The effect of cyclic deformation on the mechanical, elastic and acoustic characteristics of austenitic stainless steel

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Abstract. The effect of elastoplastic cyclic straining on the elastic and acoustic characteristics of austenitic stainless steel AISI 321 is investigated. A change of the elastic characteristics of austenitic stainless steel associated primarily with martensitic transformations that affect the accumulated energy density is found. The influence of the amplitude of strain cycle on development of the elastic anisotropy is analyzed. The possibility of determining the stress amplitude of the fatigue loading cycle by an acoustic method involving measuring the elastic characteristic of the material has been demonstrated. The relationship between changes of elastic characteristics and damage is suggested; it can be used for evaluation of fatigue life by the acoustic method.

1. Introduction
The deformation of austenitic metastable steels leads to complex structural changes, including the accumulation of microdamages and phase transformations. These processes affect the elastic and strength properties of steels.

The main phase transformations in austenitic steels consist in formation of two types of martensitic phases from the austenite phase $\gamma$: $\alpha'$-martensite having a body-centered cubic crystalline (bcc) lattice, and $\varepsilon$-martensite having a hexagonal close-packed lattice (hcp) [1-4]. Due to structural differences, $\alpha'$-martensite has a higher strength and thermodynamic stability in contrast to $\varepsilon$-martensite, and its formation is more preferable.

Experimental studies have shown a high correlation between the density of microcracks and the volume fraction of martensite crystals [5]. The amount of formed martensite can be a determining factor in the fatigue degradation of metastable austenitic steels [6].

At the same time, the formation during the loading of the rigid hardening phase of the deformation martensite, which elastic characteristics contrast with the elastic characteristics of the austenite matrix, leads to a change in the elastic properties of the entire alloy.

The aim of the work is to study the effect of cyclic deformation on the mechanical, elastic, and acoustic characteristics of AISI 321 austenitic steel.

2. The relationship between elastic moduli and acoustic characteristics
It is known that sheet materials generally relate to orthotropic materials and have nine independent constants, while only two constants are independent for an isotropic material [7].
The relationship of the elastic moduli with velocities of the longitudinal $V_{33}$ and shear $V_{31}$ and $V_{32}$ waves [8] propagating perpendicular to the sheet plane for an orthotropic material is written as:

$$V_{33} = \sqrt{\frac{c_{33}}{\rho}}, \quad V_{31} = \sqrt{\frac{c_{31}}{\rho}}, \quad V_{32} = \sqrt{\frac{c_{32}}{\rho}},$$  

(1)

where $c_{33}$, $c_{44}$, $c_{55}$ are the elastic moduli (matrix designation); $\rho$ is the density of the material. The first index in the velocity symbols corresponds to the direction of wave propagation; the second one corresponds to the direction of polarization. To describe the anisotropy of the elastic properties of polycrystalline materials, consisting of crystals with a cubic lattice, it was proposed to use the following combination of velocities representing the birefringence effect of shear elastic waves [9]:

$$A = V_{31}^2 - V_{32}^2 = \frac{1}{\tau_{33}} - \frac{1}{\tau_{32}},$$  

(2)

where $\tau_{33}$ is the propagation time of longitudinal waves, and $\tau_{31}$, $\tau_{32}$ is the propagation time of shear waves polarized along and across the loading axis respectively. Parameter $A$ is proportional to the difference in the elastic moduli $A \sim (c_{55} - c_{44})$ and is mainly determined by the crystallographic texture of the polycrystalline material [8, 9].

