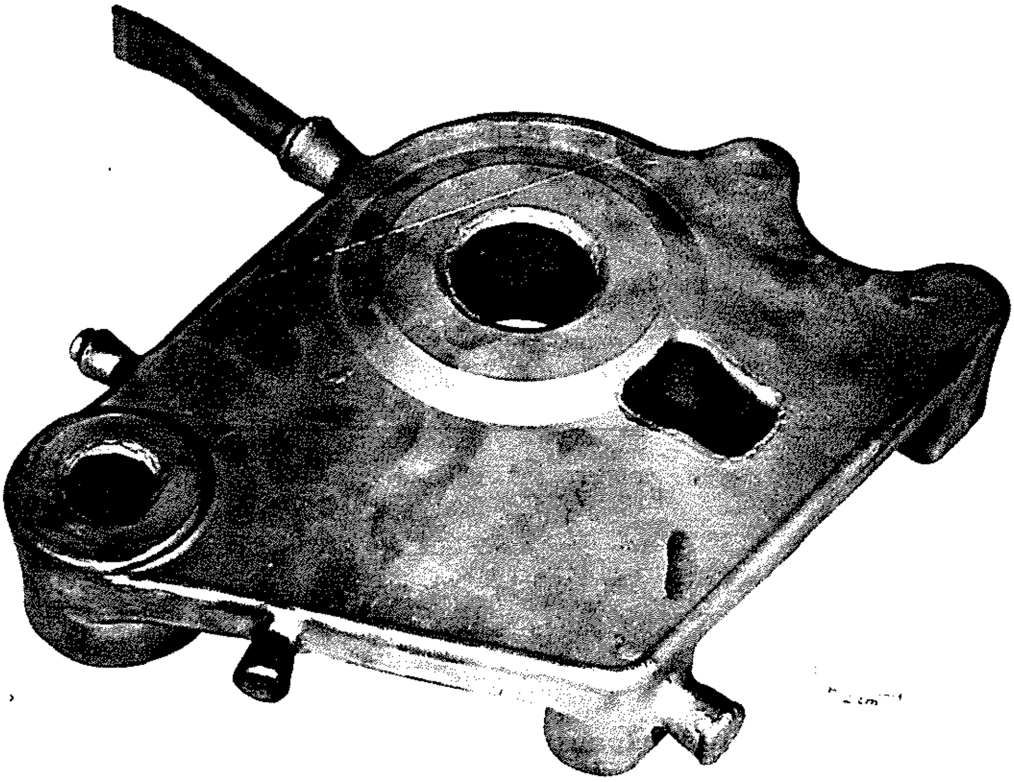


Fig 6

2.3 Hot isostatic pressing

Hot isostatic pressing is basically a sinter process. Capsules are filled with powder, evacuated and closed under vacuum. They are subjected to simultaneous isostatic pressure and high temperature. Theoretically dense (w % density) parts are obtained in a one step process. Subsequent forming or shaping is unnecessary.

Typical HIP parameters for Ti6Al4V parts are:

Temperature	: 920 - 930 °C
Pressure	: 1000 - 1500 bar
Time at Temperature (Sook)	: 1 - 3 hours

Argon acts as the pressure transfer medium in the autocalve. A typical HIP cycle is schematically shown in Fig 7.

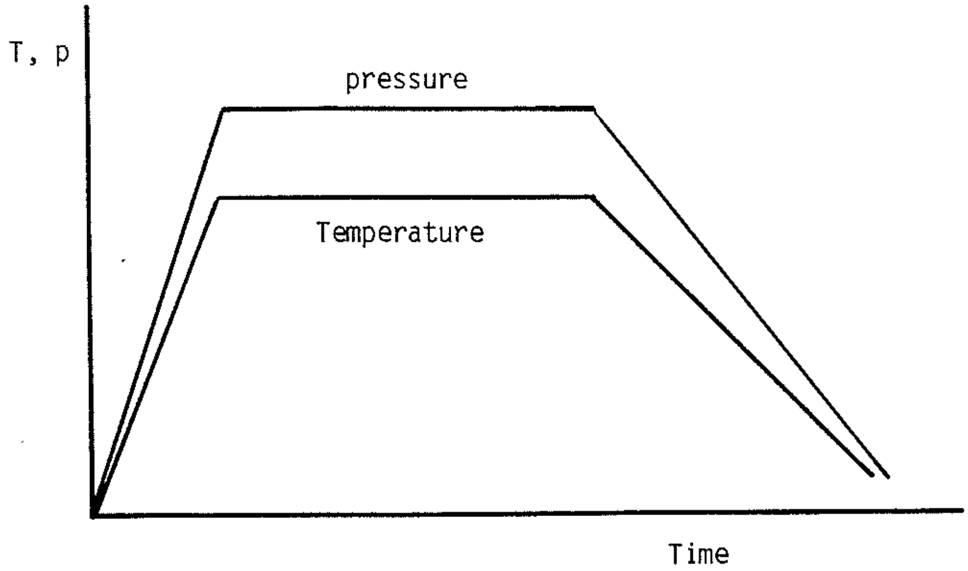


Fig. 7

Fig 7

The powder filled capsule is subjected to isostatic pressure. Due to the difference in the tap density and theoretical density of the powder, shrinkage occurs in all directions. The reduction in volume of the capsule is determined by the shrinkage factor. Expensive forging dies are not required in the HIP process.

After pressing the parts are finish-machined capsules and do not have to be removed prior to machining. This is obligatory when using ceramic capsules.

Due to uniform cooling in the autoclave, HIPed components are practivally stress relieved. Additional stress relief tempering operations are unneccesary. Dimensional disproportion due to subsequent machining dues not occur.

