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On assessing damage in austenitic steel based on combination of the acoustic and eddy current monitoring

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ABSTRACT

We suggest a methodology of assessing cyclic loading–induced damage in austenitic steel by combining the ultrasonic and magnetic monitoring. Cyclic loading increases the martensitic phase volume, thus enhancing the plastic deformation–and resulting damage–in the austenitic phase having lower strength and stiffness. The damage in the austenitic phase can be detected through wavespeeds changes. The latter, however, are small thus requiring high accuracy of wavespeeds measurements. These requirements are satisfied by focusing on *ratios* of the longitudinal and shear wavespeeds (that do not depend on imprecisely known parameters such as sheet thickness). In order to separate changes due to damage from the ones due to growth of the martensitic phase, we combine the acoustics- and magnetic data. Preliminary results on comparison with available experimental data are encouraging.

1. Introduction

The present work reports preliminary results on the methodology of monitoring fatigue of austenitic steel under cyclic loading by combining the ultrasonic and magnetic (eddy current) monitoring. Damage accumulation (microporosity, microcracking) that precedes nucleation of macrocracks (of sizes of the order of 1 mm), typically takes over 90% of lifetime; this stage of fatigue is considered here.

Cyclic loading of austenitic steel produces two main effects: (1) growth of the martensitic α'-phase and (2) development of damage in the austenitic γ - phase and along the interphase boundaries, in the form of microcracks having typical sizes of 5–20μm (reported in several works, see, for example, (Hedstrom et al., 2009; Krupp, West, & Christ, 2008; Nebel & Eifler, 2003; Singh, 1985)). Note that damage growth is enhanced by growth of the α'-phase: it has higher stiffness and yield stress and hence shifts the plastic deformation and resulting damage into the "softer" γ - phase. The present work focuses on monitoring damage growth in the γ - phase.

The growth of damage affects the elastic properties and hence acoustic wavespeeds that can be used for damage monitoring. The said changes are small, and they are difficult to detect, for the following reasons:

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Table 1
Chemical composition of 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

Table 2
Critical values of $\Delta\xi^*$ obtained in experiments with three different stress amplitudes.

σ, MPa	$\Delta\xi^*$
425	0.024
342	0.018
259	0.019

(A) The required high accuracy of the wavespeed data is difficult to achieve (in the case of metal sheets, for example, wavespeeds are estimated as ratios of the thickness of sheets to the time of wave propagation; however, the data on thickness typically have insufficient accuracy, due to factors such as surface roughness);
(B) Growth of the martensitic phase (having elastic properties different from the ones of the austenitic phase) affects the wavespeeds as well. The (A)- and (B)–factors need to be separated.

We suggest a methodology to overcome the mentioned difficulties, by (A) monitoring the *ratio* of the longitudinal wavespeed to the shear one; it is independent of the factors such as sheet thickness and can be estimated with accuracy of at least $5\bullet 10^{-4}$ (Mishakin, Klyushnikov, & Gonchar, 2015) and (B) estimating volume of the martensitic phase by the eddy current method. We note that microscale processes leading to nucleation of damage, at its earliest stage, are not discussed here.

2. The proposed approach

We focus on the ratio of the longitudinal (normal to the surface) $V_l \equiv V_{33}$ and shear wavespeeds. The material may be weakly elastically-anisotropic (in the case of metal sheets, due to rolling), so that there is some difference between two shear wavespeeds (two polarizations) V_{13}, V_{23}. As mentioned above, the two wavespeed *ratios* can be estimated with high accuracy:

$$\xi_1 = \frac{V_{33}}{V_{13}}\left(=\frac{t_{13}}{t_{33}}\right), \quad \xi_2 = \frac{V_{33}}{V_{23}}\left(=\frac{t_{23}}{t_{33}}\right) \tag{1}$$

