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Original article

Оригинальная статья

MECHANICAL AND ACOUSTIC PROPERTIES OF DEFORMABLE ALLOYS

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Abstract. The paper is devoted to correlation dependences of ultrasound velocity with characteristics of strength and plasticity in uniaxial tension of Fe18Cr10Ni austenitic stainless steel with a unique set of physical and mechanical properties. Such a successful set of mechanical properties is provided by dislocation slip and twinning, the formation of stacking faults, and martensitic transformation. It should be noted that the assessment of changes in the mechanical characteristics of metals (especially at low temperatures) is a very laborious task and requires the use of non-destructive control methods. Experimental data was obtained using a bench designed to synchronize with recording of the “stress – strain” diagram for determining the values of ultrasound velocity propagation and the attenuation coefficient of the ultrasonic wave as a function of deformation. Measurement of ultrasound velocity propagation was reduced to determining the time of passage of an ultrasonic Rayleigh pulse between transmitting and receiving transducers. Attenuation was determined from the change in pulse shape. The pulses were excited by a piezoelectric transducer at a frequency of 5 MHz. The authors experimentally studied static loading effect on acoustic characteristics and calculated the destruction parameters. The propagation of ultrasound velocity in deformable material is an informative feature for analyzing the nature of the processes that control plasticity. The effect of test temperature in the range $180\text{ K} \leq T \leq 320\text{ K}$ on acoustic and mechanical characteristics of the steel was studied to ensure control of its structural state and mechanical properties by means of non-destructive testing. The temperature range was chosen taking into account the possibility of direct $\gamma \rightarrow \alpha'$ martensitic transformation.

Keywords: strength, plastic deformation, failure, ultrasound velocity, stainless steel

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ИССЛЕДОВАНИЕ МЕХАНИЧЕСКИХ И АКУСТИЧЕСКИХ СВОЙСТВ ДЕФОРМИРУЕМЫХ СПЛАВОВ

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Аннотация. В работе исследованы зависимости между скоростью распространения ультразвука и механическими характеристиками в процессе одноосного растяжения аустенитной нержавеющей стали марки 12X18H10T, обладающей уникальным комплексом физико-механических свойств, включая высокие показатели прочности, пластичности, ударной вязкости и хладостойкости. Данный комплекс физико-механических свойств обеспечивается благодаря действию различных механизмов пластической деформации (дислокационное скольжение/двойникование, образование дефектов упаковки, мартенситное превращение). Следует отметить, что оценка изменения механических характеристик металлов (особенно при низких температурах) является весьма трудоемкой задачей и требует применения неразрушающих методов контроля. Экспериментальные результаты были получены с помощью стэнда, предназначенного для синхронизированного с записью диаграммы напряжение – деформация определения скорости распространения ультразвука и коэффициента затухания ультразвуковой волны как функций деформации. Процедура измерения скорости распространения ультразвука заключается в фиксировании времени прохождения ультразвукового рэлеевского импульса между передающим и приемным преобразователями. Затухание ультразвуковой волны вычисляется по изменению формы этого импульса. Импульсы возбуждаются пьезоэлектрическим преобразователем на частоте 5 МГц. Исследовано изменение акустических характеристик в условиях статического нагружения и рассчитаны критические параметры перехода материала в деструктивное состояние. Скорость распространения рэлеевских

ультразвуковых волн непосредственно в ходе нагружения материала является информативным признаком для анализа природы процессов, контролирующих пластичность. Обнаружено влияние температуры испытаний на акустические и механические характеристики стали. Исследуемый температурный интервал $180\text{ K} \leq T \leq 318\text{ K}$ выбран с учетом возможности реализации в стали прямого $\gamma \rightarrow \alpha'$ мартенситного превращения при растяжении.

Ключевые слова: прочность, пластическая деформация, разрушение, скорость ультразвука, нержавеющие стали

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INTRODUCTION

The level of safety in critical objects in atomic power engineering, aircraft, shipbuilding, oil and gas, as well as other industries depends significantly on the effect of resource depletion of design elements of equipment in the operation of structural materials. Therefore, the critical state of material must be forecast, and the physicochemical properties must be monitored before any breaches of its integrity, as well as actual technical state of critical design elements using non-destructive tests. Promising methods of assessment of properties of metals include, inter alia: ultrasound control of material state [1–3] exposed to plastic deformation. It is particularly important to study the effect of structural changes on acoustic parameters before the formation of macroscopic cracks. The main factor which significantly influences acoustic parameters is the change in the microheterogeneity upon deformation of materials. These deformations are related to changes in parameters of dislocation structure, density of vacancies, accumulation of micropores and microcracks, inter alia. All these processes influence the rate of ultrasound propagation. This parameter is widely used in the diagnostics of material state [4–7]. As previously shown [8–10], the change in velocity of ultrasound waves is non-monotonous. In [8] the interrelation between ultrasound velocity and mechanical properties was exemplified by high chromium steel. Regularities of changes in velocity of ultrasound propagation upon variation of composition, structure, and state of metals and alloys were detected and described in details in [11–13]. At the same time, the temperature dependences of ultrasound properties must be studied. This includes the range of lower temperatures, since the published data is insufficient [1–7].

