also be achieved in this case.

It is not possible to draw a well-defined conclusion concerning the effect of strain rate on the coefficients of variation of the mechanical characteristics (they are observed to remain constant, decrease, and increase).

The sensitivity of σ_u to strain rate is observed to increase with decreasing initial ultimate strength of the steels under investigation; this agrees well with Voloshenko-Klimovitskii's data [1].

CONSLUSIONS

1. For the materials investigated (except for steel 30KhGSA), the strength properties are improved significantly with increasing strain rate, and the deformation properties vary less appreciably in this case. For steel 30KhGSA, conversely, the strength properties experience a smaller change than the deformation properties.
2. The results that we obtained from the investigations must be considered in developing technological processes for the pressure treatment of metals and for the design of components subjected to dynamic loads.

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EFFECT OF ULTRASONIC VIBRATIONS ON THE MECHANICAL PROPERTIES OF DIFFICULT-TO-DEFORM MATERIALS

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One of the promising trends for improving the technological properties of difficult-to-deform materials is the introduction of ultrasonic vibrations to the deformation zone. Different processes of plastic shape variation, which are based on this principle, have come into increasingly widespread use during machining, pressure treatment, and treatment by surface plastic deformation [1-3]. As follows from the results of these studies, the high efficiency of ultrasonic treatment methods is governed primarily by variation in the strength and plasticity of various materials in the ultrasonic field. Information on the mechanical properties of difficult-to-deform materials under ultrasound is therefore required to resolve practical problems associated with the computation of energy-force parameters and the optimization of ultrasonic-treatment processes.

This paper presents the results of investigation of the effect of ultrasound on the mechanical properties of high-alloy steels and alloys 12Kh25N16G7AR, 10Kh12N20T3R, KhN77TYuR, KhN35VTYu, KhN70VMTYuB, KhN75VMFYu, and KhN55VMTFKYu, as well as the titanium alloys VT3-1, VT5, VT9, VT15, and OT4.

Major attention has been focused on the compression testing of specimens fashioned from

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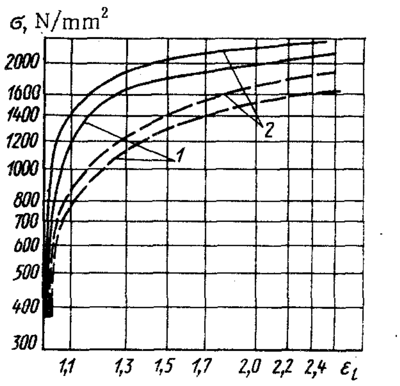

Fig. 1. Diagrams of actual stresses under conventional (solid lines) and ultrasonic compression (f = 22 kHz, ξ = 10 μm, θ = 20°C) (broken lines): 1, 2) alloys KhN77TYuR and KhN70VMTYu, respectively.

these materials, which ensures (in contrast to tension) a relatively higher degree of deformation, a virtually uniform effect of ultrasound on the entire volume being deformed, and the identical character of the strain diagram between basic technological processes involving machining and pressure treatment and the application of ultrasound.

The investigations were conducted on a special bench consisting of a modernized U20-1 testing machine with a heating unit, a device for transmitting ultrasonic vibrations to the specimen (with an automatic-frequency-control system), a UZG 10-22 ultrasound generator, and a monitoring-measuring apparatus. The mechanical properties were determined at normal and elevated temperatures θ, using the conventional loading scheme, and also the simultaneous influence exerted on the specimen by a steadily increasing static force and axial ultrasonic vibrations with a frequency f = 22 kHz and amplitude ξ = 5–20 μm. $F^c = f(\Delta h)$ diagrams, where F^c is the axial compressive load and Δh is the absolute deformation (shortening) of the specimen, were continuously recorded in the loading process. Similar diagrams were also obtained during comparative tension tests. The dimensions and number of specimens were determined, and the results of the tests treated statistically in accordance with GOST 25 503-80. As analysis of the $F^c = f(\Delta h)$ diagrams indicated, a significant reduction in the deformation forces required to produce equivalent deformations is a general law for the size reduction of the materials investigated under the simultaneous action of ultrasound, irrespective of their composition and initial mechanical properties. While a force F^c = 25 kN is required for the relative deformation of alloy KhN77TYuR specimens under normal compression with ξ = 0.2, a force of 16 kN is sufficient for deformation with the same degree in an ultrasonic field (ξ = 10 μm). The effectiveness of the ultrasound increases with increasing vibration amplitude: When ξ = 15 μm, the deformation force is reduced to 11.8 kN. For a constant vibration amplitude, the positive effect of ultrasound depends on the composition and structure of the materials investigated. Thus, the relative reduction in deformation forces is smaller for the titanium alloys under compression with the simultaneous action of ultrasound than for the dispersion-hardening alloys KhN70VMTYuB, KhN55VMTFKYu, and others when tested under similar conditions. The trend toward a reduction in ultrasound effectiveness with increasing γ'-phase content in these alloys is observed, in turn, for these materials.

