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Metallurgical and Technological Aspects of Titanium Alloys Application for Helicopter Industry.

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Synopsis

For many years Mil Moscow Helicopter Plant has been carrying out an intensive work to apply titanium alloys for highly-loaded parts of helicopter components. Productional and operational experience, gained during this time, is an evidence of effectiveness of titanium alloy application for helicopter manufacturing, especially for most heavy-lifting helicopter in the world the Mi-26. For instance, the main and tail rotor hubs, swashplate and some other helicopter components proved to be 20-30% lighter, compared to the steel ones. However, attaining of high service life under alternative loading called for systematic investigations into the influence of various metallurgical and technological factors on the fatigue life of components made of forgings. Basing on these investigations as well as on experience of titanium alloy components operation, the manufacturing technology, which is currently being used, has been developed.

The paper gives information on titanium alloys used in helicopters developed by the Mil Moscow Helicopter Plant, shows different principles of technology used for manufacturing of forgings on metallurgical and of parts on machine-building plants, presents data indicating their quality level.

Special attention is given to the development of specific quality control methods for components and half-finished products, which assure their high quality and long service life.

Introduction

The main condition of reliable work of materials in helicopters is their high fatigue strength defining vibration resistance of the components.

M. L. Mil, the founder of helicopter manufacturing in our country, once noted, that a helicopter was a flying laboratory for fatigue strength testing of materials.

The following properties mentioned below are also very important for helicopter components:

-static strength being one of the main design parameters;

-impact strength defining materials ability to withstand possible impact loads;

-fracture toughness and crack propagation resistance defining reliable operation of components;

-fretting corrosion resistance in the places of contact of various materials; intensfication of such corrosion can results in a premature failure.

As service life of helicopters increases, improvement in stability of the said properties of components, as a main condition of their reliable service, is given more and more attention.

The level and stability of titanium alloy properties depend on many metallurgical and technological factors. The main of them are alloy composition, die forging structure, surface quality of components, stress condition of their surface zones, properties of protective coatings. The existing control system for estimation of billet and component quality through the whole technological cycle plays an important role in improvement of these properties.

As it has been already noted, the paper is to give general information on the level of production and application of titanium alloys in the helicopters of the Mil Moscow Helicopter plant.

Application of Titanium Alloys in Mil Helicopter Plant

The application of titanium in helicopters of Mil Helicopter plant for decreasing their weights began early in the seventies. MI-24 was the first Mil helicopter with titanium alloy components. At present the family of such vehicles includes MI-26, MI-28 and MI-34 helicopters.

In most helicopters the total weight of titanium alloy components is rather small,about 2-3% of the total weight of a helicopter. However, titanium components, forming assemblies of main rotor system are the most highly-stressed ones.

Titanium components weight fraction in the MI-26 helicopter is the largest. The MI-26 is the largest and the most heavy-lifting helicopter in the wold (Fig.1). Its empty weight and maximum take-off weight are 28 tonnes and 56 tonnes respectively. Titanium component weight is 4.5 tonnes, i. e. about 16% of the total helicopter weight. Application of titanium instead of steel results in considerable weight savings, approximately 660 kg.

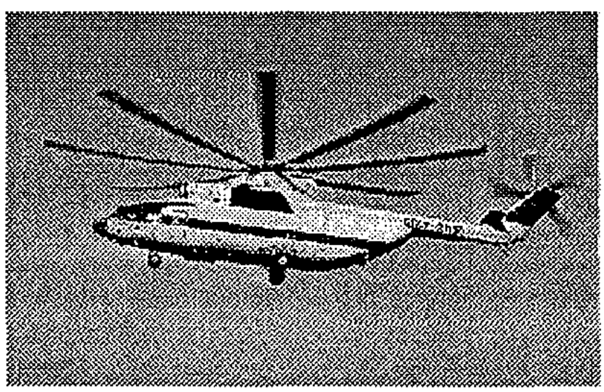

Fig. 1 The Mi-26 helicopter

Titanium alloy components of this helicopter are used in the following assemblies: main rotor and tail rotor hubs, swashplate and undercarriage, i. e. about 80 components in all and weighting from 1 to 165 kg. The largest component is a hub. Figure 2 shows a main rotor hub as an assembly and its separate parts.