This work determines the propagation velocity of ultrasound waves V , and the attenuation coefficient α , as a function of total deformation before destruction. It also examines ultimate strength in wide temperature range for austenite stainless steel, grade 12Kh18N10T.

EXPERIMENTAL

The experiments were carried out using crystallites of austenite stainless steel 12Kh18N10T with a grain size

of about $12.5\text{ }\mu\text{m}$. Flat samples with an operational surface area of $40 \times 5 \times 2\text{ mm}$ were exposed to uniaxial tension using an Instron-1185 testing machine at a constant deformation rate of $3.3 \cdot 10^{-4}\text{ s}^{-1}$. The temperature of tests in the range of $180\text{ K} \leq T \leq 320\text{ K}$ was preset by purging the working chamber containing deformed sample with nitrogen vapors from Dewar flask, and controlled by Cr/Al thermocouple. The junction was in contact with the sample [14]. The selected temperature range took into account the possibility of achieving forward $\gamma \rightarrow \alpha'$ martensitic transformation in steel [15–18].

As the loading curves on the testing rig were measured, the propagation velocity of the Rayleigh surface waves was also measured [19]. The pulses were excited by a piezoelectric converter at a frequency of 5 MHz. The measurement error did not exceed $\pm 3\text{ m/s}$. The experimental data was processed using the conventional method of statistic analysis. The applied testing rig allowed the information about standard material properties obtained in the course of mechanical tests to be significantly supplemented. These properties were: yield stress, ultimate strength, and coefficient of deformation strengthening. These properties are conditional, reflect weakly the nature of properties running in solids upon deformation and are unrelated to the existing dislocation mechanisms of strengthening [20].

RESULTS AND DISCUSSION

The tension diagrams in the conditional coordinates of stress (σ) – strain (ϵ) of steel 12Kh18N10T covered the regions of elastic, plastic deformation and destruction. Then the diagrams were replotted in the coordinates of true stresses (S) – true strains (e) [20] and in the function $S(e^{1/2})$ with the detection of the bending points on them (Fig. 1, *a*) located between the yield stress and the ultimate strength. These critical points indicate transition from elastic plastic to plastic destruction stage of deformation. This is interrelated with accumulation of microdamages in steel. The critical point D in the diagram corresponds to the stress S_D and the strain e_D (Fig. 1, *b*). They can be considered critical parameters for provision of maximum operability of metal in the considered temperature range.

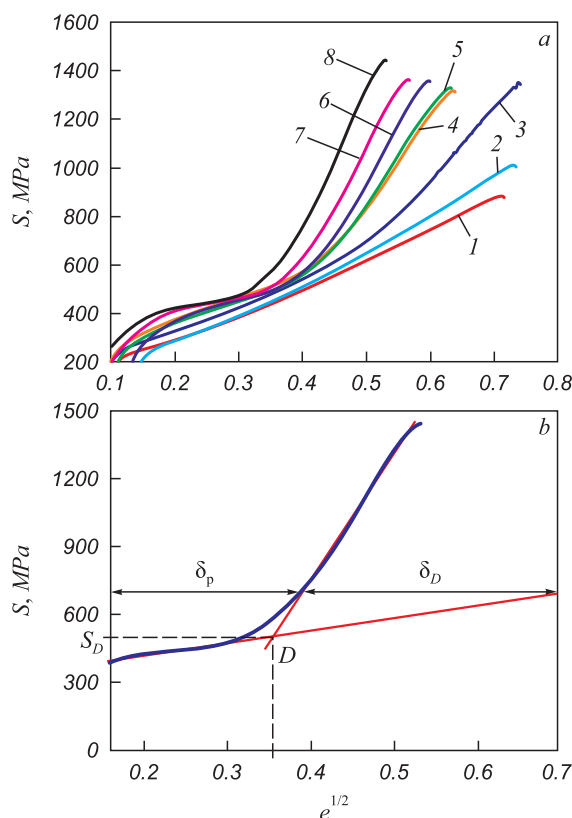


Fig. 1. Loading diagrams $S(e^{1/2})$ at temperatures 334, 318, 297, 270, 254, 227, 211 and 180 K (1 – 8) (a) and at a temperature of 211 K (b)

Рис. 1. Диаграммы нагружения $S(e^{1/2})$ при температурах 334, 318, 297, 270, 254, 227, 211 и 180 K (1 – 8) (a) и при температуре 211 K (b)