3. Microstructure of P/M HIP Ti6Al4V

The property characteristics of PM-HIP-Ti6Al4V are determined to a great extent by the microstructure. Micrographs prepared from randomly selected sections of hot isostatically pressed parts are reproduced in Fig 8 and 9. Basically the microstructure consists of acicular $\alpha+\beta$ together with some equiaxed α -grains.

Fig 8 200:1

Fig 9 200:1

The micorstructure of the HIP compact is similar to that of the powder particle. This is because hot isostatic pressing was carried out below the $\alpha + \beta / \beta$ transes. Grain growth and other microstructural charges have not occurred despite the slow cooling rate. The mechanical properties (static & dynamic) of PM Ti6Al4V hot isostatically pressed under these conditions are the same as those of the corresponding wrought alloy.

4. Mechanical properties

4.1 Static tensile tests

Static tensile tests were carried out with seven specimens at each of the following:
room temperature, -50 °C, and +300 °C. The specimens were taken from structural parts, the elongation rate was 2 mm/min.

Starting from the mean values and the corresponding scatter of the $P_{p0,2}$ and R_m results, working values for 90 % survival probability and 95 % confidence level were calculated using

MIL-HDBK-5c, Table 9.6.4.1. Table 1 shows the results. The terms in brackets are the values of the forged titanium 3.7164 as given by the German aircraft specification (LN).

	Test Temperature [°C]	Yield Strength $R_{p0,2}$ [N/mm²]	Ultimate Strength R_m [N/mm²]	Elongation A_5 [%]	RA Z[%]
HIP-Material	Room	898(870)	932 (920)	13 (10)	27(20)
	- 50	1066	1128	9	15
	300	547	685	18	51

Tab. 1: Static properties of HIP-titanium

As can be readily seen, the $R_{p0,2}$ and R_m values for HIP-titanium at room temperature macht the values of forges titanium.

The modulus of elasticity (Young's modules) obtained from the load/extension diagramme is 120 kN/mm².

A data sheet with BWB (Bundesamt für Wehrtechnik und Beschaffung - German Office for Military Procurements) approved material properties is reproduced in Figs. 10 and 11.

Werkstoff-Leistungsblatt * Oktober 1979

.	Titanlegierung Ti Al6 V4 Pulvermetallurgisch heißisostatisch gepreßte Bauteile	3.7164 Blatt

		Al	V	Fe	C	N_2 1)	O_2 2)	H_2 3)	H_2 4)	andere 5)	Ti
Chemische	Elemente	Al	V	Fe	C	N_2 1)	O_2 2)	H_2 3)	H_2 4)	andere 5)	Ti
Zusammensetzung	von	5,5	3,5	-	-	-	-	-	-	-	-
Gew.-%	bis	6,5	4,5	0,3	0,08	0,05	0,20	0,0125	0,015	(0,4)	Rest

Spalte	1	2	
Zeile 1	Werkstoff-Kennzahl	3.7164	
2	Eigenschaften im Zustand	der Anlieferung und Verwendung	
3	Herstellungsart	pulvermetallurgisch 6) heißisostatisch gepreßt 7)	
4	Wärmebehandlungszustand	-	
5	Oberflächenzustand	gebeizt oder bearbeitet	
6	Halbzeug der Bauteile Abmessungen in mm (Dicke)	Bauteile > 10 mm	
7	Probenrichtung Eigenschaften 8	L und LT 8	
8	0,2-Grenze $\sigma_{0,2}$ N/mm^2	890	
9	Zugfestigkeit σ_B N/mm^2	930	
10	Bruchdehnung δ_5 %	10	
11	Brucheinschnürung ψ %	20	
12	Härte HB 30	320 - 350	
13	E-Modul KN/mm^2	120	
14	Preßparameter Druck bar Temp. °C Haltezeit h	1000-1500 900- 930 1- 3	
15	Wärmebehandlung	Abkühlung im Autoklaven	
16	Zusätzliche Prüfungen	siehe Seite 2 Zeile 19 und 20	
17	Technische Lieferbedingungen	Entwurf ≙ LN 65040	

* Entwurf

Fig 10

Spalte	
Zeile 18	3.7164
19	Kerbzeitstandversuch bei Raumtemperatur im Zustand HIP und .1 Probenform nach LN 9047 Abmessungen Belastung Standzeit Bauteile 10 bis 30 mm 1220 N/mm^2 5 h
20	Kerbschlagzähigkeit bei Raumtemperatur a_K = 3 mkp/cm^2 (DVM-Probe)
	Bemerkungen: 1, 2, 3 Im Pulverzustand 4 Im Zustand des fertigen Teiles 5 Keine Fremdelemente, welche nicht bereits in der Verpulverungselektrode enthalten sind 6 Herstellung mittels vorkonturierte Kapseln 7 Heißisostatisch gepreßt im Autoklaven 8 Keine Anisotropie der Eigenschaften
	Bemerkung:

Fig 11

4.2 Fatigue Testing

Two series of fatigue tests have been carried out, namely (i) with bar specimens with a notch factor $\alpha_K = 1$ and (ii) plate specimens with a notch factor $\alpha_{KN} = 2.5$, see Fig. 12. Specimens have been taken out of three semifinished products: a tube, a simplified helicopter inner sleeve component and a hemispherical shell.

4.2.1 Bar Specimens ($\alpha_K = 1$)

Fatigue tests with unnotched bar specimens were rung at a stress ration of R = 0.25. Results are shown in Fig. 13. Using Stromeyer's equation, the S/N-curve for both a 50 % survival probability and confidence level is

$$\sigma = 180 + 1264 / \sqrt[3]{N}, \quad [N/mm^2]$$

where N is the number of load cycles, and 180 is the endurance limit. In Fig 13 the working curve for a survival probability of 99 % and a probability level of 95 % is also given.