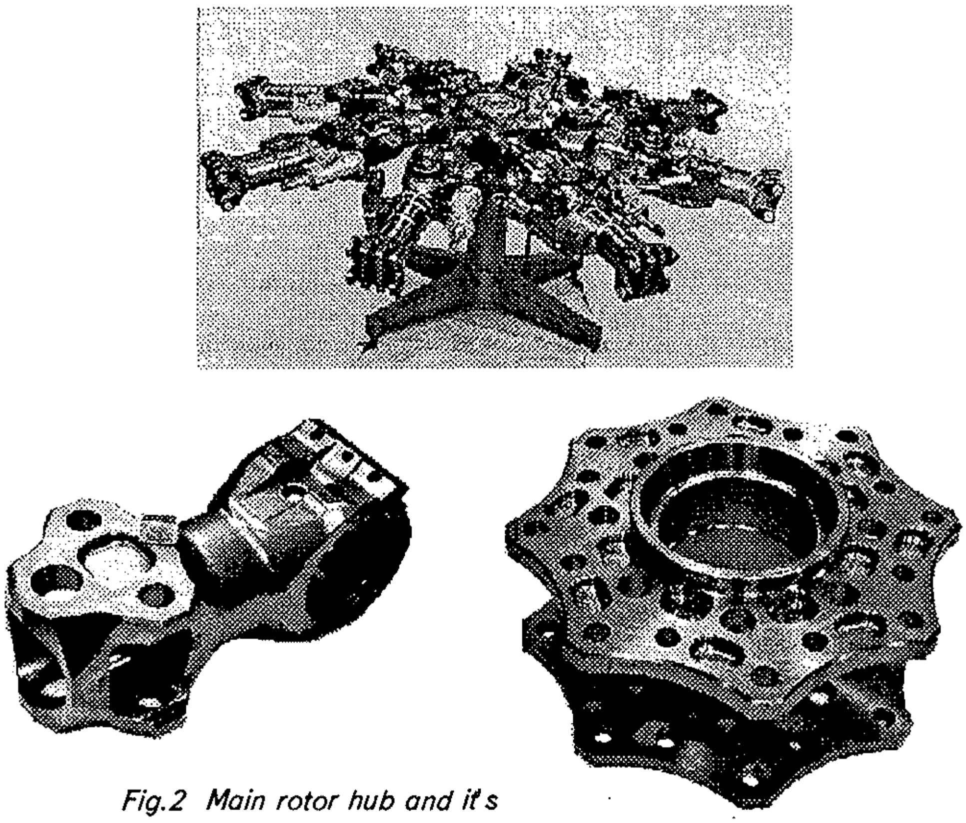

Fig.2 Main rotor hub and it's separate parts

Among titanium alloys, the VT3-1 $\alpha+\beta$ titanium alloy (Ti - 6.2AL - 2.5Mo - 1.6Cr - 0.5Fe - 0.22Si) widely used also in aircraft engine compressors has found the widest application in helicopters in Russia. In comparison with Ti-6Al-4V titanium alloy used for the same purposes in the USA, VT3-1 alloy has improved static and fatigue strength (by 5-10% and 10-15% respectively), see Table 1.

Table 1. Mechanigal properties of VT3-1 and VT6 alloy die Forgings for helicopters VT3-1 VT-6

Property	VT3-1	VT-6
	Ti - 6,2Al - 2,5Mo - 1,6Cr - 0,5Fe - 0,22Si	Ti-6Al-4V
UTS,MPa	1025	930
El, %	10	12
RA, %	35	40
KCV,J/cm	36	43
KCT,J/cm	12	16
K_{1C},MPa	71	80
Fatigue str. (σ_{-1}) MPa ($N=1*10^7$ cycl)	500	440

At the same time VT3-1 compares slightly unfavourably with the US alloy in terms of crack resistance and stress concentrator sensitivity.

Production of Die Forgings at Metallurgical Works

Die forgings are produced by two metallurgical Works. The range of the die forgings is very diverse in terms of sizes, projection areas, weights and shapes. Weight and projection area of the largest die forging (a hub) are 370 kg and about 6000 sg. cm respectively.