The ratio of the moduli $c_{33}/c_{44}$ and $c_{33}/c_{55}$ can be written as:

$$\frac{c_{33}}{c_{44}} = \frac{(\nu_{32} - 1)}{\nu_{32} - 0.5} = \frac{\tau_{32}^2}{\tau_{33}^2}, \quad c_{33} = \frac{(\nu_{31} - 1)}{\nu_{31} - 0.5} \frac{\tau_{31}^2}{\tau_{33}^2},$$  

(3)

where the coefficients $\nu_{31}$, $\nu_{32}$ are expressed similarly to (1) in terms of velocity ratios:

$$V_{31} = \frac{(V_{33}/V_{31})^2 - 2}{2[(V_{33}/V_{31})^2 - 1]}; \quad V_{32} = \frac{(V_{33}/V_{32})^2 - 2}{2[(V_{33}/V_{32})^2 - 1]}$$  

(4)

For an isotropic material $V_{31}=V_{32}=V$, $c_{44}=c_{55}=\mu$, where $\nu$ and $\mu$ are both the Poisson's ratio and the shear modulus respectively. The values of $V_{31}$ and $V_{32}$ for quasi-isotropic materials, which include steel products, may differ by several percent.

Modern methods of signal processing make it possible to perform precise measurements of wave times [10]. For this reason, the parameters determined using the ratios of propagation time for longitudinal and shear waves with different polarizations are characterized by a much smaller relative error compared to those determined from elastic wave velocities, which require measuring the length of the acoustic path for their calculations.

3. Experimental procedure

Samples of circular cross-section with the working area diameter of 12 mm were made of AISI 321 steel for fatigue tests. Two parallel sites were made for each sample on both sides of the working area for ultrasonic measurements (figure 1).
The samples were subjected to regular loading in the low-cycle fatigue region with a strain cycle amplitude $\varepsilon_a$ (0.33%, 0.56%, and 0.77%). Loading type was tension-compression, cycle asymmetry coefficient $R$ was equal to -1, loading mode was hard, and frequency was equal to 3 Hz. The numbers of loading cycles before the formation of macrocrack $N^*$ were approximately 15000, 1900 and 500 for samples with $\varepsilon_a$ equal $0.33\%$, $0.56\%$ and $0.77\%$ respectively. The loading of each sample was carried out in stages. Plane-parallel sites were divided into zones in which ultrasonic measurements were performed prior to testing and after each loading stage.

An echo-pulse method was used to measure the propagation time of longitudinal and shear elastic waves. The central frequency of piezoelectric transducers was about 5 MHz. The diameter of the transducers was 6 mm. The measurement errors were 2-3 ns for the elastic wave propagation time, $7 \times 10^{-4}$ for $v_{32}$ and $v_{31}$ and $5 \times 10^{-4}$ for parameter $A$. The tests were carried out at room temperature. More detailed description of ultrasonic measurements is given in [11].

4. Results and discussion

Velocities of the longitudinal and shear waves and their changes $\Delta V = V^N - V^0$ were calculation from results of ultrasonic studies. The change in the velocities of the shear $\Delta V_{31}$, $\Delta V_{32}$ and longitudinal $\Delta V_{33}$ waves during the cyclic loading are shown in figure 2 and figure 3.

![Figure 1](image)

**Figure 1.** Acoustic measurement scheme: X (1), Y (2), Z (3) - axis of the sample symmetry, 1 - piezoelectric transducer, 2 - sample.

![Figure 2](image)

**Figure 2.** Dependence of the shear wave velocities change $\Delta V_{31}$ (a) and $\Delta V_{32}$ (b) on the number of loading cycles $N$.
Figure 3. Dependences of the longitudinal wave velocities change $\Delta V_{33}$ on the number of loading cycles $N$.

The curves $\Delta V(N)$ are well separated at different levels of strain cycle amplitude $\varepsilon_a$.

As a result of ultrasonic studies, parameter $A$ and modulus ratios $c_{33}/c_{44}$, $c_{33}/c_{55}$ were determined before the tests and after each loading stage. The change in the anisotropy $A$ of the elastic properties depending on the relative number of loading cycles $N/N^*$ (where $N$ is the current number of cycles, $N^*$ is the number of cycles before failure) is shown in figure 4.

