SOME APPROACHES TO THE CHOICE OF MATERIALS FOR CRITICAL HELICOPTER CONSTRUCTIONS

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Abstract

The increase of helicopter resource and reliability requires both application of new constructive materials and improvement of parts production technology, as well as the deep study of mechanical, first of all fatigue characteristics of materials, that are already applied.

Materials fatigue is the main reason of constructions elements failure under the action of changing stresses.

The study of materials and construction fatigue is urgent in connection with high-rate operation regimes, development and reduction of new highly-strong materials and new technology to practice.

The increase of products resource and reliability causes the determination of constructive, technological and operational factors, effecting the fatigue strength. The aim is the operational development, optimization of production technology regimes, improvement of constructions and, as a result - the quality of products.

It is necessary to estimate both average value of fatigue strength characteristics and the degree of their scatter. In some cases material advantage is displayed in testing of the grate number of pieces. It causes the great expenditure of time, materials and therefore - money.

The paper studies the conditions of construction loading in the process of operation and the most important characteristics of materials for the most critical constructions and parts.

It is known that in a flight helicopters parts and constructions in a contrast to aeroplanes basically experience the attack of changing and often - great loads. That is why the chosen materials must, first of all, have high fatigue strength and this feature is often the definitive one.

On the basis of the facts the paper studies deeply some of the approaches to fatigue tests in the laboratory, fatigue characteristics and their dependence on different factors, justification of the choice of these or other materials for the application in different helicopter constructions.

The main problem facing all aircraft designers is not only to make their aircraft fly, but also to provide their high reliability and flight safety. The solution of this problem greatly depends on the properties and structure of the materials used . In general, an aeroplane or a helicopter can be made from any material, but in this case it will, most probably, be able to lift off, be airborne for a short time and then fall apart. That is why materials technologists have been facing a very important problem to choose the materials that ensure the following:

- high strength in combination with satisfactory ductility;
- high resistance to alternating loads, i.e. higher fatigue strength;
- low sensibility to stress concentrations, high resistance to crack propagation;
- corrosion resistance;
- reproducibility.

However, to determine which material should be used for manufacturing of which parts, it is necessary to know, first of all, the loads applied to them in flight. Table 1 presents a list of the major helicopter components, the loads applied to them in flight and the properties required for the materials used for their manufacturing.

Table №1. Operational Conditions and Most Important Properties of Materials

Component	**Flight loads, damage**	**Properties**
Blades	Alternating loads, Fretting corrosion	$\sigma_{-1}, dl/dN, E$ specific strength
Main and tail rotor heads	Alternating loads, Fretting corrosion	$\sigma_{-1}, dl/dN, K_{1C}$
Rotor drive system	Alternating loads, contact fatigue	$\sigma_{-1}, \sigma_{-1CONTACT}$
Airframe, landing gear	Repeatingly static and impact loads	$\sigma_{-1}, dl/dN\ K_{CV}$
Bolted joints, eye-joints	Alternating loads, Fretting corrosion	$\sigma_{-1}, \sigma_{-1FRET\text{-}COR.}, dl/dN$

As the paper will cover only metals, Table 2 will present properties of some typical materials used for manufacturing of critically loaded components and parts for the Mi-6, Mi-8, Mi-26, Mi-34 helicopters.

Table 2. Typical materials used in helicopter manufacturing

Components	Material designation	Type of blank	Main characteristics					
			E, Mpa	UTS, Mpa	σ_{-1} ,Mpa	El%	RA%	KCV, J/cm^2
Blade spar	40XH2MA (40CrNi2Mo)	Tube	$2,0 \cdot 10^5$	1000	480	8	55	98
	ABT1 (AVT1) Al-0.3Cu-0.6Mg-0.8Si	Section	$7,1 \cdot 10^4$	350	120	12	-	34
Main and tail rotor heads, swash plate	40CrNi2Mo	Forging	$2,0 \cdot 10^5$	1100	500	8	50	80
	BT3-1 (VT3-1) Ti-6.2Al-2.5Mo-1.6Cr	Forging	$1,1 \cdot 10^5$	950	500	8	35	36
	AK6 (AK6) Al-2.2Cu-0.6Mg-0.6Mn-1Si	Forging	$7,2 \cdot 10^4$	400	140	12	-	25
	BHC-9 (VNS-9) 0.23C-15Cr-5Ni-3Mo	Sheet	-	>1500	-	12	-	-
Gear boxes housings, gears, shafts.	МЛ5 (ML5) Mg-6Al-2.5Zn	Casting	$4,2 \cdot 10^4$	230	85	5	-	-
	12X2H4A (12Cr2Ni4)	Forging	$2,0 \cdot 10^5$	100	460	12	55	118
	АМГ3 (AMG3) Mg-3.5Al-0.45Mn-0.6Si	Tube	$7,0 \cdot 10^4$	450	-	7	-	-
Airframe, landing gear.	Д16 (D16) Al-4Cu-1.6Mg-0.6Mn	Sheet	$6,9 \cdot 10^4$	400	-	13	-	-
	AK6	Forging	$7,2 \cdot 10^4$	400	140	12	-	25
	B96T1 (V96T1) Al-2.3Cu-2.5Mg-8Zn	Tube	-	>640	-	>3.5	-	-
	30XГCA (30CrMnSi)	Rolling	$2,1 \cdot 10^5$	110	500	8	50	50

In the 50s at the beginning of quantity production of helicopters in our country the approach to material selection was relatively simple. Then, for this purpose such properties as ultimate strength, ductility, impact strength and the most general knowledge of fatigue strength were used as the main criteria. But in the course of gaining operational and technological experience, service life extension, studying the causes of parts failures during bench tests and, unfortunately, flight accidents and incidents the approach to selection and investigation of not only new materials, but materials in wide use underwent a dramatic change. To achieve long lifetime and high reliability under conditions of cyclic loading required to conduct systematic studies involved in fatigue strength, variability characteristics, influence of manufacturing factors. Dedicated studies devoted to fracture toughness, rate of fatigue crack propagation had to be conducted.

