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The effect of phase transformations induced by cyclic loading on the elastic properties and plastic hysteresis of austenitic stainless steel

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ABSTRACT

The effect of low-cycle fatigue on the elastic and acoustic characteristics of austenitic stainless steel AISI 321 is investigated. The relation between characteristics of the hysteresis loop and changes of the acoustic parameters is established. A change of the elastic characteristics of austenitic stainless steel associated primarily with martensitic transformations that affect cyclic hardening, the width of the hysteresis loop, energy loss in the cycle, and the accumulated energy density is found. The influence of the amplitude of strain cycle on development of the elastic anisotropy is analyzed. 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

Martensite formation resulting from fatigue deformation of metastable austenite is of great interest. It may cause significant changes in physical properties of the material, such as the extent of strain hardening and nucleation of microdefects. Sosnin [1] reported a strong correlation between the density of microcracks and volume fraction of martensite crystals. The volume fraction of martensite can be a key factor affecting fatigue degradation of metastable austenitic steels [2].

Deformation of the metastable austenite phase leads to the transformation from initial austenite (γ) and FCC into martensite (ε), paramagnetic HCP or ferromagnetic martensite (α′) BCT [3–7]. Therefore, applied stress or plastic deformation may induce a diffusionless martensitic phase transformation, by which the metastable austenite phase is transformed to the thermodynamically more stable martensite phase [8].

The kinetic transformation from austenite to ά-martensite is believed to be of the $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ or $\gamma \rightarrow \alpha'$ type. The amount of α′ -martensite depends on the deformation methods, amount of plastic strain, strain rate, and temperature [4,5]. An important feature of martensite is its high resistance to plastic deformation [3].

Thus, strain-induced martensitic transformations significantly affect the magnetic and the elastic properties. Changes in the effective elastic properties due to transformations lead to changes in the acoustic characteristics of a specimen.

For the isotropic elastic material the relation between Young's modulus *E,* shear modulus μ, Poisson's ratio ν and the elastic wave velocities is given by:

$$E = \frac{\rho V_\tau^2(4V_\tau^2-3V_l^2)}{V_\tau^2-V_l^2}, \mu = \rho V_\tau^2 \tag{1}$$

$$\nu = \frac{V_l^2-2V_\tau^2}{2(V_l^2-V_\tau^2)} \tag{2}$$

where V_τ and V_l are shear and longitudinal ultrasonic waves propagation velocities, respectively, and ρ is the material density.

The change in the texture of the austenite phase occurs during the cyclic deformation simultaneously with the martensitic transformation. The formation a new phase having its crystallographic texture also affects the anisotropy of the elastic properties. This affects the anisotropy of the entire material, including acoustic anisotropy. The presence of anisotropy of elastic properties leads to a difference in the velocities of shear waves polarized along and across the anisotropy axes (birefringence effect).

The acoustic anisotropy parameter *A* is often used to describe the anisotropy of elastic properties of polycrystalline materials that consist of crystals with a cubic lattice. Parameter *A* is proportional to the difference in the elastic modulus, $A \sim (c55 - c44)$, and is mainly determined by the crystallographic texture of the polycrystalline material [9,10]. For an isotropic material, we have $c_{44} = c_{55} = \mu$.

The aim of this work is to study the influence of the martensite transformation on the elastic and acoustic properties of metastable austenitic stainless steel AISI 321 under cyclic loading.

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Table 1
Chemical composition of the AISI 321 stainless steel (wt%).

C	Cr	Ni	Mn	Si	Cu	S	P	Fe
0.07	18	10	1.7	0.75	0.24	0.015	0.03	Balance

2. Experimental procedure

The material investigated was metastable austenitic stainless steel AISI 321 in as-received condition. The chemical composition is given in Table 1. The as-received microstructure is shown in Fig. 1a; the average grain size is ~32 mkm. Fig. 1b shows microstructure after tests. This sample was first mechanically polished and then electroetched using an etchant consisting of 10 pct oxalic acid and 90 pct water, at 1 V and room temperature, to reveal the grain boundaries.

In fatigue tests, we used samples with circular cross sections (diameter of the working zone was 12 mm) prepared. On each sample, plane parallel platforms 3 × 50 mm were cut on both sides of the working zone for ultrasonic measurements (Fig. 2).

The samples were subjected to regular loading in the low cycle fatigue with a strain cycle amplitude ε_a (0.33%, 0.56%, and 0.77%). The fatigue tests were conducted under the symmetric tension-compression condition (R = −1) at a loading frequency f = 3 Hz. Uniaxial cyclic loading by force P is directed along the X(1) axis (Fig. 1).

The average number N^* of loading cycles prior to the formation of a macrocrack was approximately 15,000 for samples with ε_a = 0.33%, 1900 for samples with ε_a = 0.56%, and 500 for samples with ε_a = 0.77%). Each sample was loaded in stages. Plane-parallel platforms were marked into zones in which ultrasonic measurements were taken before testing and after each loading stage.