For their production ingots with diameter of 540 to 720 mm and from 2 to 8 t. in weight are used.The ingots are melted in arc-vacuum furnaces.Charge composition,methods for its preparation and control, and ingot melting technique have been adopted to satisfy requirements for absence of metallurgical defects,to ensure rather high stability of chemical composition and $\alpha+\beta \rightarrow \beta$ transition temperature (t_β) through the whole body of ingot and in various ingots.

At present, the level of stability of chemical composition and t_β is as follows: as for Al, Mo and Cr content -0.4-0.6%, as for Fe -0.3%, as for Si -0.07%, as for O_2- 0.06% (maximum-0.15%) and as for t_β-30°C. This level is now typical for titanium alloys with the similar content of alloying additives.

Die forging production process includes hammer forging of cut -to -length billets followed by die forging. Depending on forging weight, hammer forging of initial billets is carried out on 6000 and 3000 tnf.hydraulic presses and on 3.5 and 8tnf. hammers.Die forging is performed on a 3000 tnf.hydraulic press and on 13, 23 and 25 tnf.hammers.

Bessides cut-to-length billet production the main purpose of hammer forging is effective refining of initial cast structure as well as partial transformation of laminated structure into globular or transition one.Initial structure refinement during hammer forging followed by heating resulted from recrystallisation development.It is well know, that in titanium alloys this process has a very "sluggish" nature.It results in difficulties in effective structure refining in the whole thickness of hammer forged billets (especially large -sized ones) and causes the use of complex schedules for hammer forging.

The schedules used include a complex of alternate drawing and upsetting operations at β and $\alpha+\beta$ - field temperatures. In this case it is necessary to ensure specified forging reduction ratios ($k=S_1/S_2$ or $k=H_1/H_2$, where S and H - initial and final areas or heights of billets) and fulfilment of certain requirements to hammer forging procedure. As a result of hammer forging completed in t_β field, it is possible to refine grains in billet structure from 5.000-15.000 down to 1.000-2.000 μm.

The subsequent hammer forging of cut-to-length billets is carried out at $\alpha+\beta$ field temperatures. Such hammer forging is necessary,as otherwise, because of substantial zone ununiformity of deformation, some zones of die forgings inherit structure and properties of initial billets and can essentially differ from properly deformed zones in terms of structure and properties.

This hammer forging as well as the above mentioned one is carried out according to a certain schedule and with specified reduction ratio which depend on size and weight of a billet.

Die foring as well as preliminary hammer forging is carried out at $\alpha+\beta$ field temperatures. These temperatures were used by convention in commercialization of helicopter forgings from titanium more than twenty years ago, when β-deformation process was not considered to be applicable.

