

Influence of ultrasonic sound on physico-mechanical characteristics of titanium alloys

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Abstract. The paper presents data on the influence of ultrasonic vibrations on the main physico-mechanical characteristics in the hardening of titanium alloys. Hardening was carried out during rolling and using free balls in a special working chamber with the imposition of ultrasonic vibrations. The studies have shown that ultrasonic hardening of titanium alloys promotes crushing blocks of mosaic and the formation of a fine-grain structure with a high density of dislocations, changes the phase composition of the surface layer and causes the formation of compressive residual stresses. At the same time, technological heredity is practically not manifested. The endurance range of titanium alloys increases.

1. Introduction

One of the effective ways to improve the physico-mechanical characteristics of titanium alloys is surface plastic deformation, which is carried out by various methods. A promising method for increasing the physico-mechanical characteristics of parts is ultrasonic hardening (UH), including using free balls. In this case, samples are placed in a special working chamber, to which ultrasonic vibrations are applied, under which the balls begin to move randomly [1, 2]. A positive effect is created by multiple micro-collisions in the absence of a given trajectory. This makes it possible to harden thin-walled parts of complex shape and to ensure a more uniform nature of surface deformation [3].

2. Determination of physico-mechanical characteristics

As a result, ultrasonic hardening of the surface layer formed compressive residual stresses σ_r in samples of titanium alloy VT 9. It is found that the magnitude of residual stress is influenced by various factors. Thus, the change in static force P_s of 50 N to 250 N σ_r leads to an increase from 200 to 400 MPa at a depth of up to 250 microns. The increase in the treatment time by free balls up to 150 s. also leads to an increase in σ_r . In this case, the highest values of the residual stresses are at a certain distance from the surface (Figure 1).

To study the effect of ultrasonic hardening on a thin crystal structure of titanium alloys, samples were used after annealing, turning, grinding and the ultrasonic hardening [4].

As a result of investigations, it was established that ultrasonic hardening promotes additional broadening of X-ray interference lines irrespective of the previous treatment, which is a consequence of the increase in strain hardening, which is particularly noticeable on the samples after annealing.



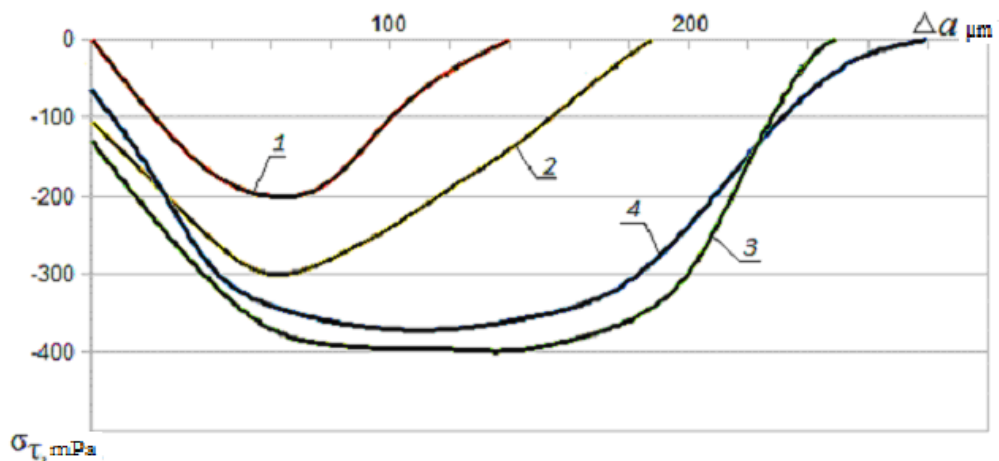


Figure 1. Diagrams of tangential residual stresses in samples of VT 9

Hardening Modes : $f=20$ kHz, $V=30$ m/min, $\xi=15$ μm

1. $P_s=50\text{N}$ 2. $P_s=100\text{N}$ 3. $P_s=200\text{N}$ 4. $P_s=250\text{N}$

Broadening X-ray diffraction lines in the annealed and hardened specimens are lower than in peeled and hardened specimens. This is due to the fact that when the samples are hardened after turning, a structure is formed in the surface layer, characterized by grinding the blocks and the development of microdistortions of the crystal lattice. As is known, when ultrasonic waves pass through the crystals, the dislocations are activated. A part of the activated dislocations acquires mobility, which leads to the localization of plastic deformation. In samples that hardened after turning, the number of mobile dislocations is smaller due to a large number of obstacles, which leads to sub-structural hardening due to the formation of smaller blocks with large micro-dips inside them. With ultrasound specimens after annealing, ultrasound-activated dislocations are not obstructed by obstacles, so they have a large path length and a lower degree of hardening [5].