4.2.2 Plate Specimens ($\alpha_{KN} = 2.5$)

Constant amplitude tests for notched plate specimens with a notch factor $\alpha_{KN} = 2.5$ (related to the net cross section) taken from a hemispherical shell were carried out for stress ratios R = 0.1, 0.25 and R = -1.
The tests yielded the 50 % survival probability S/N-curves

$$\sigma = 120 + 2656 / \sqrt[3]{N} \quad [N/mm^2] \quad \text{for } R = 0.1$$

$$\sigma = 110 + 1921 / \sqrt[3]{N} \quad [N/mm^2] \quad \text{for } R = 0.25$$

and $$\sigma = 169 + 2125 / \sqrt[3]{N} \quad [N/mm^2] \quad \text{for } R = -1,$$

see Figs. 14 a, b, c.

The corresponding scatter factors were

$$s = 0.0402,$$

$$s = 0.0416$$

and $$s = 0.0602.$$

From the above tests, a modified Goodman diagramme was derived, see Fig 15.

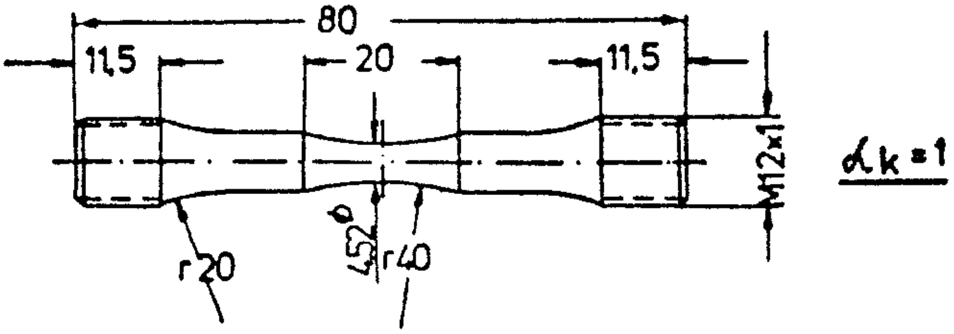


Fig 12 a) Bar specimen for fatigue testing, α_K = 1

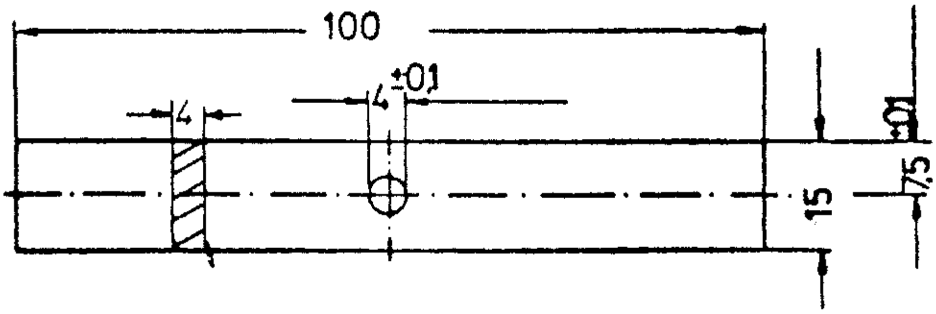


Fig. 12 b) Plate specimen for fatigue testing, α_{KN} = 2.5

4.3 Static & dynamic values of a PM HIP Blade fitting

Test coupons taken from a PM HIP blade fitting (Fig 12) were used to determine static & dynamic values. These are compared with the nominal values for forges Ti6Al4V in the following table.

The dynamic values were obtained in tension-tension tests.

Test parameters: Stress range : $R = 0{,}1$

Form factor : $\alpha_K = 2{,}5$

In the S-N diagramme, the values marked with an open circle o were obtained with test coupons taken from the blade fitting.

	Nominal value wrought material	Actual value HIP-material
Ultimate strength R_m N/mm²	900 - 1150	965
Yield strength $R_{p0,2}$ N/mm²	840	895
Elongation A_5 %	8	14
Hardness HB30	350	320
Impact strength a_k J/cm²	25	39

