Efficiency of surface cold-work hardening of titanium alloys having different phase composition

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Abstract

The characteristic features of influence of preliminary plastic deformation degree (\(\varepsilon'\)) on endurance limit (\(\sigma_s\)) of titanium alloys having different phase composition are revealed.

The connection between character of relation (\(\sigma_s - \varepsilon'\)) and efficiency of hardening of parts by methods of surface plastic deformation (SPD) is shown.

On the basis of the analysis of investigations of \(\alpha\), pseudo-\(\alpha\), and \(\alpha + \beta\) titanium alloys a conclusion is confirmed experimentally that the absence of sharp decrease of endurance limit of a material in the field of minimum plastic deformations makes hardening of parts by methods of SPD effective.

It is shown, that the realization of tests on the base of \(10^7\) cycles of loading is sufficient for study of change of resistance to fatigue of titanium alloys under influence of preliminary plastic deformation, while the results of these investigations allow to predict effect of decrease of endurance limit of subjected to SPD parts, which reveals itself only at increase of test base up to from \(10^8\) to \(10^9\) cycles of loading.
1 Introduction

Presently an increase of resistance to fatigue by different methods of surface hardening is one of the effective means of service life and reliability enhancement of modern machine parts. For this purpose such kinds of hardening are applied as surface cold working with balls and rollers, shot peening, vibrotumbling, rolling etc. All these types of working are connected with plastic deformation.

In many cases with the help of surface plastic deformation (SPD) it is possible rather essentially to increase resistance to failure of parts working in conditions of alternating loads. SPD is effective for large number of industrial metals: steels of different grades, non-ferrous metals, and also titanium alloys. It was recognized in the study [1], that surface cold working with rollers and vibrotumbling enhance endurance limit of parts from titanium-based alloy on from 25 to 30 %. In this case surface cold working reduces dissipation of resistance to fatigue characteristics, which in its turn additionally leads to increase of efficiency of hardening with decreasing of destruction probability. The examples are known also, when the application of SPD methods allows to increase a conditional endurance limit of parts from titanium alloys by 2 times, and durability by from 17 to 20 times [2]. However such sharp improvement of fatigue properties for titanium alloys is not typical.

Basically, in high cycle region of fatigue the endurance limit is increased maximum by from 40 to 50 %. For example, the hardening with balls actuated by an ultrasonic generator, results in increase of resistance to fatigue on from 29 to 32 % [3]. In the study [4] it is shown that it is possible successfully to apply SPD for nitrided titanium alloys. In the study /5/ it is shown that used methods of SPD of titanium alloys provide favorable conditions for uniform plastic deformation of surface layers of a material, the power content of metal is increased, and, as the consequence, compressive residual stresses are imparted in the surface layer and resistance to fatigue is increased. It explains, in particular, the increase of endurance limit of BT9 alloy (6.5Al; 3.5Mo; 0.2Si; 2Zr) by from 340 up to 400 MPa as a result of SPD by shot peening with micro-balls. At the same time there are also examples of negative influence of surface cold working on resistance to fatigue of titanium alloys. In the study /3/ it is shown that smooth specimens from titanium alloy of 20 and 32 mm in diameter after surface cold working with a roller and applied force of above 5000 N do not increase, but reduce resistance to fatigue. Thus, the available items of information on application of SPD are rather contradictive. In some cases surface cold working makes negative results, in others - positive.

There is a conventional opinion, that a major factor, determining positive influence of hardening on resistance to fatigue of parts, is an imparting, as a result of surface cold working, of favorable compressive residual stresses /1/. Thus in the literature practically there are no data about study of such factor, as altering of physical-mechanical properties of a surface layer as a result of plastic deformation.
2 Realization of experiments

The analysis of the international literary data on a question of influence of preliminary plastic deformation on fatigue properties of metals allows to show disadvantages of techniques usually used in similar investigations, for example in /6,7/. One of the main disadvantages of these techniques is that during realization of experiments the specimen for fatigue tests were deformed uniformly only up to certain discrete degrees of preliminary deformation. The values of endurance limits of metals were determined at different fixed values of preliminary deformation and consequently the intervals between discrete values of deformations remained unexplored. The second essential disadvantage of used techniques is, that the steps of deformation of specimen were taken too large and as a result of it the important area of minimum plastic deformations has appeared almost unexplored.