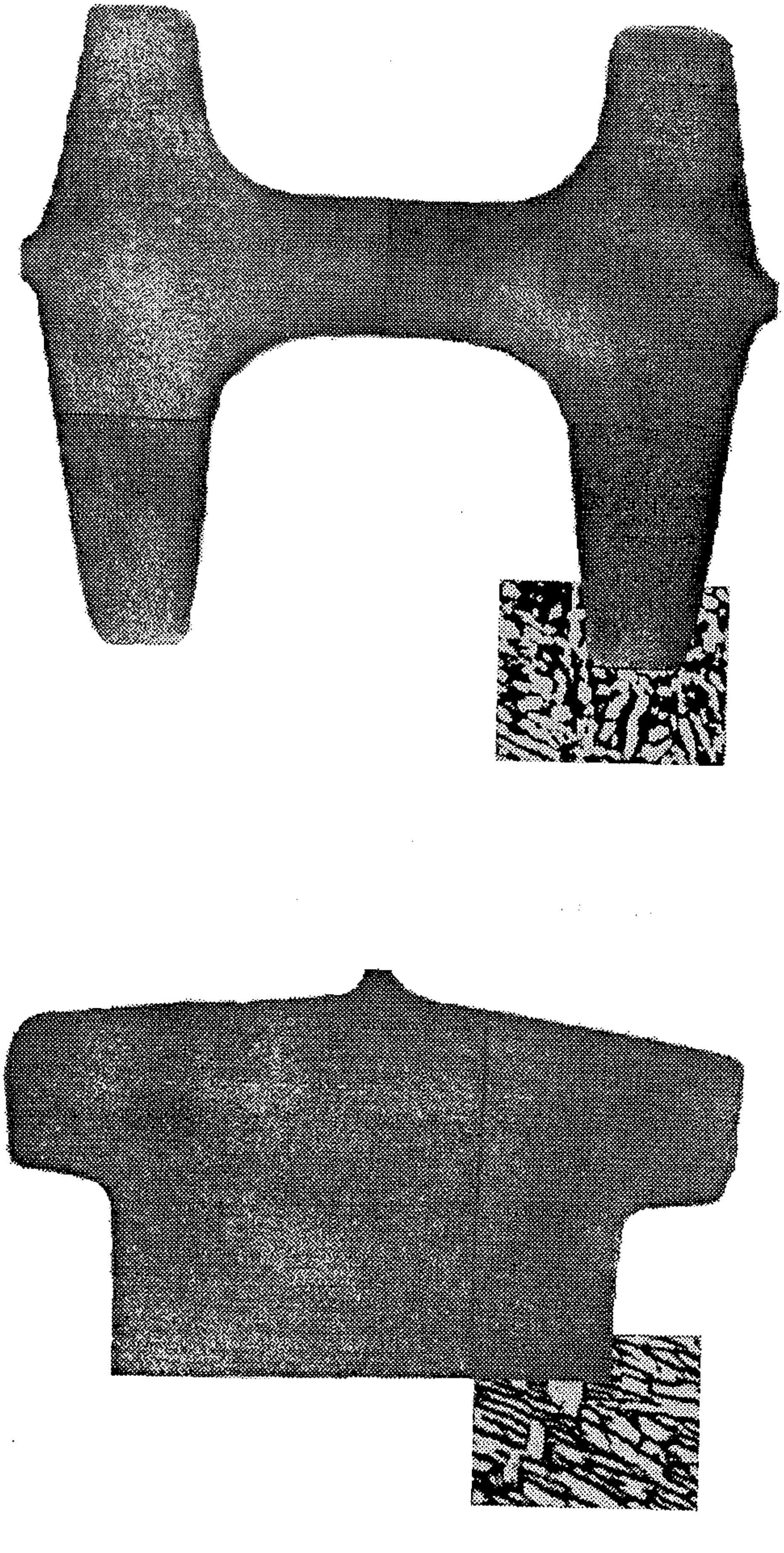

Fig3. The typical structure of die forgings

The typical structure of helicopter die forgings produced by $\alpha+\beta$ deformation is show in Fig.3. It is predominantly globular structure or transition one with high globularisation degree.

Heat treatment is the final operation in the process of die forging manufacture at metallurgical works. At engineering works heat treatment of especially large-size die forgings follow preliminary machining. The conditions used provide for heating 20-30°C lower than T_{β}, cooling at a certain rate and stabilizing annealing at 550°C.

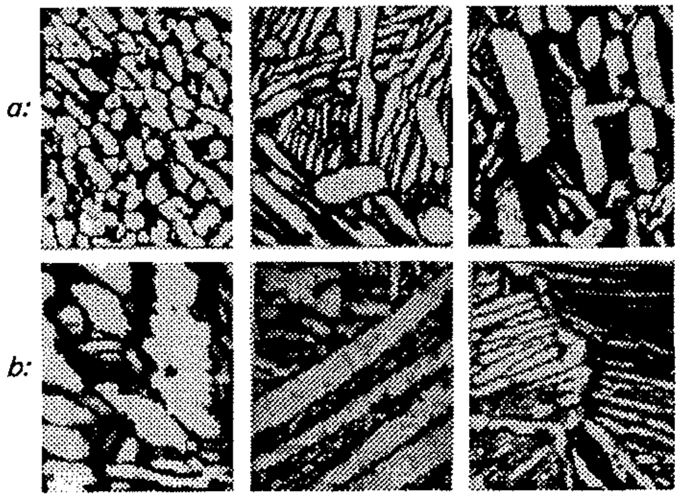

Fig4. Microstruture: a - admissible
b -

We paid special attention to the control of microstructure influencing to a great extent the level of fatigue strenqth. As a result of enormons work done on statistical processing of several thousands of microsections cut out from the fatigue test specimens. We have defined the types of admissible and inadmissible structures. Fig.4 shows a number of such microsedions and corresponding fatique life curves Fig 5. On these grounds we have defined the normis of minimum permissible fatigue life egual to $N \geq 10^5$ cycles in testing under $\sigma_a = \pm 500$ MPa stress.