To measure the time of propagation of longitudinal and shear elastic waves, we used the echo-pulse method. We use broadband acoustic transducers V156-RM (shear wave) and V110-RM (longitudinal wave) by production Olympus. The central frequency of the piezoelectric transducers (PZT) was ~5 MHz, their diameter was 6 mm. A commercially available ultrasonic flaw detector (model A1212 MASTER), digital oscilloscope (model LA-n10USB) and PC were used for ultrasonic measurements. Working frequencies of A1212 MASTER is from 0.5 to 15.0 MHz. Maximum sampling frequency of LA-n10USB is 100 MHz.

Longitudinal and shear waves propagate along the Z(3) axis (Fig. 1); and the polarization of shear waves can be directed along the loading axis X(1) or across it (along the Y(2) axis). We use the long-wavelength approximation. The velocity of ultrasonic waves varies for several main reasons. It changes due to the accumulation of microdamages in the form of micropores, microcracks, changes in the dislocation structure, changes in the crystallographic texture, and formation of the martensite phase during cyclic loading, etc.

The amplitude-time diagram of echo pulses series for shear wave was recorded in each zone (Fig. 3). The elastic wave propagation time $t = 0.5(t_3 - t_1)$ was measured between the first t_1 and the third t_3 echo pulses. Values of elastic waves were obtained from the ratio of h to the times of propagation of the elastic waves:

$$V = \frac{2h}{t} \tag{3}$$

where h - thickness of the sample was measured by a micrometer.

To describe anisotropy in the elastic properties of polycrystalline materials that consist of crystals with a cubic lattice, the following combination of times or velocities was proposed in [13]:

$$A = \frac{t_{32}^2 - t_{31}^2}{\sum_{i=1}^{3} t_{3i}^2} = \frac{V_{31}^2 - V_{32}^2}{\sum_{i=1}^{3} V_{3i}^2} \tag{4}$$

where t_{33}, V_{33} are longitudinal time and wave propagation velocity respectively, and t_{31}, V_{31}, t_{32}, V_{32} are shear times and waves propagation velocities polarized along and across the loading axis, respectively.

Parameters for the orthotropic material ν_{31} and ν_{32} are expressed analogously to Eq. (2) in terms of the ratios of velocities as follows:

$$\nu_{31} = \frac{(t_{31}/t_{33})^2 - 2}{2[(t_{31}/t_{33})^2 - 1]} = \frac{(V_{33}/V_{31})^2 - 2}{2[(V_{33}/V_{31})^2 - 1]}; \nu_{32} = \frac{(t_{31}/t_{33})^2 - 2}{2[(t_{31}/t_{33})^2 - 1]} = \frac{(V_{33}/V_{32})^2 - 2}{2[(V_{33}/V_{32})^2 - 1]} \tag{5}$$

For an isotropic material, we have $\nu_{31} = \nu_{32} = \nu$. The values of ν_{31} and ν_{32} for quasi-isotropic materials, including steel rolling articles, may differ by a few percent.

Modern methods of signal processing make it possible to perform precise measurements of wave times [11]. For this reason, the parameters determined using the ratios of times of propagation 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.

The error in the measurement of the elastic wave propagation time was 2–3 ns, the error in the measurement of ν_{32} and ν_{31} was 7×10^{-4}, and parameter A was 5×10^{-4}. Testing was performed at room temperature.

3. Results

In cyclic loading, stress-strain hysteresis loops that reflect plastic deformation were recorded for each deformation cycle. Redistribution was observed between the elastic ε_{el} and plastic ε_{pl} components of strain, $\varepsilon_a = \varepsilon_{el} + \varepsilon_{pl}$. Hardening of the material has occurred, the strain cycle amplitude decreased, and the stress cycle amplitude increased (Fig. 4).

For ε_a = 0.56% and for ε_a = 0.77% the stress cycle amplitude σ_A

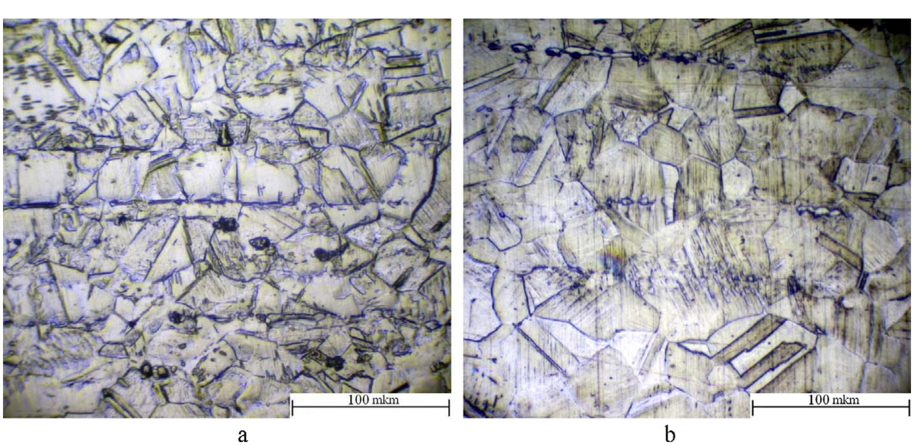

Fig. 1. Optical micrograph of the metastable austenitic stainless steel AISI 321.