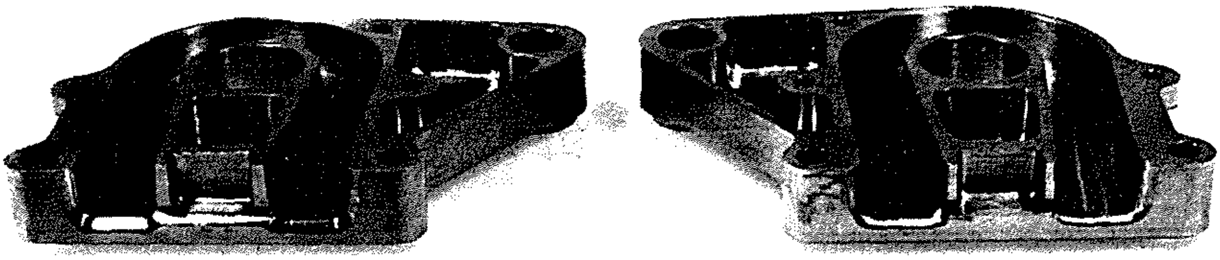


Fig. 12

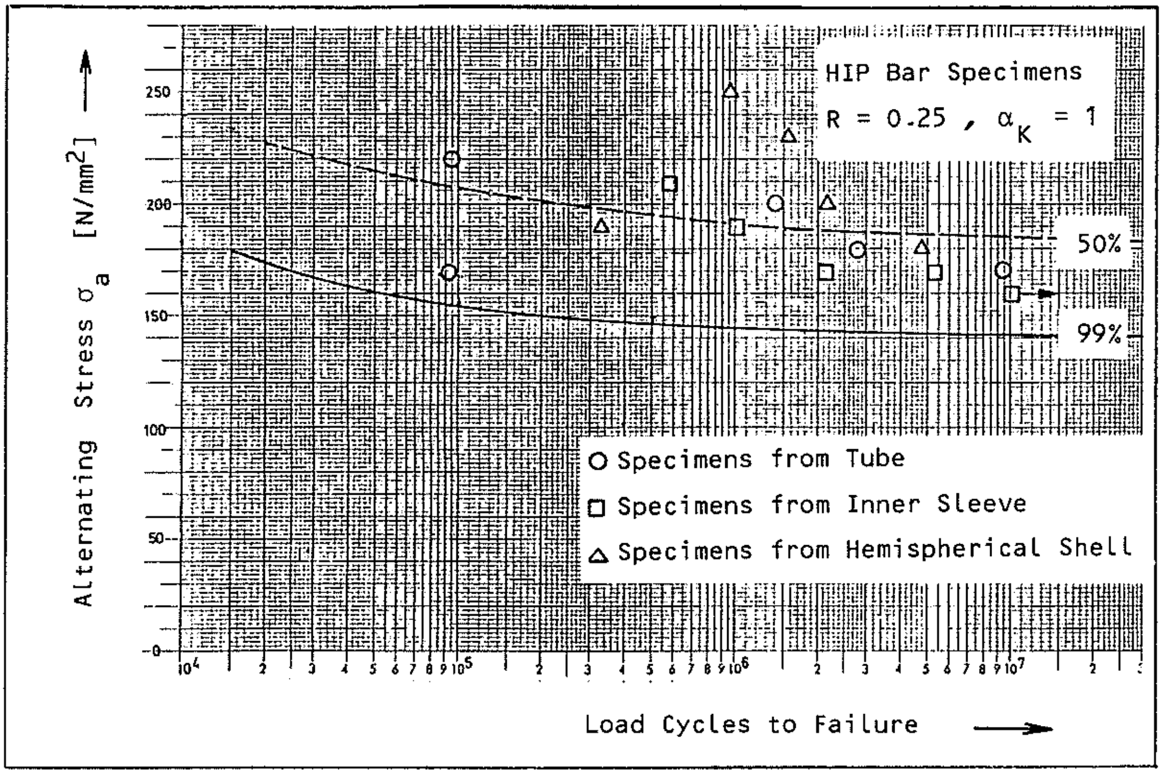


Fig. 13: Fatigue test results from unnotched bar specimens

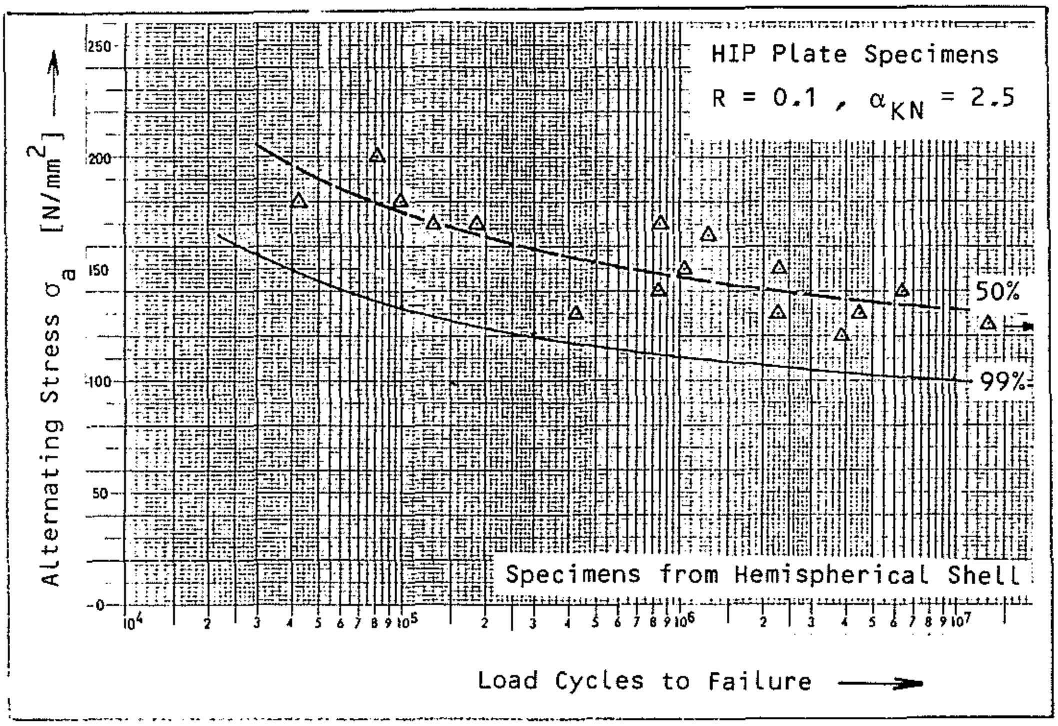


Fig. 14a: Fatigue test results from notched plate specimens (R = 0.1)