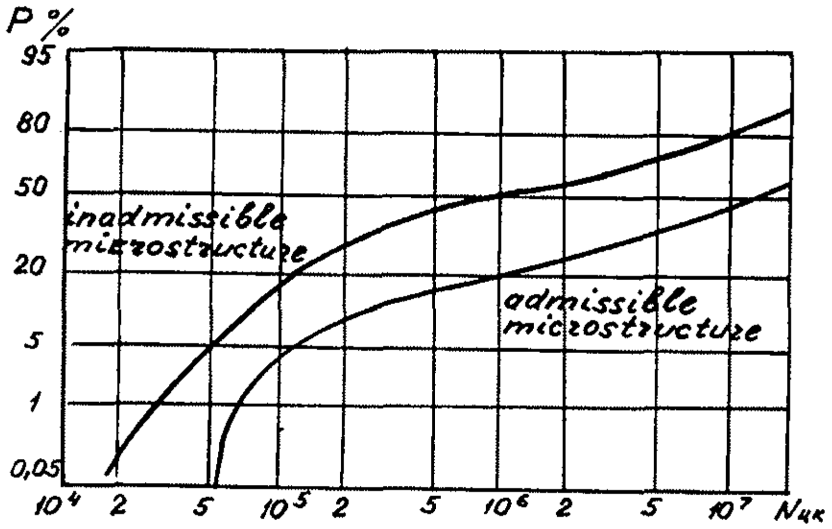

Fig.5 Sample fatigue live distribution curves for VT3-1 alloy $\sigma_a = \pm 500$MPa

Die forgings are supplied according to branch standart. Requirements to the structure and properties are as follows:

Grain size of macrostructure is not more than 8 numbers according to the existing standart scale (grain size is not more than 2000-3000 μm); variations in graininess is not more than 5 numbers; tonality of macrostructure is mat, i. e. this assures the absence of lamellar or weakly globularized transition microstructure; microstructire should be of admissible type. When die forgings are supplied their fatigue properties control is indispensable condition. Basing on the investigations done we have determined that fatigue test sperimens cut out from the die forgings must be tested without failure fo $N=10^5$ cycles unden alternating stress equal to $\sigma_a = \pm 500$ MPa.

In general, the obtained guality level of the die forgings is highly appreciated,but specified reguirements in terms of macrostructure and microstructure should be more stringent. All this, as well as restriction of alloying elements composition ranges, is necessary to improve the reproducibility of mechanical properties.

However, making of a good die forging is only part of a job. Now we have to make a component without loss of high quality obtained during the machining.

In order to study the effect of varions methods of machining, surface hardening and coatings on titanium samples fatigue life and surface layer quality we have determined the processing types, sequences and combinations which should be used in manufacturing of helicopter parts. In accordance with the selection made, the components samples have been manufactured and different technological variants have been tested.

Test results analysis shows (see table 2) that titanium fatigue strength is hiqhly affected by residual stress level on the surface of the component.

Table №2: The effect of different methods of machining on fatigue strength of VT3-1 alloy

№	Type of machining	The depth of hardened layer $h_{cold\text{-}hard}$ mm	Level of residual stresses σ_{res} MPa	Fatigue strength at $1*10^7$ cycles σ_{-1} MPa
1.	Turning	0.07	-470	480
2.	Turning+vacuum annealing at 525 C	0.07	-20	550
3.	Turning+surface hardening	0.43	-520	640
4.	Turning+pickling	-	+20	350
5.	Turning+coating with Cu or Ag	-	-	450
6.	Turning+electophoretic coating by fluoroplastic	-	-	520
7.	Turning+pickling +surface hardening	0.38	-420	500
8.	Turning+pickling +vacuum annealing at 525°C	0	-	430
9.	Turning+grinding	0.10	-100	370

For example, after selected cutting rate final machining including turning, boring and milling, the σ_{res}=-(430..540)MPa and the depth of the hardened layer is about 0.05-0.07 mm. Such a residual stress ensure sufficient enough fatigue strength of VT3-1 alloy, i.e. σ_{-1}=480MPa. At the same time, when the class 8 surface roughness is reached (Russian standart), without chanqinq cutting rate, it is possible to obtain ofter turning the σ_{res}=+650MPa and two times fatigue limit reduction.