On the basis of analysis of distribution broadening interference depth lines, it was found that after turning the samples are characterized by a deformation hardening depth of up to 100 μm hardened after turning to 150 μm , and after annealing and ultrasonic hardening to 210 μm (Figure 2).

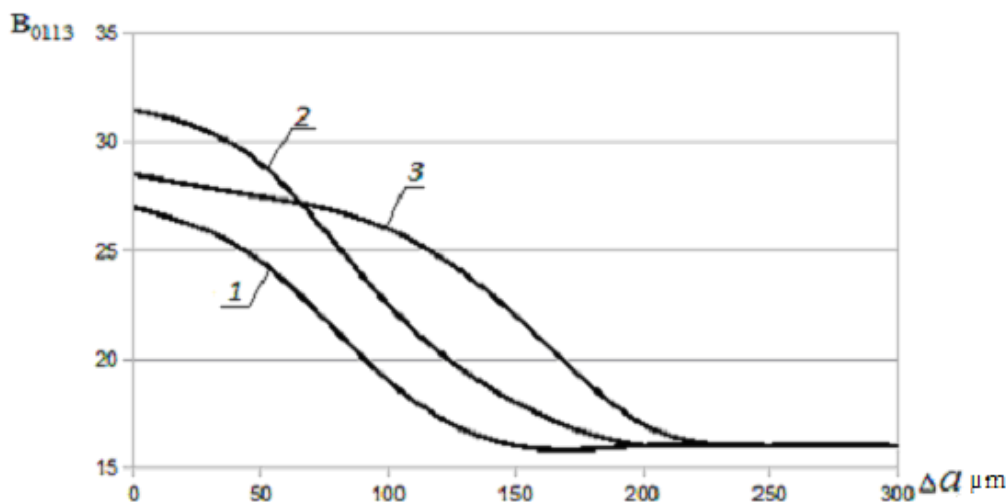


Figure 2. Distribution lines broadening depth in samples of B_{0113} depth in samples of VT3-1

Hardening Modes : $P_s=200\text{N}$, $\xi=15$ μm , $d_b=5$ mm, $S=0.07$ mm/rev, $V=30$ m/min

1 - after turning ,

2 - after turning and ultrasonic hardening ,

3 - after annealing and ultrasonic hardening

It has been established by investigations that ultrasonic hardening by free balls of titanium alloys VT9, VT20 also contributes to the crushing of mosaic blocks, the development of microarrays and the increase in the dislocation density. This is due to the fact that local heating, stress relieving, unlocking the dislocations, and increasing their mobility occur in places of elementary plastic shear. These factors indicate a softening effect of ultrasound and cause a more uniform plastic deformation during hardening. The softening effect is confirmed by measuring the microhardness of the surface layer of samples from alloy VT 20. The results of these studies have shown that the degree of strain hardening with ultrasonic hardening by free balls is approximately 10% less than during ball strengthening without ultrasound, although the residual stresses have close values.

Investigation of the effect of ultrasonic hardening on the phase composition of the surface layer of titanium alloy OT4 showed that the largest phase transformations occur in annealed samples. Thus, with the ultrasonic hardening of the samples after annealing, the content of the β -phase on the surface decreased from 18% to 12%; the depth of phase transformations in this case was 100-150 μm . When the hardened samples were hardened, the amount of the β - phase decreased from 10% to 4 ... 5%.

Analysis of the integrated intensities of the α - and β -phase lines of the annealed OT4 alloy shows that ultrasonic hardening leads to $\beta \rightarrow \alpha$ transformations. Studies have shown that the main reason for these transformations is the power factor.

The decomposition of the metastable β -phase under the influence of plastic deformation alters the nature of the residual stresses since the phases have different densities. Since the density of the β - phase is smaller than the α -phase density, $\beta \rightarrow \alpha$ transformations decrease the volume of the surface layer and cause the formation of tensile residual stresses. In the OT4 alloy, the tangential and axial compressive residual stresses are 100-150 mPa higher than for the VT20, VT9 alloys, and the amount of the free β -phase in the initial state does not exceed 4 ... 5%.

Ultrasound hardening is characterized by intense plastic deformation. Investigation of the stress-strain state in the contact zone was carried out in the ANSYS software complex using the finite element method. The results of determination of strain intensity ε_i as a function of the hardening force showed that with increasing of the latter when rolling with a ball, ε_i increases to 0.12 with UH and up to 0.096 when rolling with a ball without imposing ultrasonic vibrations. This is due to the fact that the rate of deformation at UH is much higher, which is a consequence of the rapid spread of the pressure front localized in a small volume.

As it is known, high-speed and quasi-static deformations affect the crystal lattice in various ways. High-speed deformation redistributes the influence of individual factors on the physico-mechanical characteristics of the material. In connection with this, ultrasonic hardening is formed by a fine-grained structure with a high dislocation density. The greatest values of the intensity of stresses and deformations are at some distance from the surface, which is connected with the localization of the maximum tangential stresses in this region.