Due to specific conditions, helicopter components connected mainly with the main rotor operation are highly affected by heavy alternating loads. That is why the problems related to investigations of materials strength characteristics have become of paramount importance among the above mentioned ones. The paper presents some information on fatigue strength of some alloys used in manufacturing the most critical structural helicopter components as well as investigation procedures used to obtain the information.

The problem of improving reliability and increasing guaranteed lifetime of highly loaded structural members requires to consider variability of materials strength properties when structural analysis is made alongside the knowledge of ultimate strength. This, in its turn, specifies the probability approach to reliability and lifetime evaluation. In this connection it is necessary to pay great attention to problems of lifetime and fatigue limit variability in studies devoted to fatigue strength.

By way of example, Fig. 1 shows fatigue curves for some steel and titanium alloys which were used or expected to be used for manufacture of main rotor head parts, while Fig. 2 shows the distribution of their fatigue limits. Figs. 3 and 4 present the similar curves for aluminum alloys which were used or were expected to be used for manufacture of main rotor blade spars.

This or that material is approved for application with due consideration of other factors as well; one of those factors being material sensitivity to stress concentrations. Some time ago, to improve the service life of the blades installed in the widely used Mi-8 helicopter the AVT1 (ABT1) alloy was planned to be replaced by the high-strength V91T1 (B91T1) alloy whose fatigue strength was much higher (ref. Figs. 3 and 4). But the fatigue tests of notched specimens revealed that the V91T1 (B91T1) alloy is more sensitive to stress concentration than the AVT1 (ABT1) alloy (ref. Table 3).

Table №3. Coefficients of stress concentration sensitivity for aluminium alloys

$$q = \frac{K_\alpha - 1}{K_t - 1} ,$$

K_α - effective stress concentration factor

K_t - design stress concentration factor

Alloy	K_t	Failure probability				
		1%	30%	50%	70%	90%
V91T1	2,27	0,98	0,94	0,9	0,88	0,83
AVT1		0,88	0,74	0,74	0,73	0,72
V91T1	1,45	0,87	0,77	0,76	0,74	0,73
AVT1		0,77	0,70	0,68	0,67	0,70

The bench tests of the blades made of these two alloys showed the following results. Fatigue fracture of the blade spar made of the V91T1 alloy had mostly initiated at joint bolt holes whereas no fatigue fracture had been registered in similar locations of the spars made of the AVT1 alloy. Proceeding from the results obtained from tests of laboratory and full-scale specimens the use of the seemingly promising alloy had been given up.

It is common knowledge that parts fabricated from castings are cheaper than those made from forgings. However, it is sometimes extremely difficult to evaluate fatigue strength of casting alloys proceeding from tests of small-size laboratory specimens due to their structural features. Therefore, for proper statistical evaluation of possible application of parts fabricated from steel or titanium castings we have investigated fatigue strength of rather large-size specimens cast in a special way. Lugs whose size was in accordance with that of the Mi-6 main rotor feathering hinge housing lugs were cast. For almost 30 years the Mi-6 remained the world's most heavy-lift helicopter till the advent of the Mi-26. The test results for these lugs are given in Fig. 5 as the durability distribution curves. The analysis of the curves shows that, in terms of fatigue properties, the VNL3 casting stainless steel (0.12C-1Ni-2CR-1.2W-0.Mo UTS=1,000-1,250 MPa) is as good as the 0.3XH3MΦA forged steel (0.3Cr3Ni3Mo UTS=1,100 MPa), and, in terms of durability, it even approaches to surface hardened specimens of forged steel. Later on this casting steel was used to manufacture critical parts for helicopters of new design.

Recently great attention is paid to manufacturing of flexible structural members in main rotor head designs. Thus, the Mi-26 torsion packs used instead of thrust bearings are manufactured by winding high-strength steel wire. These components are subject to heavy alternating loads in flight. Therefore we investigated fatigue strength of two wire grades: high-carbon cold-drawn wire 0.9 C whose ultimate strength is 2,250-2,500 MPa, and wire made of the VNS9 stainless steel (0.24C-15Cr-5Ni-3Mo) whose ultimate strength is 2,850-3,050 MPa. To conduct fatigue tests, a special test bench was built. This test bench provides wire testing for simultaneous application of tensile and alternating bending stresses. This loading condition simulates, to a great extent, the loading condition of the above flexible member in flight. Fig. 6 shows fatigue limits of these two steel alloys versus static load applied. Proceeding from the test results obtained, the steel alloy was chosen to manufacture flexible members and data were obtained for structural analysis.

It is common knowledge that all materials have higher or lower variability of their strength properties; variability of fatigue durability is of the greatest importance to us. This variability depends on many factors. One of these factors is a metallurgical one which is caused, whether we like it or not, by different defects available in the metal, the so-called melt defects. The lesser the cross-section of the part, the greater is the effect of the above melt defects on the variability of fatigue durability. It would be of interest to study this effect by giving the following example.