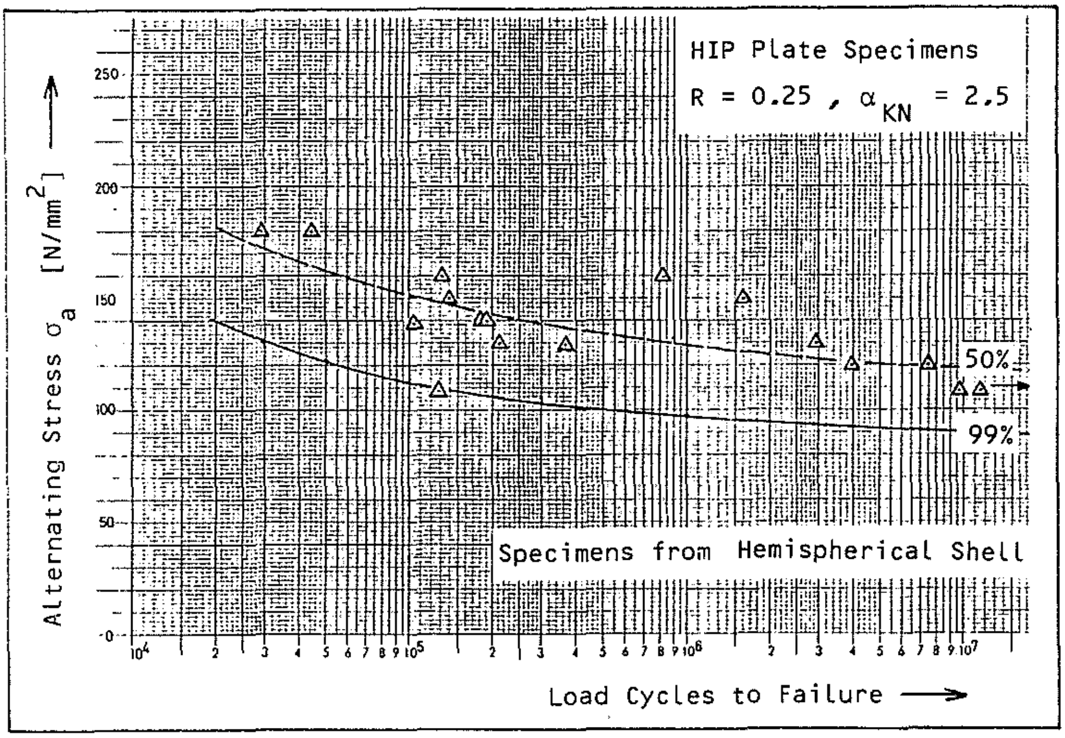


Fig. 14b: Fatigue test results from notched plate specimens (R = 0,25)

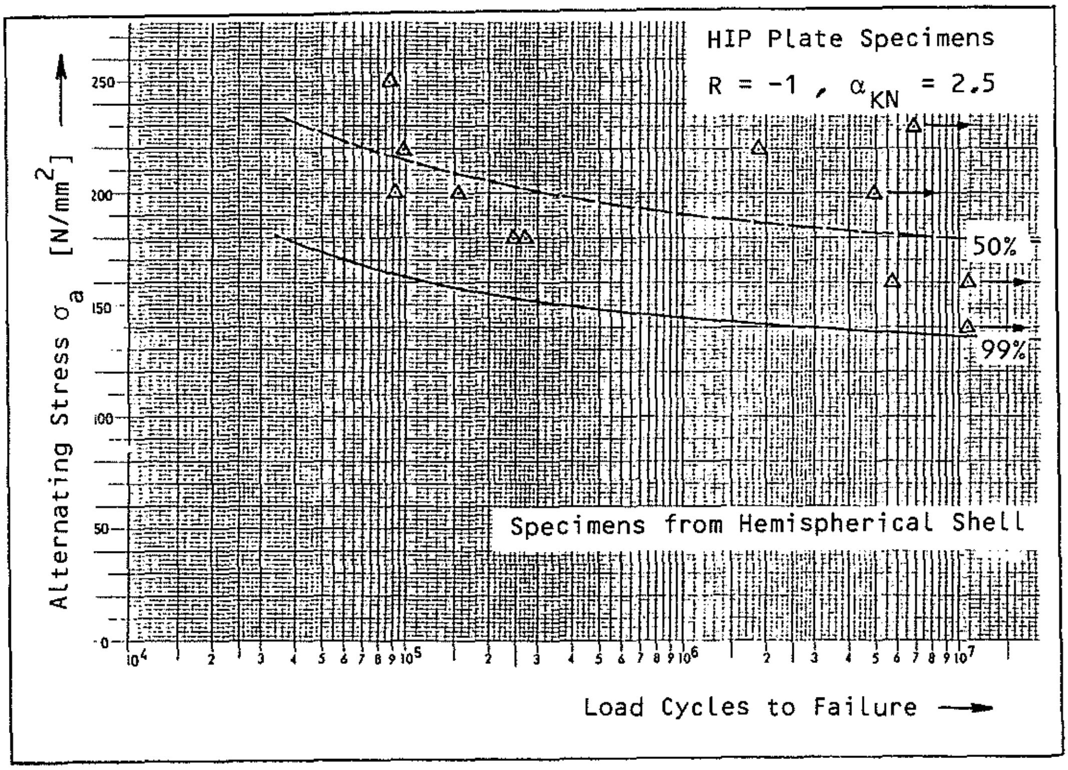


Fig. 14c: Fatigue test results fromnotched plate specimens (R = -1)