Fatigue stength increases

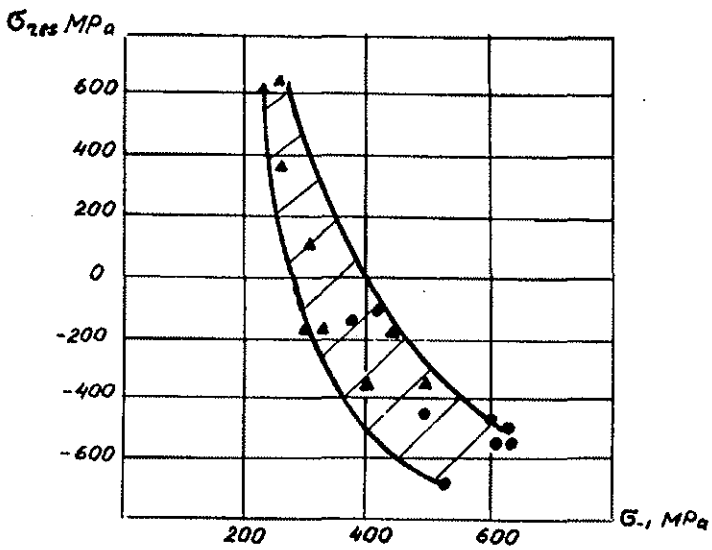

Fig. 6 The effect of residual stress level on fatigue strength limit of VT3-1 alloy

substantially after round specimen surface hardening by vibration or rolling by a ball; at the bored openings and for flat milled specimen such effect was not observed. The data regarding the effect of surface hardening on fatigue strength of round specimens indicate that there is the most favourable combination of surface compression stress and the depth of its bedding: surface residual stress around σ_{res}=-(500-700)MPa (Fig.6) and surface hardened layer relative depth of 0.08....0.1 (Fig.7).

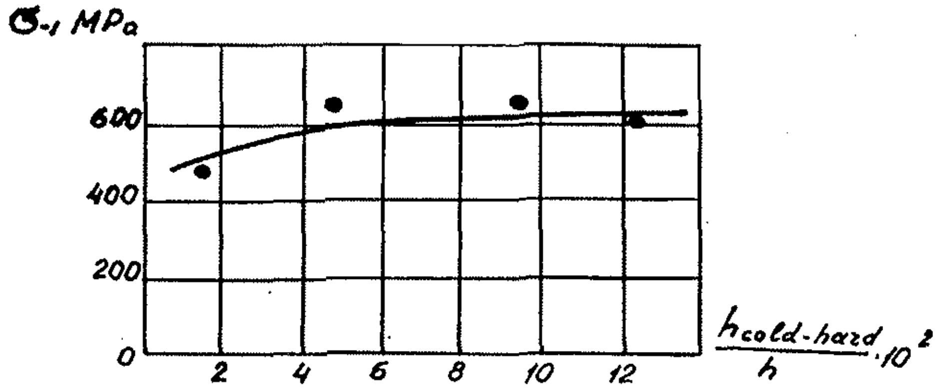

Fig.7 The effect of relative depth of cold-hardened layer on fatigue strength limit of VT3-1 alloy

The selected modes of titanium alloy processing practically do not cause the surface layers hydrogen saturation Nevertheless,for the specimens with class 6-7 surface roughness and zero residual stress, the function of specimens fatigue limit versus surface layer hydrogen content shows monotonous decrease of fatigue strength. Therefore,it is advisable to limit the surface layer hydrogen content to 0.01 weight %, ensuring σ_{-1}=500 Mpa (Fig.8).