One of the main structural member of the Mi-34 main rotor head is the torsion pack which is manufactured from the above mentioned VNS9 (BHC9) sheet stainless steel 0.3 mm thick whose ultimate strength is 1,500-1,600 MPa. To evaluate stability of fatigue properties of this steel, the effect of melt defects on variability of fatigue durability was studied. Fig. 7 shows durability distribution curves for specimens made from three tapes. These tapes were manufactured from three melts. The results obtained allowed us to draw a conclusion that, although material durability varies from one melt to another, this variability is relatively small, being within the acceptable limits, and that metallurgy can provide the required stability of properties.

As a rule, fatigue failure initiates on the part surfaces due to concentrations of metallurgical and manufacturing defects in the surface layers. Besides, under loading conditions the greatest stresses occur in surface layers. Thus the condition of the surface layers produces a certain effect on fatigue strength of parts. The most effective method of improving fatigue strength of structural components is shot peening leading to hardening of metal surface layers and occurrence of favorable residual compressive stresses. Let us study one of the approaches used to study fatigue properties of surface hardened materials by providing the following example. In those times when titanium alloys started to be widely used for manufacturing of highly loaded structures, it was believed that surface hardening of titanium alloys would not improve their fatigue strength as much as it had been done in steel and aluminum alloys. Therefore it was necessary not only to study the effect of shot peening on fatigue strength of titanium alloys, but variability of fatigue properties as well. To do that, several hundreds of laboratory specimens were made and tested. In Figs. 1 and 2 above some data on fatigue strength of the VT3-1 (BT3-1) titanium alloy were shown. Fig. 8 presents fatigue curves for initial specimens and surface hardened specimens made of this alloy for different failure probability. The analysis of the curves presented here shows that hardening of titanium alloys is quite effective; the lesser is failure probability, the greater is the shot peening effect. More promising results showing the efficiency of shot peening and its extremely desired application in the manufacturing process of parts have been obtained from the analysis of durability distribution curves. Shot peening leads to reduced variability of fatigue properties. This is a result of higher hardening of the weakest areas of the material, thus leading to leveling of mechanical properties. Fig.9 shows durability logarithm mean-root-square error versus average number of cycles. As can be seen, the efficiency of shot peening, from the point of view of reduced durability variability, increases as the number of cycles till failure increases too. The results obtained turned out to be very important for analyzing the reliability of structural members made of titanium alloys.

Surface hardening effectiveness was studied for manufacturing of bolted joints. A simple joint consisting of a nut and a bolt subject to tensile stresses is one of the most difficult problems to be solved in designing to a required strength. Maximum stresses occur in rounded areas at the bolt thread bottom in close vicinity of the nut stressed surface. They can be attributed both to a high local load applied to a turn of thread and to a total axial load. Changed thread shape can lead to a much lower stress concentration coefficient. But such solutions are often unacceptable. However, there are some technological procedures used to improve bolt fatigue strength. One of the most effective methods is to have rolled thread instead of machine-cut one. As can be seen from Fig. 10, fatigue strength of bolts made of the 40CrNi2Mo and having rolled thread is 1.5 times higher than that of bolts having machine-cut thread. This good effect is caused by the favorable influence of surface residual compressive stresses occurring at the thread bottom due to shot peening.

The foregoing information does not cover all the problems related to fatigue studies and data available on fatigue properties of materials and alloys used in helicopter industry. Our task was to show the severity of the problems facing materials technologists by giving examples, and to highlight some approaches and methods used in fatigue studies.