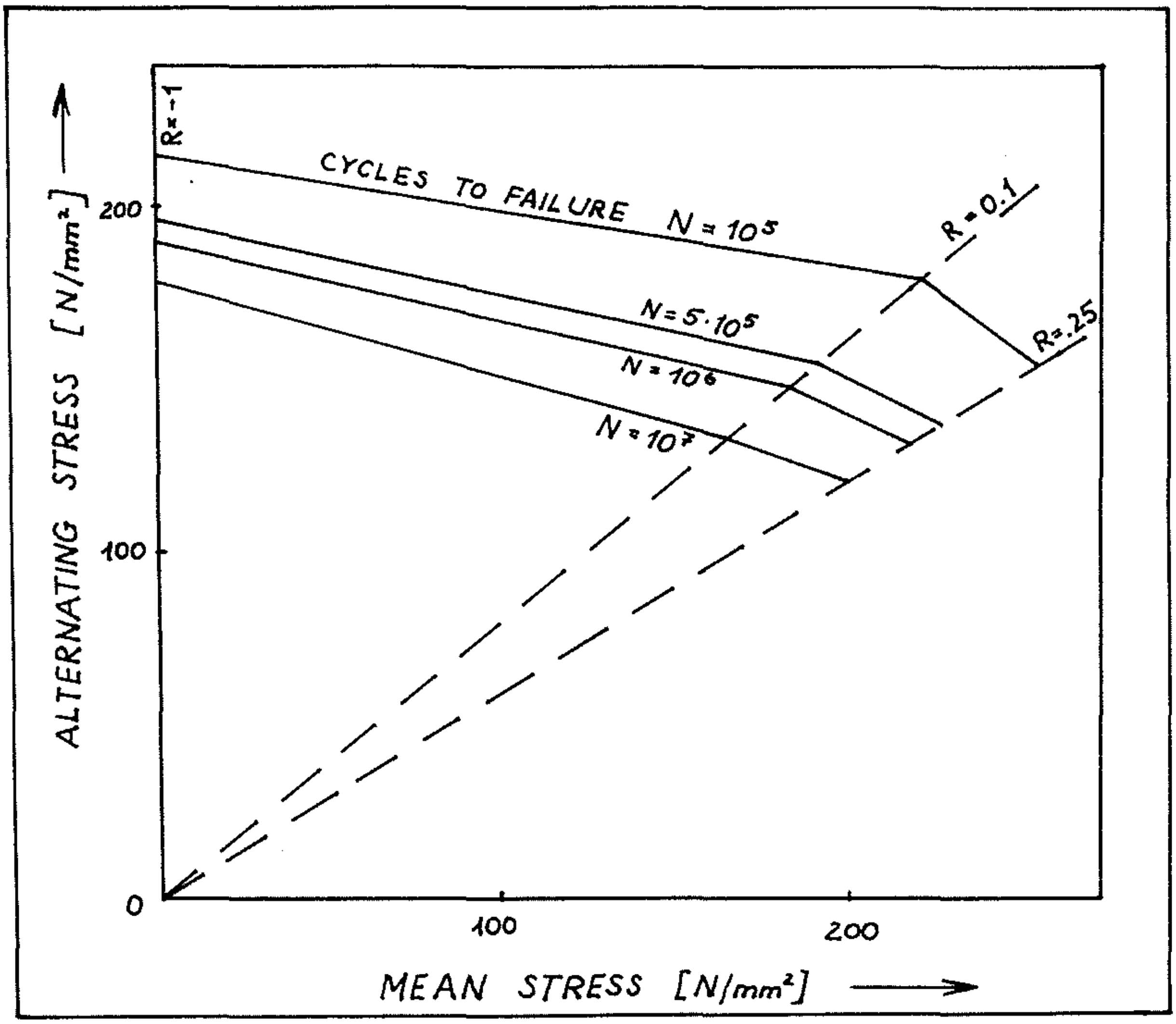


Fig 15: Modified Goodman diagramme for HIP-titanium, $\alpha_{KN} = 2.5$

5. Component Test

Besides the testing of specimens, a HIP manufactured helicopter blade fitting was also fatigue tested.

The BO 105 main rotor blade fitting transmits the main rotor blade loads to the rotor blade, see Fig 16. In the test rig, which is shown in Figs. 17 and 18, the blade fitting and the blade root section have been simultaneously tested.
The constant amplitutde test was accelerated by using excess loads, namely

- alternating flapwise and chordwise bending moments of ± 3000 Nm with respect to the main blade bolt,
- alternating torsional moment of ± 200 Nm, and
- constant centrifugal force of 152 kN.

Tests were rung at a frequency of 4 Hz, with an allowable temperature in the blade fitting about 45 °C. Former tests revealed maximum 0.48 °/₀₀ strain in unnotched sections of the blade fitting.

The blade root failed at $5.76 \cdot 10^6$ load cycles, which is far beyond the number of load cycles corresponding to 50% survival probability and confidence level. This is shown in Fig 19, which reveals an S/N-curve which was deduced from a set of similarly conducted fatigue tests with forged titanium blade fittings.

Except for minor fretting corrosion marks, see Fig 20, the HIP-titanium blade fitting showed no degradation. The result proved the full integrity of this component.

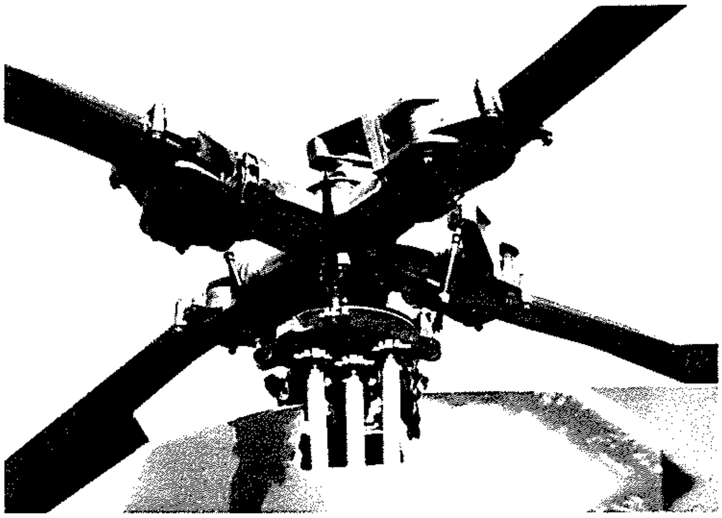


Fig 16:

BO 105 Main Rotor Hub

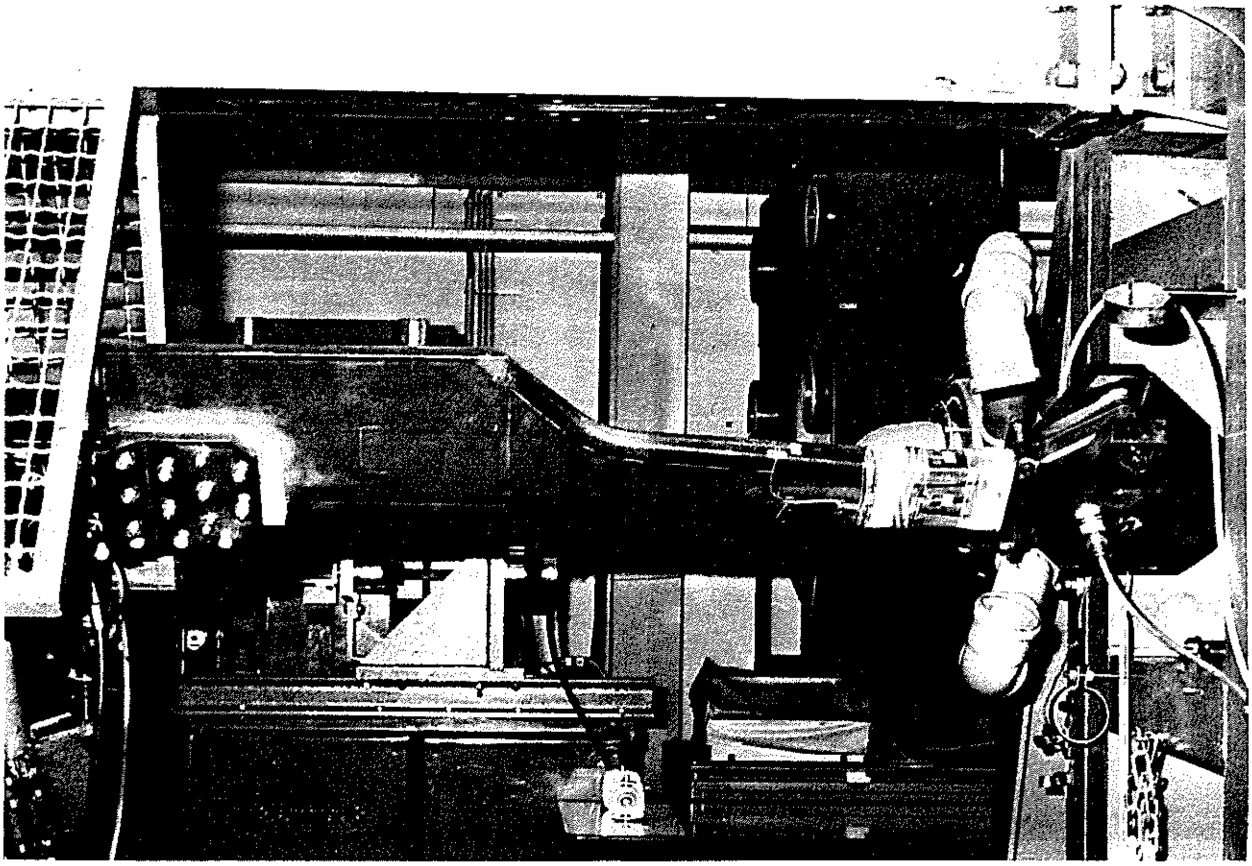
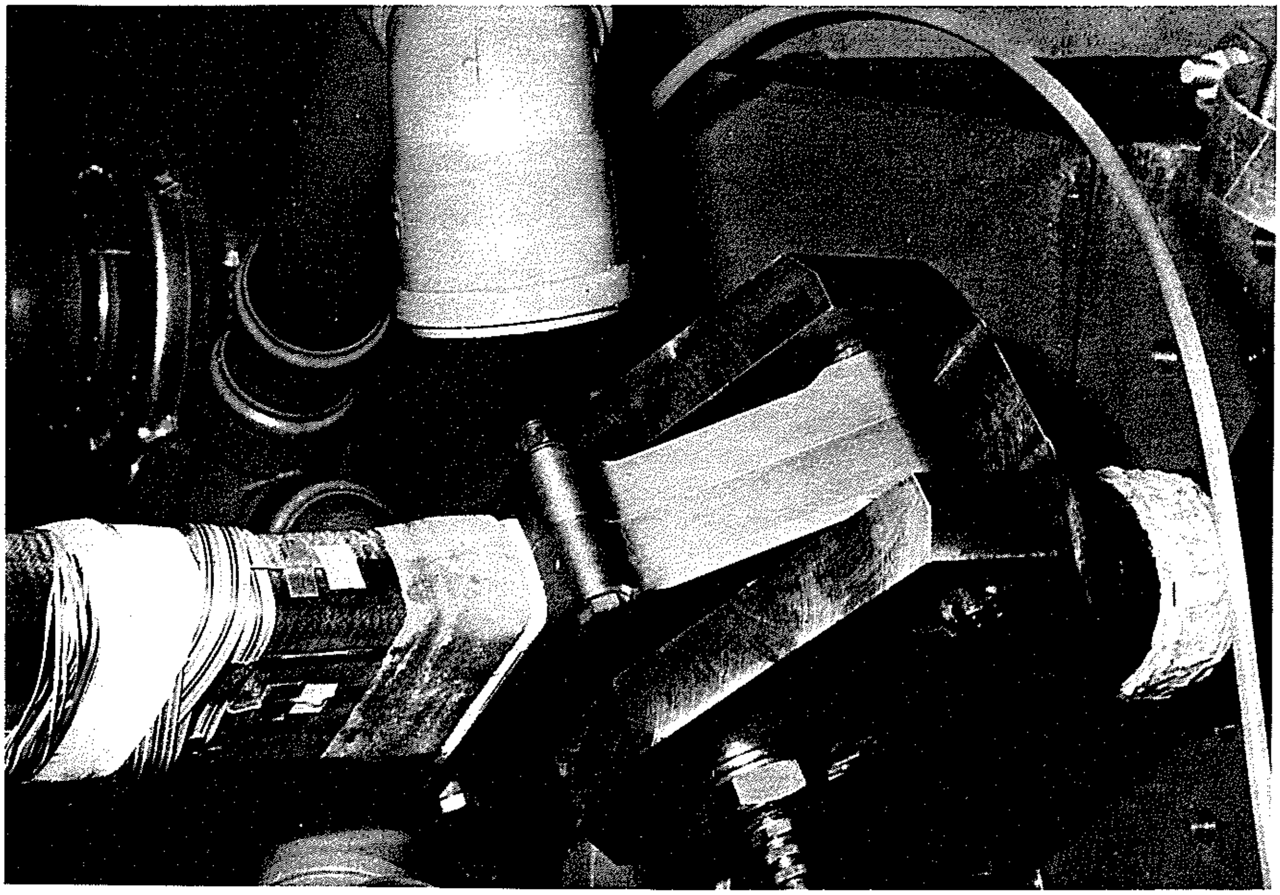