(t's are propagation times). The changes $\Delta\xi_1, \Delta\xi_2$ can be used as ultrasonic indicators of the microstructural evolution (that incorporates both development of damage and growth of the α'-phase). As discussed in Section 4, the difference between ξ_1 and ξ_2–and hence the elastic anisotropy–is relatively small and cannot be reliably accounted for (particularly in view of data scatter). Therefore, we set $V_{13} \approx V_{23} \equiv V_\tau$ and operate with the averages:

$$\frac{V_l}{V_\tau} \approx \frac{\xi_1 + \xi_2}{2} \equiv \xi \tag{2}$$

Note that the ratios ξ_1, ξ_2 can be given in terms of the overall elastic constants (in the isotropic case, $\xi_1 = \xi_2 \equiv \xi$ can be expressed in terms of the effective Poisson's ratio: $\xi^2 = 2(1-\nu)/(1-2\nu)$; in cases of anisotropy, $\xi_1 = \sqrt{c_{55}/c_{33}}$, $\xi_2 = \sqrt{c_{44}/c_{33}}$). However, such functional dependencies are not needed for the present analysis since monitoring can be done directly in terms of ξ.

The part of the change of ξ that is due to damage (denoted by superscript ϕ) can be obtained by subtraction from the overall (measured) change $\Delta\xi$ the change $\Delta\xi^M$ that is due to growth of the martensitic phase: $\Delta\xi^\phi = \Delta\xi - \Delta\xi^M$. We express the change $\Delta\xi^M$ in terms of change of the volume fraction of the martensitic phase $\Delta\vartheta^M$. Since the current value of ξ can be represented in the form

$$\xi = \xi_0 + \Delta\xi\left(\phi, \Delta\vartheta^M\right) \tag{3}$$

(the subscript "0″ refers to the state prior to loading) and the overall change $\Delta\xi$ is small: $\Delta\xi < < \xi_0$ (see Fig. 2 of Section 4) we expand $\Delta\xi(\phi, \Delta\vartheta^M)$ into Taylor series up to linear terms:

$$\Delta\xi\left(\phi, \vartheta^M\right) \approx \frac{\partial\xi}{\partial\phi}\phi + \frac{\partial\xi}{\partial\vartheta^M}\Delta\vartheta^M = \Delta\xi^\phi + k\Delta\vartheta^M \tag{4}$$

(all derivatives are evaluated at the state prior to loading). Here, ϕ represents some volume average measure of damage (such as microcrack density).

Remark. The usual definition of microcrack density assumes that cracks are penny-shaped whereas their actual geometries are quite different; therefore, ϕ should be viewed as certain measure of crack density that may not be explicitly related to crack geometries. In our analysis, however, the exact microstructural interpretation of ϕ will not be needed.

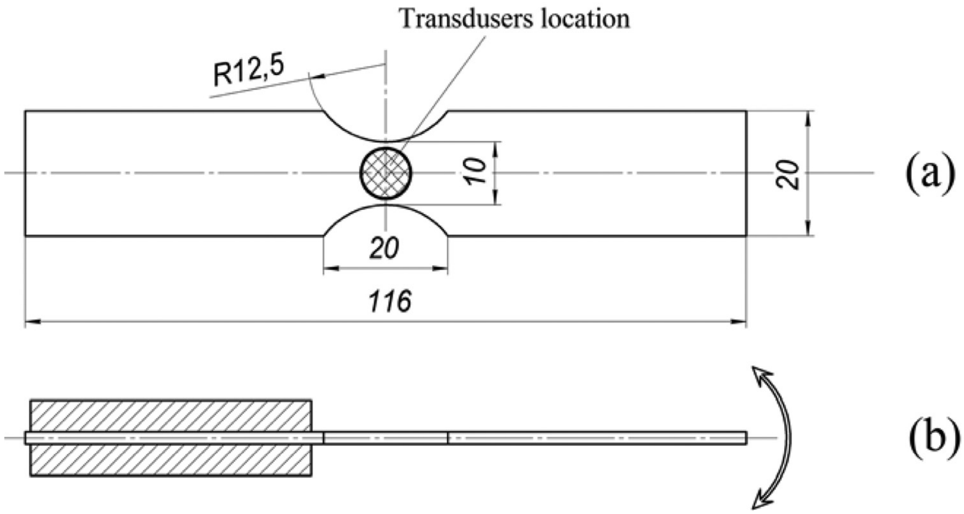

Fig. 1. Cyclic bending test.