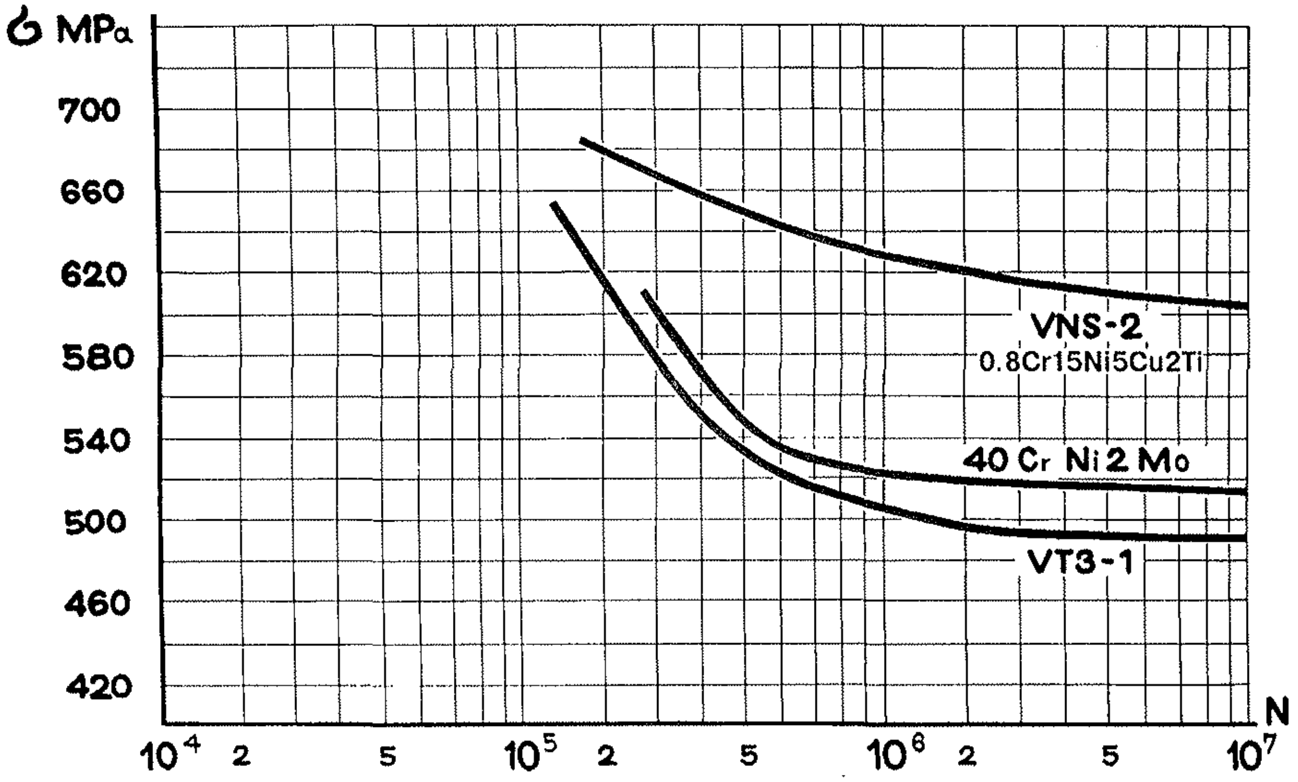


Fig. 1. Stress-Cycle Curves for Some Steel and Titanium Alloys.

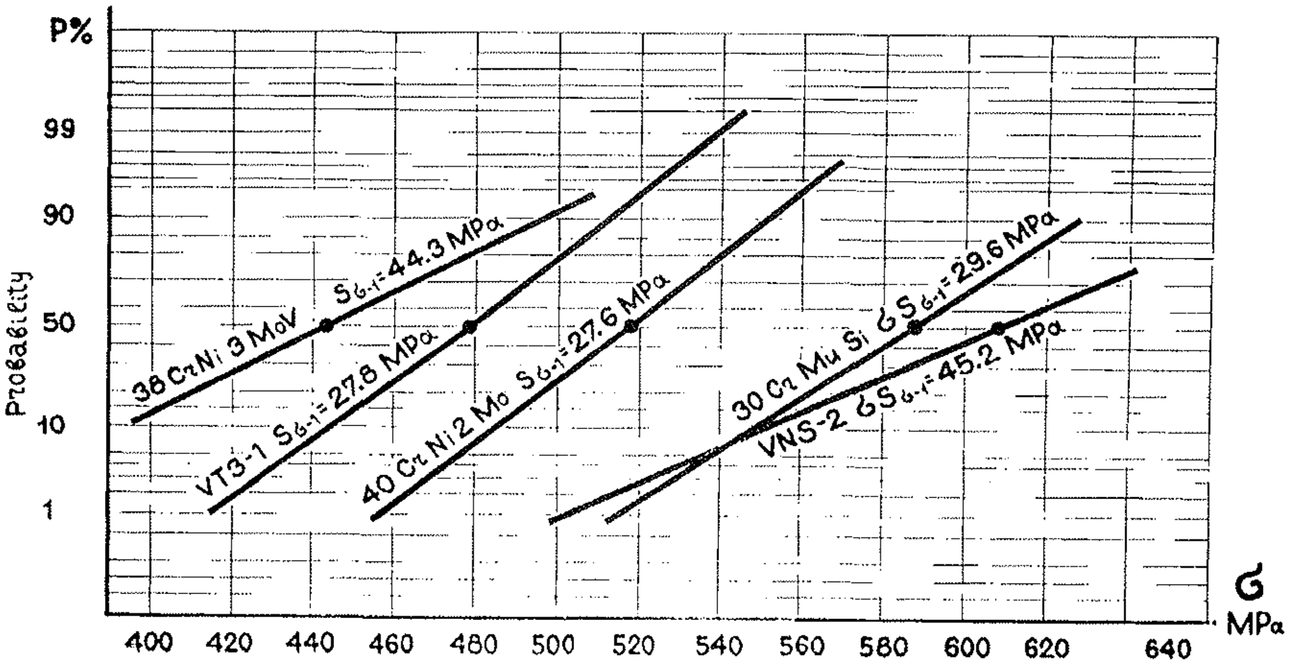


Fig. 2. Distribution of Fatigue Limits for Some Steel and Titanium Alloys Based on $N=10^7$ cycles.