Fig 17: Blade root fatigue test rig with HIP-titanium blade fitting



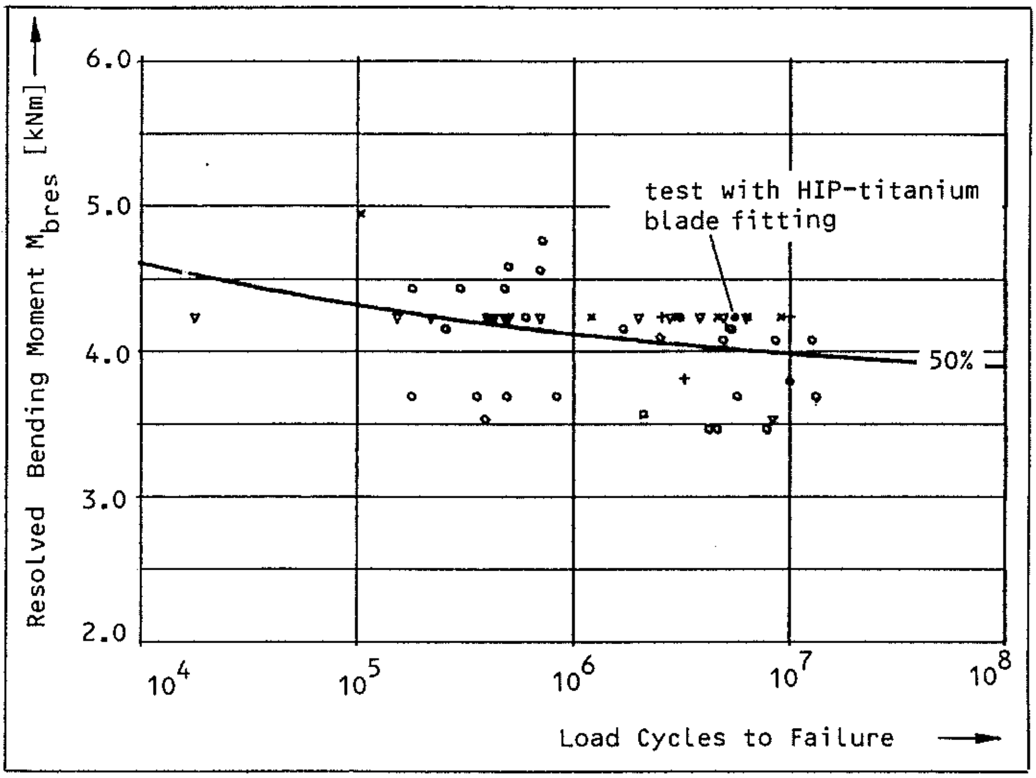


Fig. 19: Blade root test with HIP-titanium blade grip

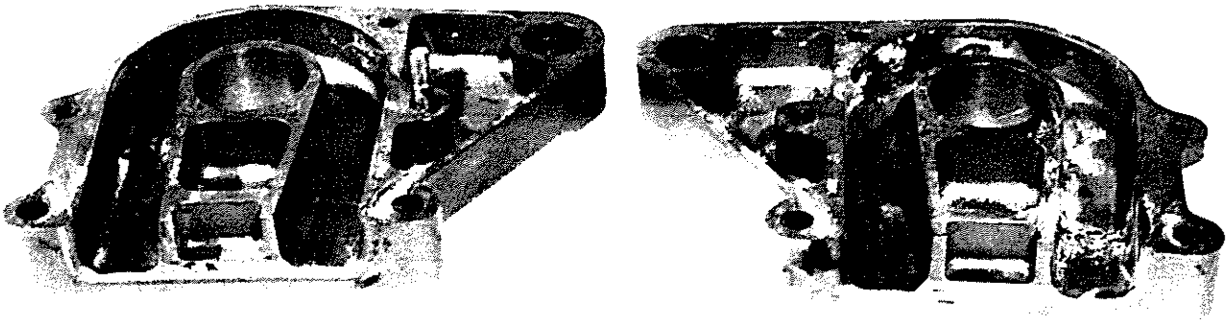


Fig 20: HIP-titanium blade fitting after 5.76 $.10^6$ load cycles

6. Conclusions

The investigations showed that the P/M-HIP-manufactured blade fitting fulfilled the static and dynamic strength requirements.

The values obtained with test coupons were the same as those obtained with the corresponding wrought alloy.

As a result of the reduction in the extent of machining as well as the weight of starting material a considerable economic saving can be realised by using PM-HIP-components in the aerospace industry.

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