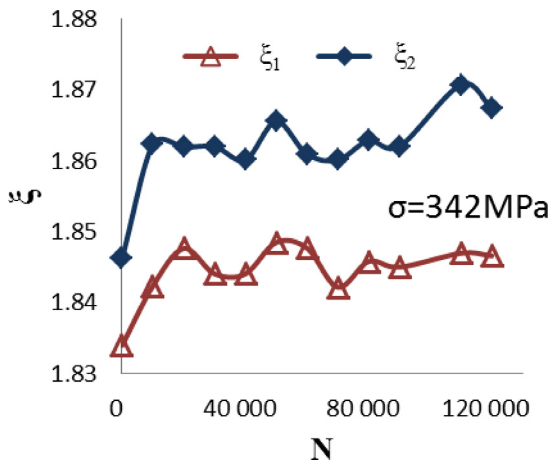

Fig. 2. Changes in ξ_1, ξ_2 under cyclic loading of stress amplitude 342 MPa (stress-controlled experiments).

Coefficient $k = \partial\xi/\partial\vartheta^M$ in the term $k\Delta\vartheta^M$ characterizes the sensitivity of $\Delta\xi$ to volume fraction of the martensitic phase. It could, in principle, be calculated, had shapes and elastic properties of the martensitic particles been known. However, this knowledge is presently not available. Alternatively, k can be determined from experimental data on the *initial stage* of cyclic loading (low number of cycles) since there is noticeable delay in damage development in the γ-phase whereas growth of the martensitic phase starts almost immediately with the onset of microplasticity.

We formulate the following criterion of material failure (more precisely, of the point where macrocracks form): The change of ξ due to damage in the austenitic phase reaches certain critical value:

$$\Delta\xi^{\phi} = \Delta\xi^{*} \tag{5}$$

Note that fatigue data, in general, exhibit substantial variability. Therefore, the critical value $\Delta\xi^*$ should be as approximate one; practically speaking, one can expect certain interval of values of $\Delta\xi^*$ (see Section 4).

Remark. Since ϕ is a volume average quantity, such criterion may not, generally, be adequate for brittle solids (for example, it is not sensitive to formation of defect clusters that may play a crucial role in fracture processes, see Kachanov, 1994 for discussion in detail). However, it is adequate for damage that has "diffused" character, as in the considered case.

We now present preliminary results on the comparison of the proposed criterion of failure (5) with available experimental data.

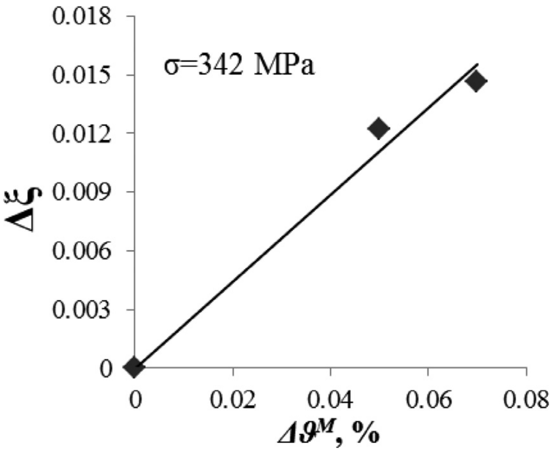

Fig. 3. Relation between the $\Delta\xi$ and $\Delta\vartheta^M$ at early stages cycling loading (stress amplitude $\sigma = 342$ *MPa*). The straight line represents estimation of coefficient *k*.