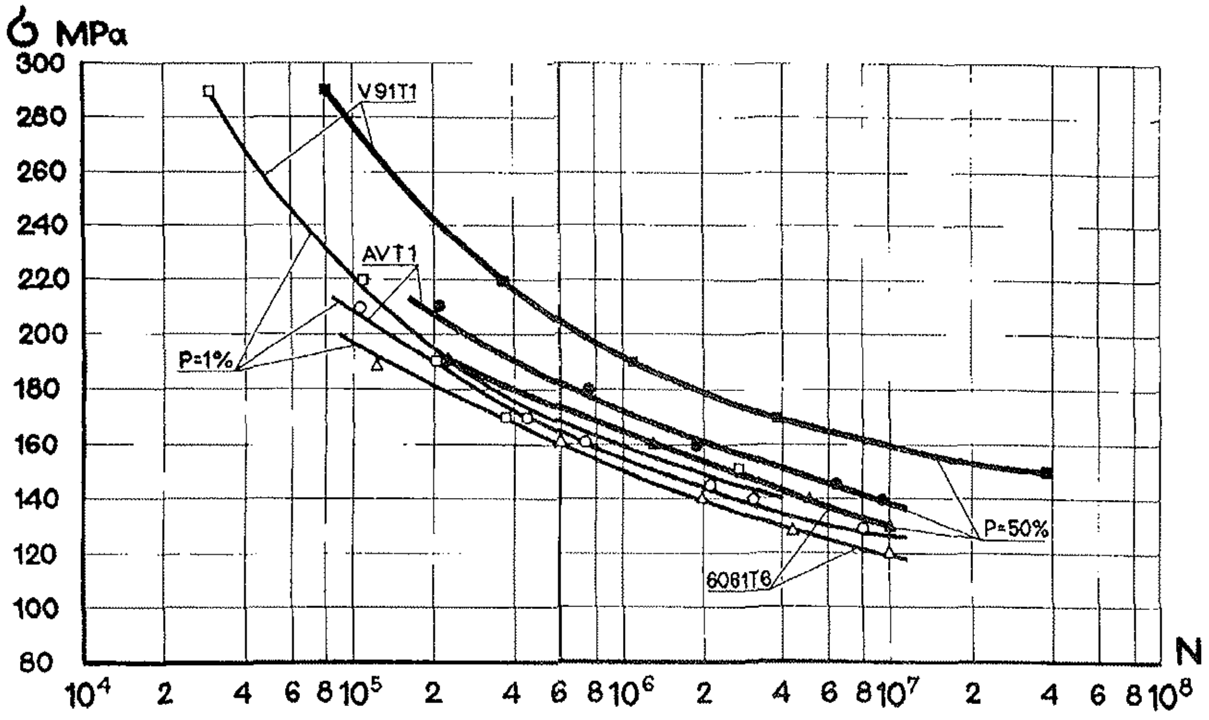


Fig. 3. Stress-Cycle Curves for AVT1 and V91T1 Aluminium Alloys.

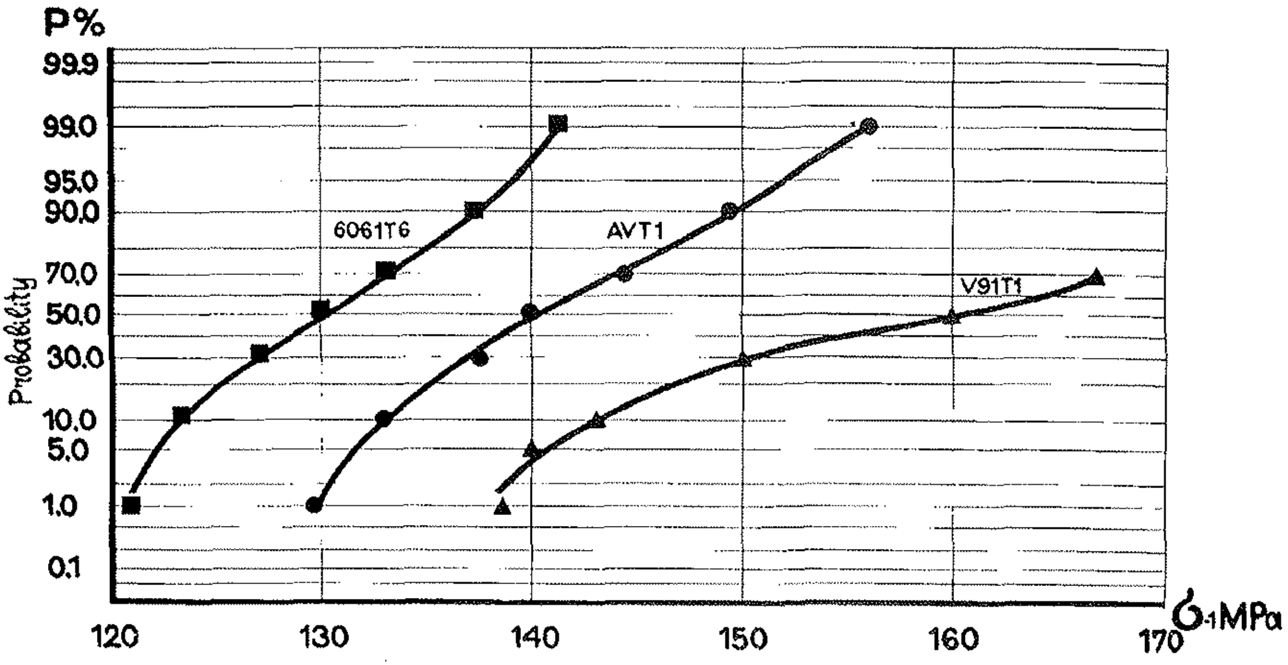
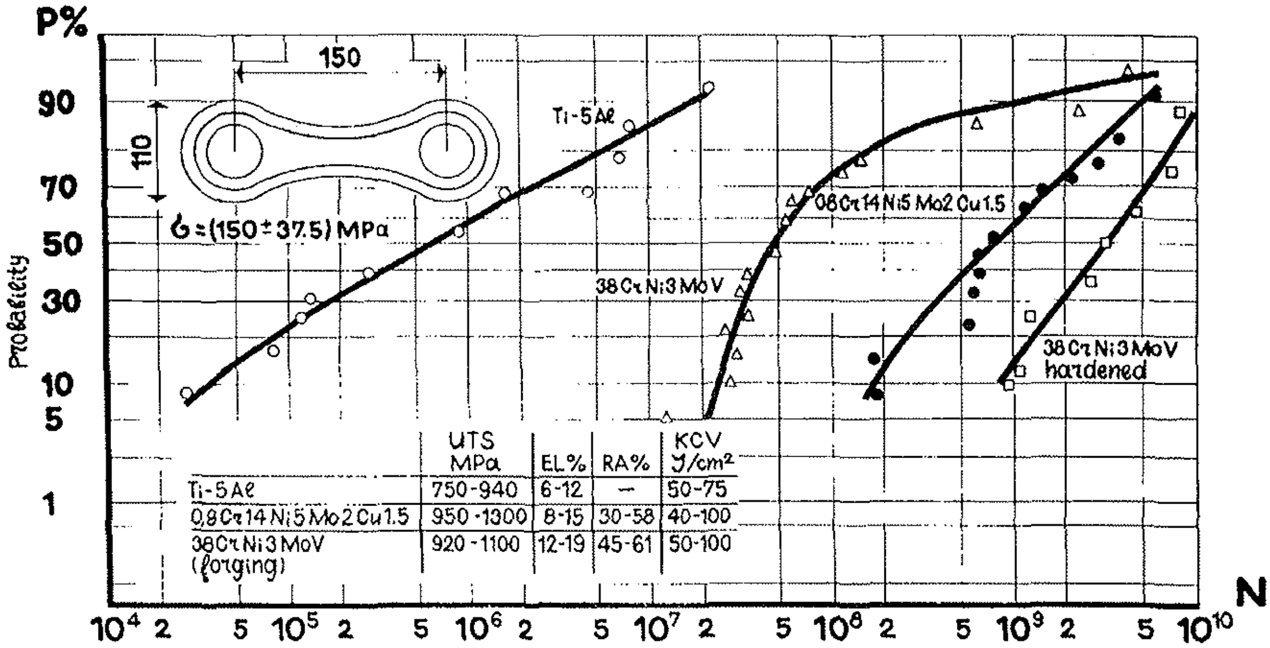