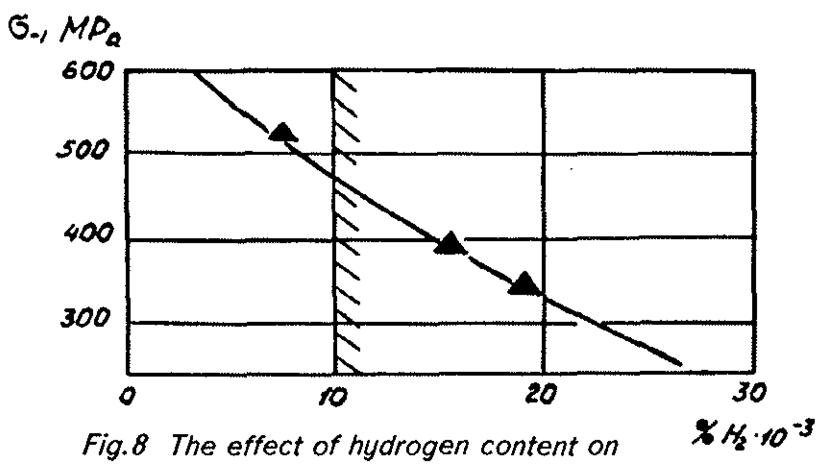

Fig.8 The effect of hydrogen content on fatigue strength of VT3-1 alloy

Application of vacuum annealing causes release of residual stresses through the whole cross-section of the part, partial hydrogen coutent decreaqe, some-stabilization of the structure and improvement of fatigue strength. Thus, the above operation should be carried out as a final one especially because vacuum annealing, as in table 2, practically doesn't cause warp.

Fretting-corrosion protection of the components is of great importance for successful application of titanium alloys. Well-known methods of conjugate surfaces protection by galvanic cooper- and silver plating, by solid grease containing MoS_2 are ineffective for titanium alloys. Good results were obtained through the application of technology worked out at the Mil Moscow Helicopter Plant, i. e. plating of the part's surface with a composition of fluoroplast and phenol-formaldehyde resin by electrophoresis method. Bench testing has shown that unprotected, cooper- and solid grease plated samples had the running time of 10-30 min., 1-2 hours and 5-8 hours respectively prior to appearance of fretting-corrosion segns. Those samples processed by electrophoresis method had more then 50 hours running time (Fig.9). At the same time their fatique strength slightly inereased.

Thus, the analysis of the billet's quality and evaluation of manufacturing operations enabled to find the correct approach to perfect the technology of highstrength titanium alloy helicopter components. Fig.10 shows the technological process scheme of components

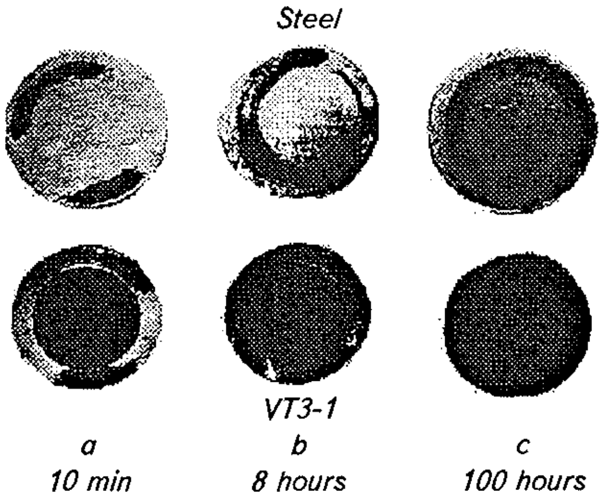

Fig.9 Fretting-corrosion tests comparative results:

a - no platting;
b - solid grease coatinng;
c - electrophoretic coating by fluoroplastic.
Special pressure P=800 MPa.
Oscillation frequency f=1000 cycles/min.
Amplitude a=0,15 mm.

manufacturing and quality control. As it may be seen the billets are subjected to heat treatment under the conditions mentioned above. After anneling the samples for macro- and microstructure control (Control N1) speciments for mechanical properties testing and, if needed, for fatique tests are cut out from the most important components by a special scheme.