The results of electron microscopic studies presented in Figure 3 showed that the maximum decay of the β - phase is observed on the surface of the sample and reaches a depth of 100 μm .

As can be seen from the presented photographs (Figure 3a), in the samples in the initial state two phases clearly differ: a light α -phase and dark, in the form of bands, β - phase. As a result of ultrasonic hardening, intense phase transformations occur on the surface, which are characterized by a significant crushing and delamination of the β - phase boundaries (Figure 3b).

A similar picture takes place at a depth of 50 μm (Figure 3c). At a distance of 100 μm from the surface, the intensity of phase transformations, as in the case of radiographic analysis, is insignificant (Figure 3d).

Thus, electron microscopic studies confirm the data of X-ray analysis and indicate the presence of $\beta \rightarrow \alpha$ transformations in the surface layer.

It is known that technological heredity has a significant effect on the magnitude and nature of the distribution of residual stresses after hardening and in some cases leads to a significant decrease in strength characteristics of parts. Therefore, the choice of ultrasonic hardening parameters should be carried out taking into account the nature of the preceding treatment. The results of the study show that when the specimen is cast from the VT9 alloy with carbide cutter BK8 and polycrystalline diamond, the compressive residual stresses in the surface layer are $\sigma_\tau = 150 \dots 220$ mPa at a depth of 50 ... 80 μm . After grinding, tensile residual stresses are formed in the surface layer $\sigma_\tau = 300 \dots 400$ mPa with a depth of 75-90 μm . Regardless of the type of previous treatment after ultrasonic hardening, compressive residual stresses are formed in the surface layer with approximately the same value $\sigma_\tau =$

330 ... 400 mPa and a bedding depth of up to 250 μm . Consequently, with ultrasonic hardening, technological heredity is practically not manifested.

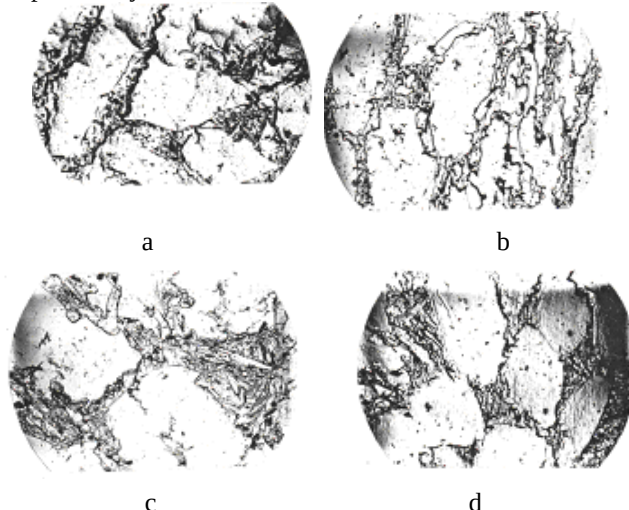


Figure 3. Crystalline transformation in samples of VT9 alloy: a - the surface in the initial state; b - after ultrasonic hardening; c - after ultrasonic hardening at a depth of 50 μm ; d - after ultrasonic hardening at a depth of 100 μm .

Studies of fatigue fractures of ground and hardened specimens made it possible to determine characteristic fracture zones: the crack initiation zone, the transition zone, which is characterized by mixed destruction, and the dolomite zone. A significant difference between the unstressed and hardened samples is that in the first case the crack nucleation starts from the surface, and in the hardened samples the crack initiation zone is at a certain depth and is characterized by the presence of fatigue macroscopes. Depending on the hardening conditions, the endurance limit of titanium alloys is increased to 450 MPa.

With ultrasonic hardening, an increase in the endurance limit is determined not only by residual stresses and the degree of plastic deformation, but also by the features of the physical state of the surface layer under conditions of high-frequency cyclic action of ultrasonic vibrations. These features include - increased dislocation density, significant micro-distortion, intensive inhibition of various structural defects, changes in the energy state, phase transformations, etc.

The positive effect of hardening also lies in the fact that the strengthened layer limits the yield of dislocations to the surface during cyclic deformation, thereby increasing the overall energy intensity of the material and, as a consequence, the growth of the fatigue strength.

3. Conclusion

Optimum regimes of hardening are determined experimentally which are within the following limits: amplitude of oscillations $\xi = 10 \dots 30 \mu\text{m}$, diameter of balls $d = 1.5 \dots 3 \text{ mm}$, processing time $t = 100 \dots 200 \text{ s}$.

Ultrasound hardening leads to a significant improvement in the physico-mechanical characteristics of titanium alloys and a significant increase in their fatigue strength (up to 48%). In this case, the nucleation zone of the fatigue crack shifts below the surface.

References

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