For study of a material endurance limit altering in a continuously varied succession of preliminary deformations the complex of appliances were created and original experimental technique [8] was developed. The main essence of the technique is in the following: a cantilever type specimen for rotating bending fatigue tests is used, the test portion of which has smoothly varied diameter, the largest being near the grip portion and the smallest being at the end, where bending load is applied. The manner of diameter variation provides for equal resistance to bending stresses in each cross-section along test portion of the specimen. Such specimen is then subjected to preliminary axial loading (tensile or compressive), which imparts on the specimen continuously varied succession of preliminary deformations, proportional in each cross-section to its diameter. The maximum deformation is formed in cross-section with least diameter and in the course of diameter increase the residual plastic deformation is reduced being transient to elastic. As a result of subsequent cyclic loading of such specimen the fatigue failure occurs in that cross-section, where the preliminary local plastic deformation results in the greatest decrease of the material fatigue strength. Thus the technique allows in the given continuous succession of values of preliminary residual deformations to find a critical value of deformation, which most greatly decreases fatigue strength of a material, and degree of this decrease.

The proposed experimental technique has allowed to reveal characteristic features of influence of preliminary plastic deformation on endurance limit of titanium alloys of different phase composition (α, pseudo-α, and α+ β).

Chemical composition of some of the investigated materials and their mechanical characteristics are displayed in Table 1.
Table 1: chemical composition and mechanical characteristics.

<table>
<thead>
<tr>
<th>β-stabilization factor $K_{\beta}$</th>
<th>Type of alloy</th>
<th>Alloying elements content (average), %</th>
<th>Yield strength $\sigma_{0.2}$, MPa</th>
<th>Tensile strength $\sigma_b$, MPa</th>
<th>Elongation $\delta$, %</th>
<th>Reduction of area $\psi$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\alpha$</td>
<td>Ti (100%)</td>
<td>285</td>
<td>405</td>
<td>27.4</td>
<td>69.0</td>
</tr>
<tr>
<td>0.25</td>
<td>pseudo-$\alpha$</td>
<td>1) 4.3Al; 1.9V; 2) 5.1Al; 2.5 Sn</td>
<td>655</td>
<td>720</td>
<td>14</td>
<td>36.0</td>
</tr>
<tr>
<td>from 0.3 to 0.9</td>
<td>$\alpha+\beta$</td>
<td>3) 6.0Al; 4.4V; 4 6.4Al; 3.3Mn; 0.3Si</td>
<td>922</td>
<td>952</td>
<td>18.0</td>
<td>51.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5) 6.4Al; 3.3Mn; 0.3Si</td>
<td>1000</td>
<td>1100</td>
<td>14.9</td>
<td>43.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1060</td>
<td>1185</td>
<td>11.0</td>
<td>52.0</td>
</tr>
</tbody>
</table>

3 Results and their discussion

For $\alpha$ alloys, having the lowest among considered types of alloys endurance limit in the non-deformed condition, the absence of negative influence of plastic deformations on resistance to fatigue is characteristic. For pseudo-$\alpha$ alloys, having higher endurance limit in the non-deformed condition than that of $\alpha$ alloys and lower, than that of $\alpha+\beta$ alloys, the typical is a sharp decrease of resistance to fatigue in the field of small deformations, transient from elastic to elastic-plastic, and slight increase of endurance limit with the further increase of a degree of preliminary deformation. $\alpha+\beta$ alloys with the highest endurance limit inherent to them among considered types of alloys are characterized by monotone decrease of resistance to fatigue in the course of increase of degree $\varepsilon$' (Fig. 1).

It is detected, that in the course of increase of preliminary deformation degree, an equalization takes place of resistance to fatigue of titanium alloys having different phase composition.

It is possible to explain a detected phenomenon of influence of a phase composition on resistance to fatigue of preliminary deformed alloys by hardening effect of $\beta$-phase and unblocking of this effect by plastic deformations.

The analysis of detected general regularities of influence of preliminary plastic deformations on resistance to fatigue of titanium alloys having different phase
composition has allowed to expect effect of positive application of SPD for parts made of $\alpha + \beta$ alloys.

The given assumption was checked experimentally. For study of SPD effect on resistance to fatigue of $\alpha + \beta$ structural alloy the method of surface cold working by rollers, allowing to harden parts such as shafts and axes, was selected. The fact of positive effect of SPD on strength of shaft type parts (Fig. 2) was established: the surface cold working with rollers of 10 mm in diameter specimen with applied force of $P = 1.0$ KN has increased endurance limit at high cycle base of tests. Unlike pseudo-$\alpha$ alloys the positive effect of SPD on $\alpha + \beta$ alloy persists while increasing the number of cycles of loading up to $10^8$ and above. On the basis of the analysis of investigations of $\alpha$, pseudo-$\alpha$, and $\alpha + \beta$ titanium alloys a conclusion is confirmed experimentally that the absence of sharp drop of endurance limit of a material in the field of minimum plastic deformations makes hardening of parts by methods of SPD effective.