Fig. 4. Distribution of Fatigue Limits for AVT1(ABT1) and V91T1(B91T1) Aluminium Alloys.



	UTS MPa	EL%	RA%	KCV J/cm^2
Ti-5Al	750-940	6-12	—	50-75
0,8Cr14Ni5Mo2Cu1.5	950-1300	8-15	30-58	40-100
38CrNi3MoV (forging)	920-1100	12-19	45-61	50-100

Fig. 5. Comparison of Results Obtained from Dynamic Tests of Cast Lugs for Featheting Hinge Housing.

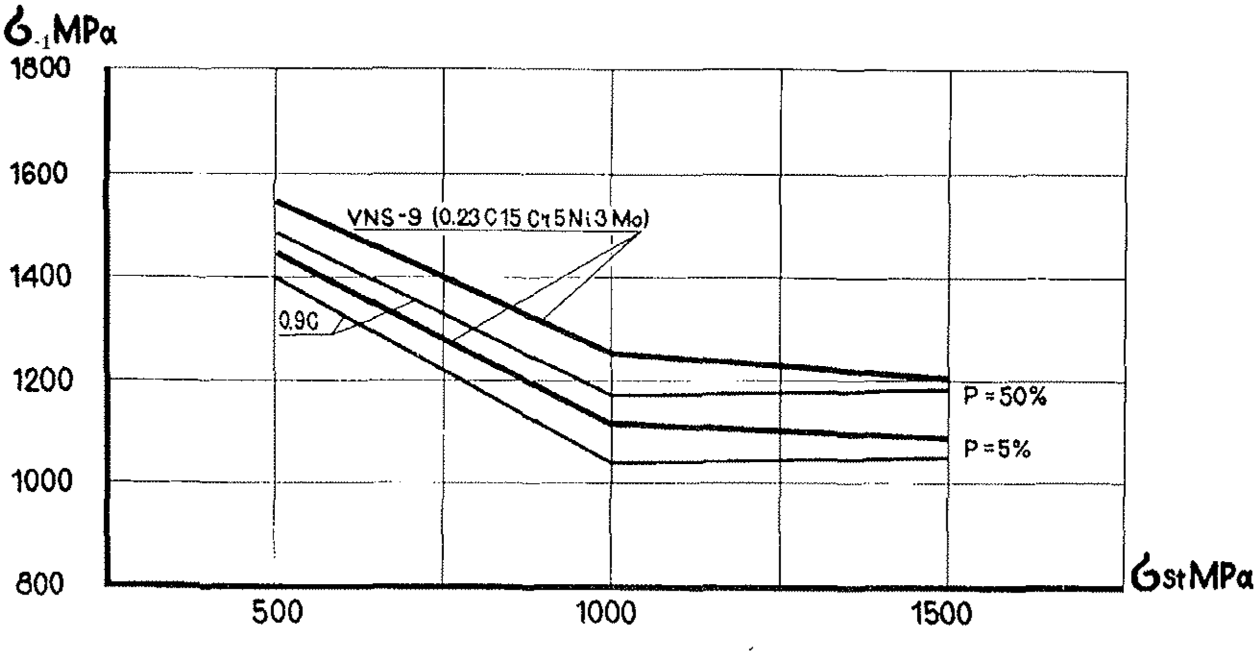


Fig. 6. Fatigue Limit Versus Static Load for Wire Made of VNS-9(BHC-9) Stainless Steel and High-Carbon Steel (0.9 C).