After the control N1 billets are subjected to preliminary machining; the allowance of 2-3 mm for final machining is left in order to check, the macrostructure of all the part's surfaces. (Control N2).Then final machining using the selected rates is carried out, followed by vacuum annealing, surface hardening and anti-friction plating by electrophoresis. Surface cracks are controlled by fluorescent method. (Control N3 and N4).

In case the grindinq of any kind is done as a final machining procedure the vacuum annealing followed by subsequent surface hardening are obligatory.

It is advisable to follow the above technological processes sequence for almost all the parts made of titanium alloys. The scope of quality control operations is defined for each particular component, depending on the requirements to be met.

In spite of complexity and large number of quality control procedures the technology secures high quality and reliability of titanium alloy parts.

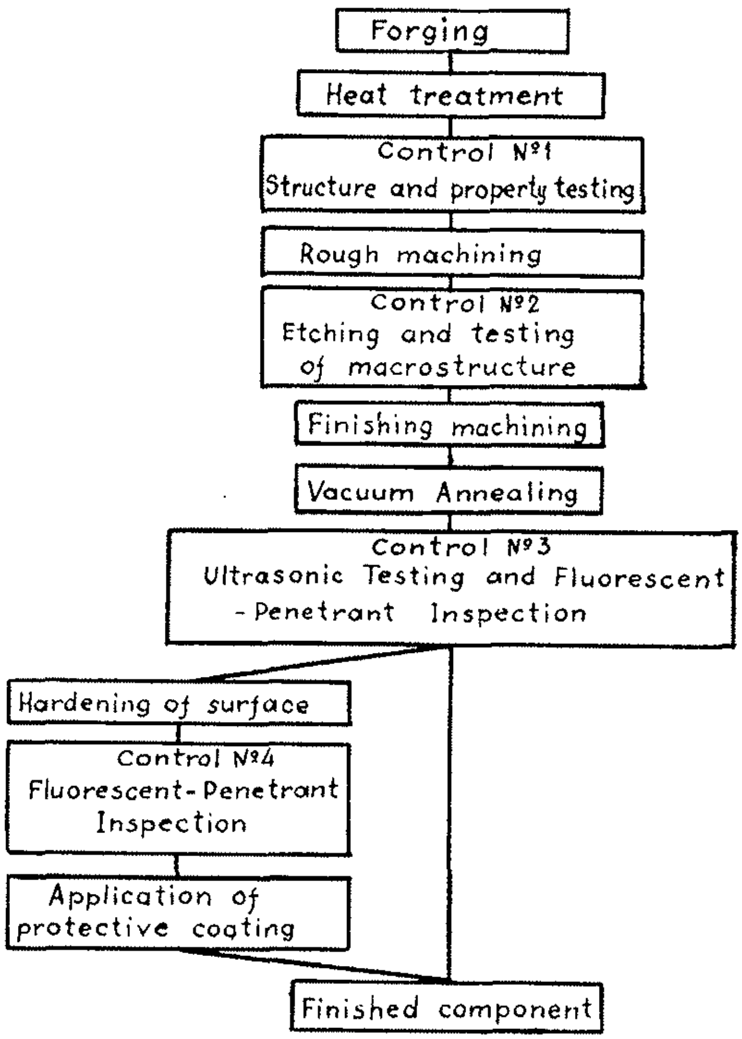

Fig. 10 Scheme of the components production process and quality control system at engeneering works

CONCLUSION

1. Due to high specific fatigue strength titanium alloys are widely used for manufacturing of high-stressed components, such as main rotor and tail rotor hubs and swashplates for helicopters.

2. The MI-26 transport helicopter has the greatest titanium alloys, weight fraction, i. e. about 4.5t or 16% of the helicopter empty weight. This ensures weight saving of about 660 kg.

3. VT3-1 $\alpha+\beta$ alloy (Ti - 6.2Al - 2.5Mo - 1.6Cr - 0.5Fe - 0.22Si) with guaranteed level of static strength UTS$\geq$930 MPa has found the widest application in the Russion helicopter industry.

4. The present $\alpha+\beta$ technology for production of die forgings for helicopter components ensures formation of homogeneous mainly globular,structure and a combination of high mechanical properties.

5. The complex of machining operations and their sequence, surfase hardening, quality control of die forgings, billets and components ensure high reliability of the products.

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