Figure 4. Dependence of the parameter change $\Delta A$ on the relative number of loading cycles.

As can be seen from figure 4, the parameter $A$ behaviour depends on the strain cycle amplitude $\varepsilon_a$. It can be assumed that the change in parameter $A$ is determined by two processes: a change in the crystallographic texture of the initial austenite phase and a martensite phase precipitation of a certain crystallographic orientation. The difference between the values of parameter $A$ at the fracture point for amplitudes 0.33 and 0.77 reaches $\approx 0.032$.

The effect of the relative number of loading cycles on the modulus ratio $c_{33}/c_{44}$ and $c_{33}/c_{55}$ is shown in figure 5.
Figure 5. Dependence of the module ratios \( c_{33}/c_{44} \) (a) and \( c_{33}/c_{55} \) (b) on the relative number of loading cycles.

The relation between \( \Delta(c_{33}/c_{44}) \) and \( \Delta(c_{33}/c_{55}) \) is well approximated by a linear dependence (see figure 6). The slope of these dependences is determined by the strain cycle amplitude \( \varepsilon_a \). At the maximum strain cycle amplitude (\( \varepsilon_a = 0.77\% \)) a minimal change in the ratio \( c_{33}/c_{44} \) is observed.

As a result of data analysis, it was found that the length \( L \) of the curves shown in figure 6 at the time of the macrocrack (1 mm) formation remains approximately constant for different amplitudes of cyclic deformation, \( L' \approx 0.2 \). A condition for the crack formation is to achieve the ratio \( D = L/L' = 1 \).

The relationship of the relative number of loading cycles with the \( D \) value for all strain cycle amplitudes \( \varepsilon_a \) can be approximated by an exponential dependence (see formula (5) and figure 7):

\[
\frac{N}{N^*} = 0.0025 \times e^{5.1D}
\]  
(5)
This expression allows to evaluate the relative number of loading cycles under a cyclic regular loading regime in the low-cycle fatigue region at the deformation amplitude of AISI 321 metastable austenitic steel by determining of the elastic characteristic change using the acoustic method. The error in calculating relative number of cycles is about 20%.

Phase changes lead to both hardening and the elastic characteristic change of the material.

It was found that the dependence of the stress cycle amplitude $\sigma_A$ on the Poisson’s ratio change, which is defined as $\Delta\nu=(\Delta\nu_{11}+\Delta\nu_{12})/2$, was close to linear one (see figure 8a).

As a result of the hysteresis loop processing, it was found that the dependence of the energy density $W = \int_{-\epsilon_a}^{\epsilon_a} \sigma_y d\epsilon_y$, spent on deformation in the cycle, on the average value of the Poisson’s ratio change has a linear form (see figure 8b).
The straight lines are separated in accordance with the cycle deformation amplitude $\varepsilon_a$. Linear dependencies can be represented as follows:

$$ W = k_w \times \Delta \nu + b_w $$

where $k_w = 900 \cdot \varepsilon_a - 407$ [MJ·m$^{-3}$], $b_w = 10.4 \cdot \varepsilon_a - 1.77$ [MJ·m$^{-3}$].

The correlation coefficient is not less than 0.95.

Thus, we can estimate the change in $W$ without registering the hysteresis loop using only acoustic measurements to calculate the parameter $\Delta \nu$ and setting the strain amplitude.

5. Conclusion

The cyclic deformation of austenitic steel AISI 321 leads to complex structural changes that affect the elastic and mechanical characteristics of the alloy. Studies have shown that the ratio of elastic moduli measured by the acoustic method allows obtaining an estimated value of the relative number of loading cycles of the material during cyclic loading.

It was found that the relationship between the stress cycle amplitude, the energy density spent on deformation in the cycle and the Poisson's ratio is linear. Monitoring of acoustic characteristics makes it possible to determine the degree of hardening of the material during cyclic loading by a non-destructive testing method.

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