Fig. 2, *a* illustrates dependences of deformation strength properties corresponding to the point D : $S_D(e_D)$ (curve 1), $S_D(T)$ (curve 2) and $e_D(T)$ (curve 3). The temperature dependences of deformation strength properties

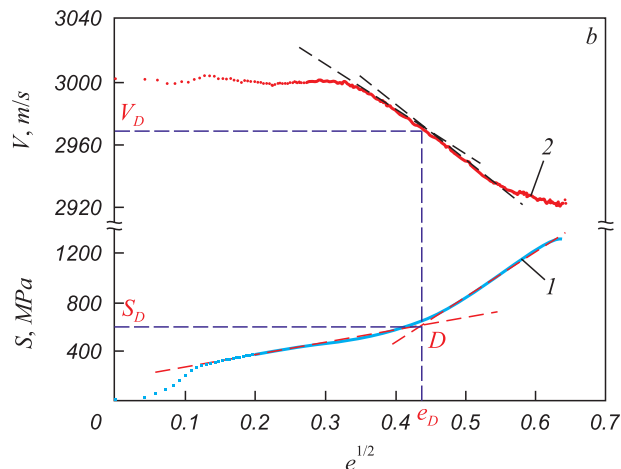
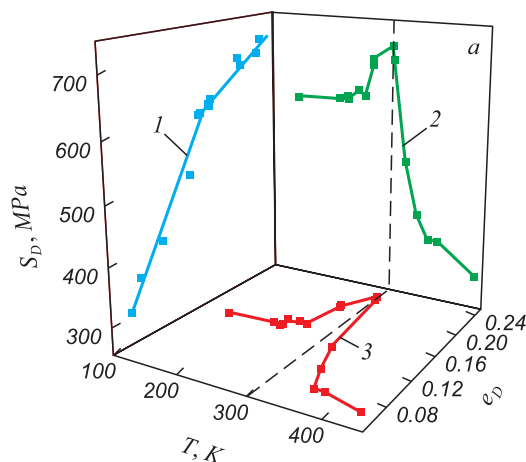


Fig. 2. Temperature dependences of deformation-strength characteristics corresponding to the critical point (a) and diagram $S(e^{1/2})$ (1) and the change in ultrasound velocity $V(e^{1/2})$ (2) with an increase in total deformation at a temperature of 318 K (b)

Рис. 2. Температурные зависимости деформационно-прочностных характеристик, соответствующих критической точке (a), а также диаграмма $S(e^{1/2})$ (1) и изменение скорости ультразвука $V(e^{1/2})$ (2) с ростом общей деформации при температуре 318 K (b)

demonstrate an extreme pattern. For all points D the critical parameter $\Delta = \delta_D / \delta_p$ can be calculated (where δ_p is the elastic plastic constituent in relative elongation before rupture. δ_D is the plastic destruction constituent in relative elongation before rupture) (Fig. 1, *b*).

Fig. 2, *b* combines the diagram $S(e^{1/2})$ (curve 1) and measured velocities of ultrasound propagation $V(e^{1/2})$ (curve 2), as a function of total deformation. Point D is also shown corresponding to the critical ultrasound velocity V_D . A decrease in the testing temperature during tension of steel samples leads to an increase in the density of defects and growth of martensitic phase. Thus, as a consequence, in leads to an increase in local stresses (stresses of the 2nd kind). All this is reflected by a decrease in the ultrasound velocity with an increase in total deformation and acting stresses. Achievement of the ultrasound velocity $V = V_D$ at the considered temperatures indicates transition from elastic plastic to plastic destruction stage of deformation.

The processing of changes in the velocity of ultrasound propagation at various temperatures for fixed values of total plastic deformation allowed linear pattern of $V(T)$ dependence with the correlation coefficient $R = 0.97$ to be established. With a decrease in the testing temperature in the considered range, the change in ultrasound velocity reaches 20 % in the non-deformed sample, and 15 % in the deformed sample (at total deformation of 0.3), in comparison with the ultrasound velocity in the non-deformed material at ambient temperature.

Fig. 3, *a* illustrates temperature sigmoidal dependences of the coefficient of ultrasound attenuation $\alpha(T)$ (curve 1), corresponding to the point D , and the critical parameter $\Delta(T)$ (curve 2). It was also established that in the deformable samples, the coefficient of ultrasound attenuation as a function of ultimate strength $\alpha(\sigma_u)$ is