A reduction in the deformation force, which is proportional to the vibration amplitude, is also observed during tension tests; in this case, however, the application of ultrasonic vibrations is accompanied by a reduction in the plastic properties of the materials investigated in contrast to the compression tests. As the comparative analysis indicated, the stage of uniform specimen elongation is appreciably shortened under tension, and localized plastic deformation is virtually absent: specimen failure occurs at the initial moment of neck formation. This is confirmed, for example, by the results of an investigation of the specimens after failure: during tensioning accompanied by ultrasound, the relative necking ψ of alloy KhN77TYuR is reduced by 17%, and that of alloy KhN35VTYu by 22%. The relative and actual

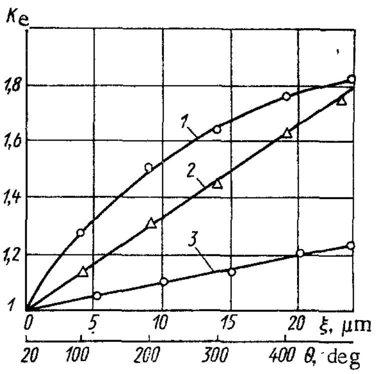

Fig. 2. Relative variation in conventional yield point of titanium alloy VT3-1 as function of amplitude of ultrasonic vibrations (ξ) and test temperature (θ): 1) ultrasonic compression at various temperatures (f = 22 kHz, ξ = 10 μm); 2) normal compression; 3) ultrasonic compression (f = 22 kHz, ξ = 10 μm, θ = 20°C).

elongation of the specimen $l = \ln[1/(1-\psi)]$, which, according to [4], is proportional to the limiting degree of shear deformation, characterizing the material's plasticity, are reduced simultaneously. These data suggest a reduction in the plasticity of alloy KhN77TYuR and are in qualitative agreement with the results obtained by Severdenko et al. [2] during the tensioning of alloy D16, copper M1, and commericial iron with ultrasonic vibrations. Similar results are also obtained during the "ultrasonic tensioning" of the other materials investigated. The observed reduction in the limiting plastic deformation under the action of ultrasound is associated with the formation of an increased concentration of dislocations and vacancies in local volumes of the specimen, and as a result of this with the development of micro- and submicrodiscontinuities and with the disintegration of the crystal structure. The latter manifests itself, for example, as a reduction in microhardness in the failure zone as compared with the initial hardness.

Graphs of the actual stresses σ versus the logarithmic strains ε_l, which make it possible to estimate the effect of ultrasound on the conventional yield points $\sigma^c_{0.2}$ and the yield points σ^c_0 extrapolated from the rectilinear "polytropic" portion of the compression curve, i.e., the stresses that would have been observed had plastic deformations developed from the outset of loading, were plotted in conventional and logarithmic coordinates on the basis of analysis of the $F^c = f(\Delta h)$ diagrams. As we know, the yield points σ^c_0 are independent of the ratio h_0/d_0, and are therefore a highly valued mechanical characteristic of the material under conventional and "ultrasonic compression." The indicator K_e, which is equal to the ratio of $\sigma^c_{0.2}$ under normal conditions to the similar characteristic obtained under an ultrasonic or thermal effect, was used as a criterion for evaluating the efficiency of an additional energy effect.

It is apparent from Fig. 1 that with the superposition of ultrasonic vibrations, the resistance of the alloys to compressive plastic deformation is diminished and the process itself is characterized by lower $\sigma^c_{0.2}$ and σ^c_0 values. This effect manifests itself to a large degree during the compression of high-alloy materials that do not contain the hardening γ'-phase, for example, the heat-resistant steel 12Kh25N16G7AR. For alloys in which the γ'-phase forms during cooling, the effectiveness of ultrasound decreases with increasing content of this phase. As the γ'-phase content increases from 10-12% (alloy KhN35VTYu) to 40% (alloy KhN55VMTFKYu), K_e decreases from 1.35 to 1.24, respectively. For the titanium alloys, K_e is 1.13-1.21, depending on the phase composition; in this case, better results are obtained for the comparison of titanium alloy VT5. As is apparent from Fig. 2, indicator K_e increases in proportion to ξ and θ; the variation in K_e as a result of the combined effect of these factors is more complex: when $\theta \leq 300°C$, this indicator increases and exceeds the values obtained for the separate effect of ξ and θ; with a further increase in θ, the effectiveness of ultrasound decreases, and at θ = 450-500°C, the conventional yield point is reduced virtually as a result of the thermal effect alone. For the titanium alloys, the value of K_e can be determined for different loading forms, using the equation

$$\sigma_u^c = \sigma_{0,2}^c - m\xi;\ \sigma_\theta^c = \sigma_{0,2} - n\theta;\ \sigma_{u,\theta}^c = \\ = \sigma_{0,2} - p\theta^{0,27},$$

where σ_u^c, σ_θ^c, and $\sigma_{u,\theta}^c$ are the conventional yield points for the ultrasonic, thermal, and combined (thermal and ultrasonic) effects, respectively, and m, n, and p are coefficients dependent on the material of the specimens and the loading conditions. For the titanium alloy VT3-1, m = 0.8, n = 0.08, and p = 7.52 in the temperature and vibration-amplitude intervals investigated.