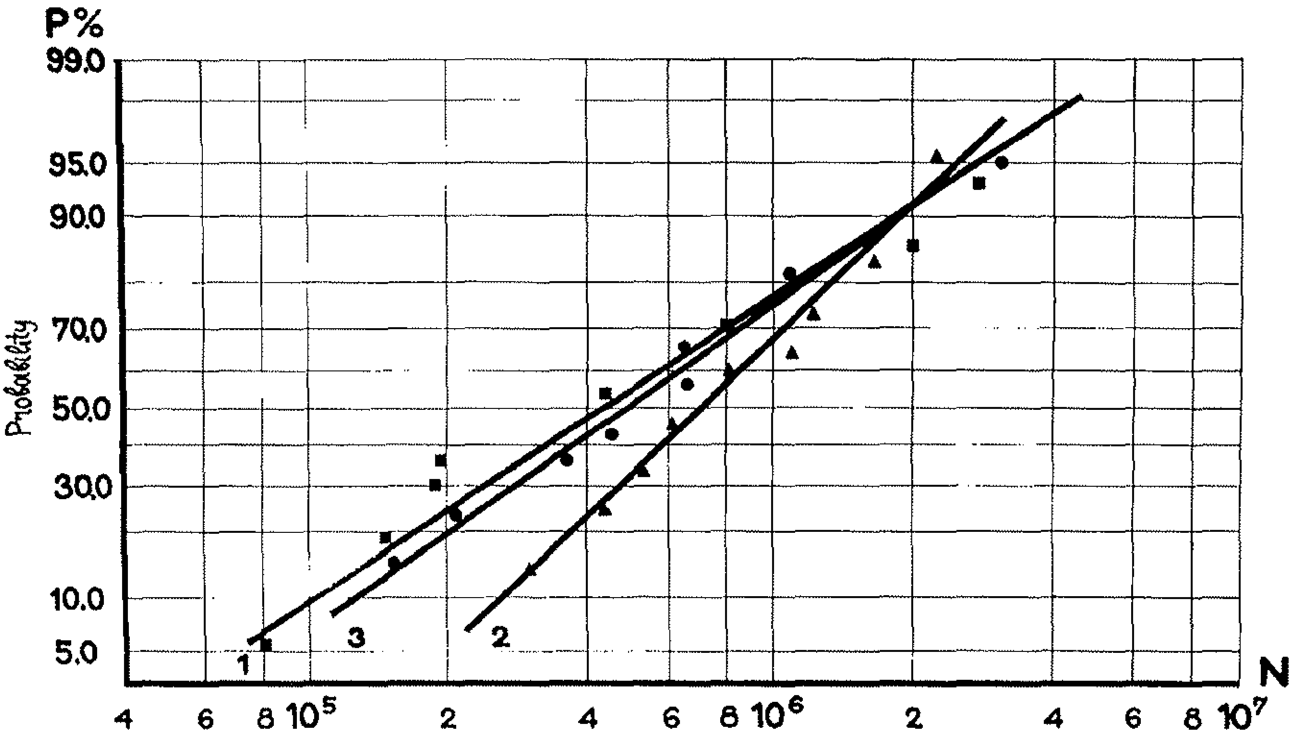


Fig. 7. Distribution of Durability for VNS-9(BHC-9) Steel Alloy Taken from Three Melts.

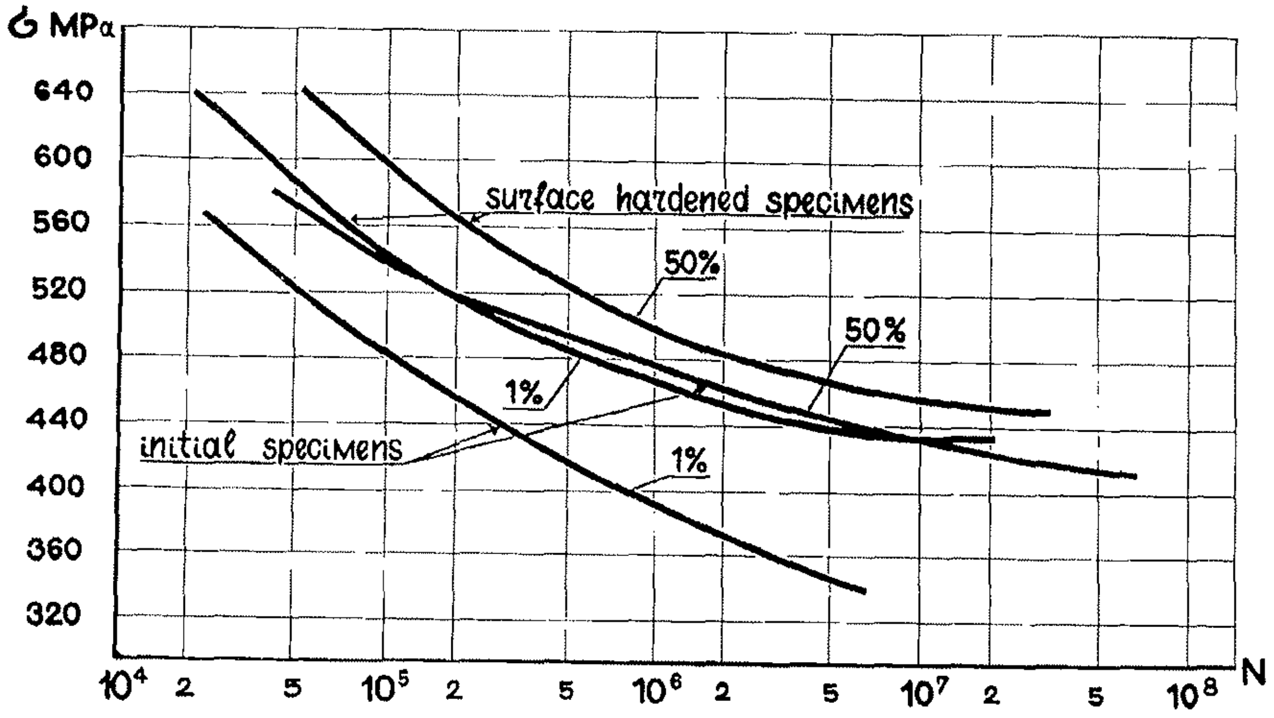


Fig. 8. Stress-Cycle Curves for VT3-1(BT3-1) Alloy.