The proposed experimental technique for study the influence of preliminary deformation on resistance to fatigue has gained practical use during investigations of strength properties of BT8 (6.5%Al; 3.5%Moe; 0.2%Si) industrial titanium alloy used on Zaporozhye «Motor Sich» PJSC for manufacturing of a gas turbine engine parts.

The effect of monotone decrease of endurance limit of BT8 $\alpha + \beta$ alloy was detected in the course of increase of preliminary deformation value (Fig. 3). The given fact conforms with an offered hypothesis about influence of phase composition on fatigue strength sensitivity to plastic deformation.

The proposed technique of investigations, providing automatic detection of a degree $\varepsilon'$ causing the greatest decrease of fatigue strength, allows to make guaranteed statement that the sharp drops of values of endurance limit, which are characteristic for a number of titanium alloys, are absent in BT8 alloy.

Above-stated has enabled to recommend application of hardening procedure by methods of surface plastic deformation of parts from BT8 alloy for durability increase of products. The application of used experimental technique has provided: increase of accuracy of investigations, significant reduction of experiments volume, decrease of costs on manual labour, material and power resources.

Introduction of surface cold working by a method of hardening with balls actuated by an ultrasonic generator in manufacturing process of compressor blades on Zaporozhye «Motor Sich» PJSC has increased resistance to fatigue of the blades by 20 %. The endurance limit on the base of $10^8$ cycles of loading for blades without SPD made 400 MPa, $K_v = 1.00$, and for blades after SPD it became equal to 480 MPa, $K_v = 1.20$.

It is important to mark the following: the tests of BT8 $\alpha + \beta$ titanium alloy and of $\alpha + \beta$ alloy of BT6 type (6%Al; 4%V) on high-cycle fatigue have shown, that the endurance limit of non-deformed and deformed by stretching or compression specimen, determined on the base of $10^7$ cycles of loading, was not reduced at
the increase of base up to $10^8$ cycles; thus, the base of tests of $10^7$ cycles is sufficient for study of altering of resistance to fatigue of a material under influence of preliminary deformation. The results of tests on this base of cycles allow to predict effect of decrease of resistance to fatigue of the parts, subjected to surface deformation, which manifests itself only in case of increase of the tests base up to $10^8$ and even $10^9$ cycles of loading.

4 Conclusions

1. The application of designed technique for investigation of influence of preliminary plastic deformation on endurance limit of a material has enabled to establish characteristic features of this influence for titanium alloys having different phase composition ($\alpha$, pseudo-$\alpha$, and $\alpha + \beta$). It is revealed, that the presence of $\beta$-phase while increasing endurance limit of alloys augments sensitivity of fatigue strength to plastic deformation. In case of large degrees of deformation convergence of values of endurance limits of alloys takes place irrespective of a phase composition.
2. On the basis of investigations of a wide class of titanium alloys of different phase composition the connection between character of interrelation "endurance limit - degree $\varepsilon$" and effectiveness of employing SPD is detected. The experimental technique of study of preliminary deformation influence on resistance to fatigue has received practical use on Zaporozhye PJSC «Motor Sich» when making analysis of manufacturing process of gas turbine engine parts. The introduction of surface cold working by a method of hardening with balls actuated by an ultrasonic generator in manufacturing process of compressor blades has increased resistance to fatigue of the blades by 20%.
Figure 1: Comparison of sensitivity of fatigue properties of titanium alloys having different phase composition to preliminary plastic deformations: 1 - $\alpha + \beta$ alloys, 2, 3 - pseudo-$\alpha$ alloys, 4 - $\alpha$ alloy.
Figure 2: Comparison of influence of SPD parameters on resistance to fatigue of pseudo-\(\alpha\) and \(\alpha + \beta\) titanium alloys. Base of tests is \(4 \cdot 10^7\) cycles of loading.

1 - \(\alpha + \beta\) alloy
2 - pseudo-\(\alpha\) alloy
Figure 3: Relative change of BT-8 alloy endurance limit depending on value of preliminary plastic deformation.
5 References