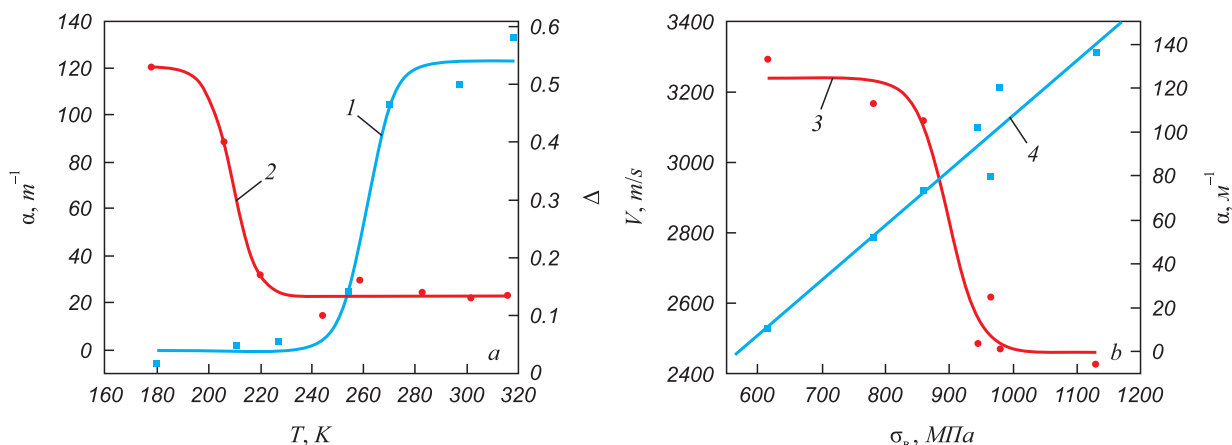


Fig. 3. Temperature dependences of the attenuation coefficient of ultrasound (I) and the critical parameter Δ (2) (a); dependences of the attenuation coefficient α (3) and ultrasound velocity V (4) on the strength limit σ_u (b)

Рис. 3. Температурные зависимости коэффициента затухания ультразвука (I) и критического параметра Δ (2) (a) и зависимости коэффициента затухания α (3) и скорости ультразвука V (4) от предела прочности σ_u (b)

of sigmoidal shape (Fig. 3, b). However, the ultrasound velocity as a function of ultimate strength $V(\sigma_u)$ is linear in the temperature range considered. Stresses corresponding to the maximum rate of increase in volumetric fraction of martensitic α' phase and decrease in the ultrasound velocity were determined.

Mechanical uniaxial tensile tests of steel samples demonstrated that a decrease in the testing temperature results in an increase in yield stress. The ultimate strength against the background of plasticity decreases. The linear pattern of the ultrasound velocity as a function of ultimate strength $V(\sigma_u)$ is probably stipulated by the functional interrelation of the ultimate strength σ_u with elastic properties of steel. Since the velocity of transversal ultrasound waves is $V = (G/\rho)^{1/2}$ (where G is the modulus of shift; ρ is the density), then the difference of the elasticity moduli of increasing martensitic phase upon $\gamma \rightarrow \alpha'$ martensitic transformation during plastic deformation [15] from the moduli of steel matrix leads to changes in elastic and acoustic properties of overall alloy.

Therefore, on the basis of velocities of ultrasound propagation and the attenuation coefficient, it is possible to forecast ultimate strength and maximum operability of a considered metal at low temperatures. It is thus assumed that fulfillment of the condition $e < e_D$ indicates that the current deformation corresponds to the elastic plastic constituent δ_p and $\Delta \rightarrow 0$. This is as a consequence of fabrication or operation of the item $\Delta \neq 0$, which is evidence that the material is already operating in the plastic destruction stage.

CONCLUSIONS

The study determined that tension of samples of austenite stainless steel, Grade 12Kh18N10T, in the temperature range of $180\text{ K} \leq T \leq 320\text{ K}$ leads to significant

changes in ultrasound velocity. The temperature dependences of ultrasound velocity, attenuation coefficient, yield stress and ultimate strength were established. The critical parameters of transition from elastic plastic to plastic destruction stage of deformation were determined. The correlations between the parameters provide evidence that it is possible to obtain regression dependences between them, and this can be used for recovery of one property on the basis of other determined experimentally. Among all such pairs of dependences, of most practical interest are the interrelations between the pairs of mechanical and acoustic parameters. Since measurements of the latter is less labor-consuming, they can be measured directly on analyzed element during operation without destruction, and the experiments do not require fabrication of samples.

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Contribution of the Authors

Вклад авторов

S. A. Barannikova – concept formulation, discussion of the results, writing the text.

M V. Nadezhkin – conducting studies of acoustic and mechanical characteristics, analysis of the results.

P. V. Iskhakova – literary review, preparation of the samples for studies of mechanical characteristics, discussion of the results.

С. А. Баранникова – формулирование концепции работы, обсуждение результатов, написание текста статьи.

М. В. Надежкин – проведение исследований акустических и механических характеристик, анализ результатов.

П. В. Исхакова – обзор литературы, подготовка образцов для исследований механических характеристик, обсуждение результатов.

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