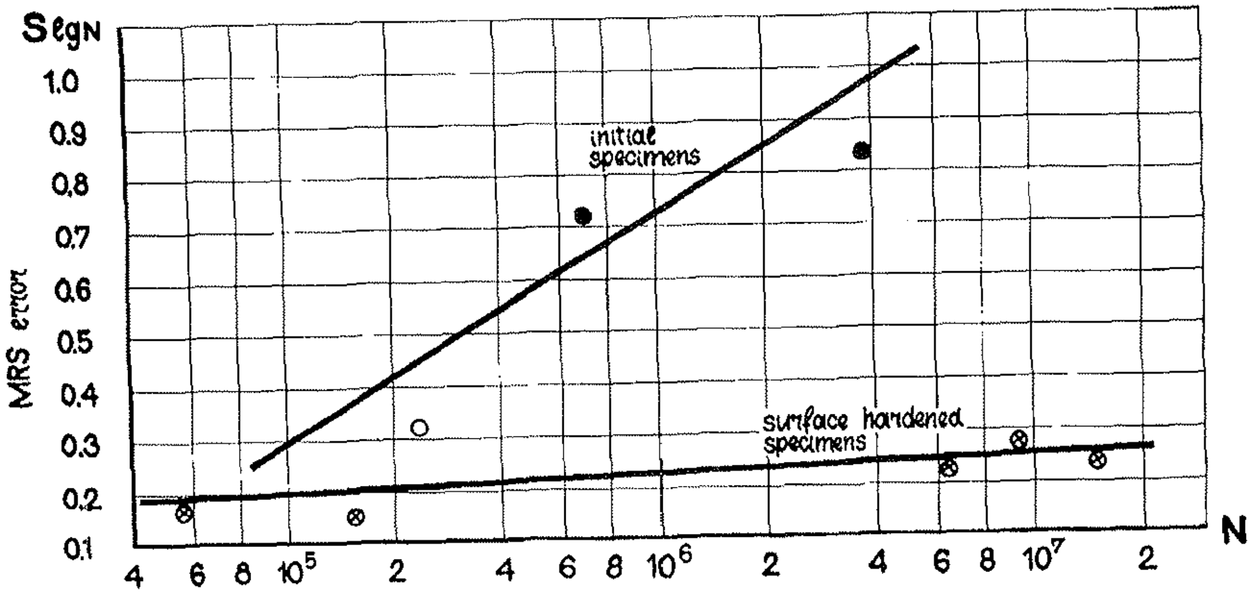


Fig. 9. Durability Logarithm Mean-Root-Square Error Versus Average Number of Cycles till Failure (VT3-1 Titanium Alloy).

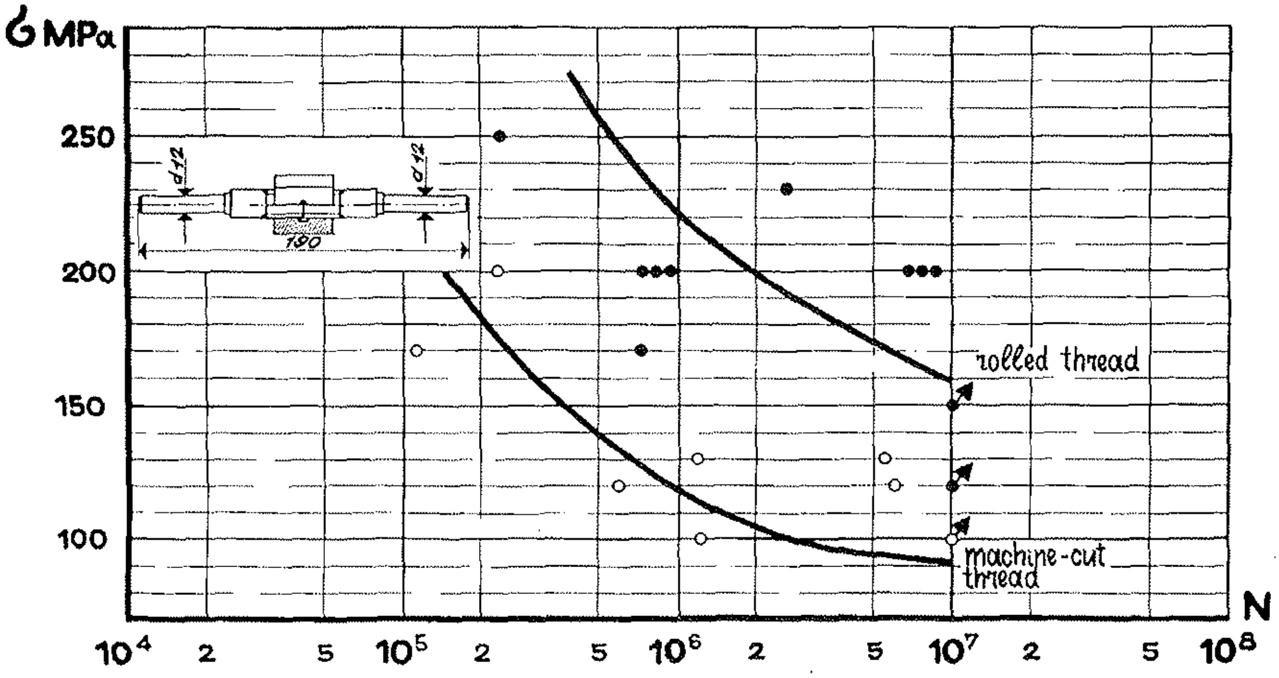


Fig. 10. Stress-Cycle Curves for Bolts Made of 40CrNi2Mo Steel Alloy.