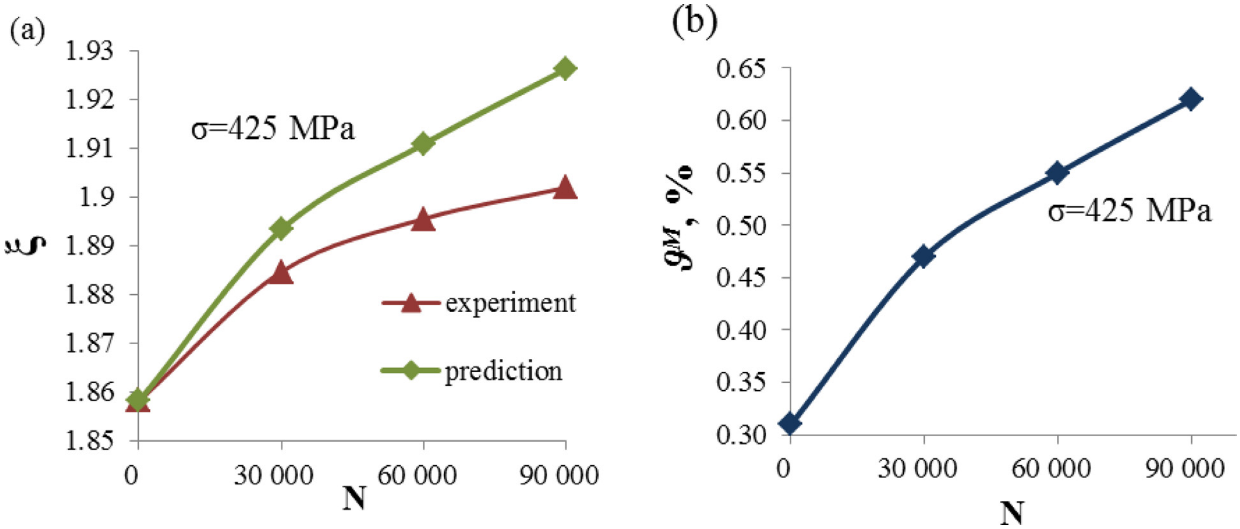

Fig. 4. (a) The observed change of parameter ξ (upper curve) and the change that would occur due solely to growth of the martensitic phase (neglecting damage); (b) Growth of relative volume of the martensitic phase. Stress amplitude $\sigma = 425$ *MPa*.