As is apparent from Fig. 1, compression tests do not make it possible to bring high-alloy materials to failure, and, in this manner, to use the results obtained for direct determination of their strength properties. We therefore evaluated the effect of ultrasound on the ultimate compressive strength by comparing the actual values of this characteristic, which correspond to the initial ordinate of the "polytropic" segment of the compression diagram [5]. The results of this evaluation suggest that a reduction in the actual ultimate strength is 15-22% on average for the ultrasonic compression of the high-alloy metals in the amplitude region investigated. In contrast to the high-alloy metals, the normal and ultrasonic compression of specimens of the titanium alloys is accompanied by their failure; here, failure occurs by shear in both cases, and a macroscopic failure surface forms when the direction of F^c is at an angle of approximately 45°.

It is established that during the ultrasonic compression of the titanium alloys VT3-1, VT8, VT5, and VT15, σ_u^c decreases with increasing vibration amplitude; here, this effect is manifested to a large degree during the compression of alloy VT5, the σ_u^c of which is decreased by 16%. With the combined thermal and ultrasonic effect (θ = 300°C, ξ = 15 μm), the σ_u^c of this alloy is decreased by 43%; with a further increase in temperature, however, the effect of ultrasound on this characteristic is manifested to a lesser degree.

As we know, tools, the effective elements of which are fabricated in the form of a sphere and wedge, are used for various plastic-shaping processes utilizing ultrasound. Accordingly, the effect of ultrasonic vibrations on the resistance of the materials investigated to plastic deformation during the embedment of spherical and wedge-shape strikers formed from steels ShKh15, R18, and R6M5 was determined together with the standard tests.

The resistance to plastic deformation was evaluated from the variation in the vertical P_1 and horizontal P_2 components of the deformation force as a function of the amplitude and directions of the ultrasonic vibrations. Analysis of the results of the investigations indicated that the above-mentioned laws governing the effect of ultrasound on the deformation forces are also retained basically for loading schemes characteristic for real working conditions.

Thus, a force P_1 = 1520 N is required to produce an impression 20 μm deep in titanium alloy VT9 during the normal embedment of a ball 5 mm in diameter, while force P_1 = 640 N is required with the superposition of ultrasonic vibrations perpendicular to the surface of the specimen (f = 20 kHz, ξ = 5 μm). The depth of the impression is 167 μm, however, for ultrasonic loading with a force P_1 = 1520 N. According to Kazantsev [6], if the results of these tests are treated as a unique Brinell test, we can conclude that ultrasound contributes to a significant reduction in the hardness of the metals; in this case, a similar effect manifests itself to a greater degree with increasing vibration amplitude.

Similar results are obtained during the embedment and displacement of wedge-shape strikers.

CONCLUSIONS

1. The superposition of ultrasonic vibrations during the compression and tensioning of difficult-to-deform materials contributes to a reduction in their resistance to plastic deformation, yield points, and strength.

2. The effect of ultrasound during the tensioning of difficult-to-deform materials is accompanied by a reduction in the limiting plastic deformations as a result of the formation of additional damage to the crystal structure.

3. The effectiveness of ultrasound on the mechanical properties of difficult-to-work materials is determined by their chemical composition and structure, as well as by the parameters of the ultrasound and the temperature of the tests.

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EFFECT OF RESIDUAL STRESSES IN SURFACE LAYERS ON THE PROPERTIES OF STEEL 30KhGSA

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It is known that the formation of residual compressive stresses on the surface contributes to an increase in the longevity of structural components subjected to cyclic loads. For many components of complex shape, which operate under low-cycle loading, however, surface hardening by mechanical methods is impossible.

We have established that it is possible to select that cooling regime for similar elements for which the cooling rate of the component's surface layers is significantly higher than the cooling rate of the internal layers. As a result of the development of a pronounced temperature gradient across the section of a component in the surface layers, residual tensile strains may develop, since by retaining its own dimensions, the heated core prevents compression of the surface layers. In this case, compressive deformations develop in the core. When the temperatures are equalized across the section of a component and it has cooled to normal temperature in the surface layers, residual compressive stresses develop as a result of compression of the core material. In this case, the largest temperature gradient across the surface of a specimen or component is attained after they have been heated to temperatures below the temperature of the polymorphic transformation and cooled in liquid nitrogen for a specified time (subsequent cooling in air) (Fig. 1).

The inert medium (nitrogen) does not cause the surface of the material to oxidize.

Residual compressive stresses were induced in the surface layers of specimens and components in accordance with the following regime.

1. Heating of the specimen to a temperature t_h (°C) below the temperature of the material's polymorphic transformation:

$$t_h = \frac{\sigma_{0,2}}{\alpha E},$$

where $\sigma_{0.2}$ is the conventional yield point of the material in N/mm², E is the modulus of longitudinal elasticity in N/mm², and α is the temperature coefficient of the material's linear expansion in 1/°K.

2. Cooling of the specimen in liquid nitrogen at −196°C with holding, the optimal duration of which was determined from experiments.

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