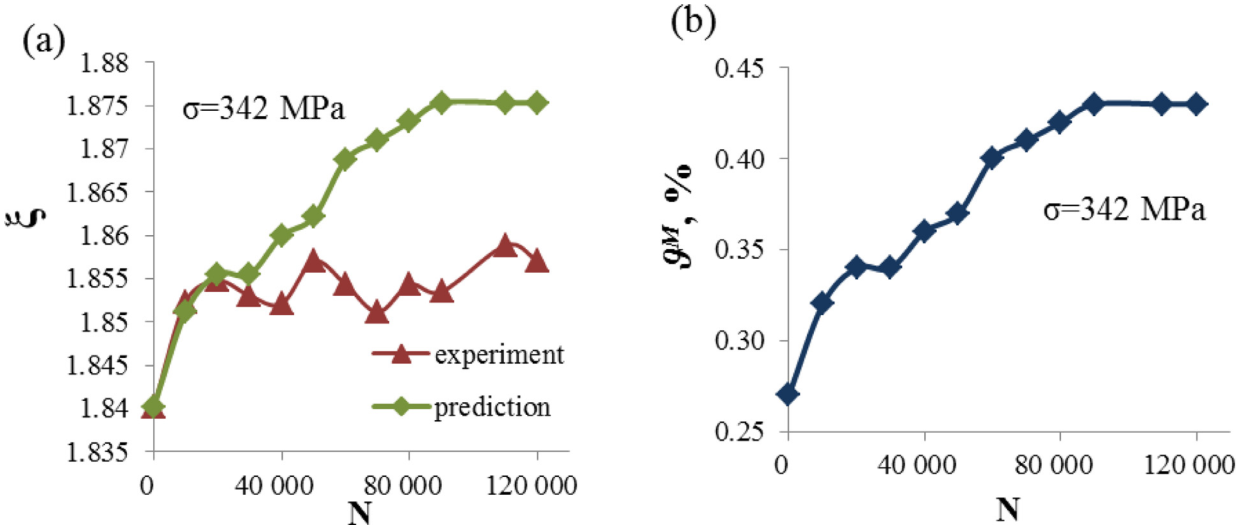

Fig. 5. Same as Fig. 4. Stress amplitude $\sigma = 342$ *MPa*.

3. Experiments

Experiments were done at room temperature, on specimens of industrially manufactured austenitic stainless steel AISI 321 in as-received condition. The chemical composition of the steel is given in Table 1.

Stress-controlled cyclic bending was conducted on cantilevered specimens shown in Fig. 1a, bending (Fig. 1b) at loading frequency of 10 Hz (stress ratio was $R = -1$). Three specimens were tested, with stress amplitudes of 290, 342 и 450 MPa respectively.

The specimens were subsequently used for magnetic and ultrasonic measurements.

In the ultrasonic measurements, in order to measure propagation times of the longitudinal and shear elastic waves, the echo-pulse method was used, using broadband piezoelectric transducers V156-RM (shear wave) and V110-RM (longitudinal wave) made by Olympus. The central frequency of the piezoelectric transducers was 5 MHz, their diameter was 6 mm. The width of the ultrasonic signals was 0.6 ms. The direction of wave propagation was normal to the specimen surface. The error in measuring wave propagation times did not exceed 2–3 ns and errors in measuring the ratio ξ were below 10^{-3}. High accuracy of time measurements was made possible by stability of transducer-specimen contacts and high accuracy of their positioning. The accuracy was further enhanced by taking at least ten measurements at each loading stage (more detailed description of the technique was given in (Gonchar, Mishakin, Klyushnikov, & Kurashkin, 2017)).

In the magnetic measurements, the multifunctional eddy current instrument IMP-2 M made by SPC Ltd "Kropus-IN" was used to determine volume fraction of the magnetic phase. The instrument has been calibrated on specimens with known ferritic content ensuring the accuracy of $\pm 0.05 \bullet (1 + \text{ferritometers reading } (\%))$. When several measurements are taken and results are averaged the statistical error is within 0.01%.

4. Results and discussion

In the text to follow, we show experimental results and discuss their implications.

- Typical changes of ξ_1, ξ_2 under cyclic loading (stress amplitude of 342 MPa) are shown in Fig. 2. It is seen that the difference between ξ_1 and ξ_2 is relatively small thus justifying the replacement of ξ_1, ξ_2 by their average value (2).
- The coefficient k characterizing the effect of the martensitic phase on the wavespeed ratio ξ in formula (4) is determined from the slope of the $\xi - N$ data at low number of cycles (when growth of the phase has started but damage has not developed, yet). As implied by Fig. 3, this coefficient $k \approx 0.22$.
- Having determined the coefficient k, we compare the observed changes of ξ with the ones that would occur in absence of damage, Figs. 4–6. It is seen that the two effects, of the martensitic phase and of damage, have opposite signs: the martensitic phase increases ξ whereas damage reduces it. This effect of damage can be explained as follows. Assuming that the material is approximately isotropic, the relation between ξ and the effective Poisson's ratio $\xi^2 = 2(1-\nu)/(1-2\nu)$ shows that ξ decreases if ν decreases. The decrease of the effective value of ν with increasing damage is predicted by formulas of micromechanics for defect geometries representing opposite extremes–cracks and spherical pores.

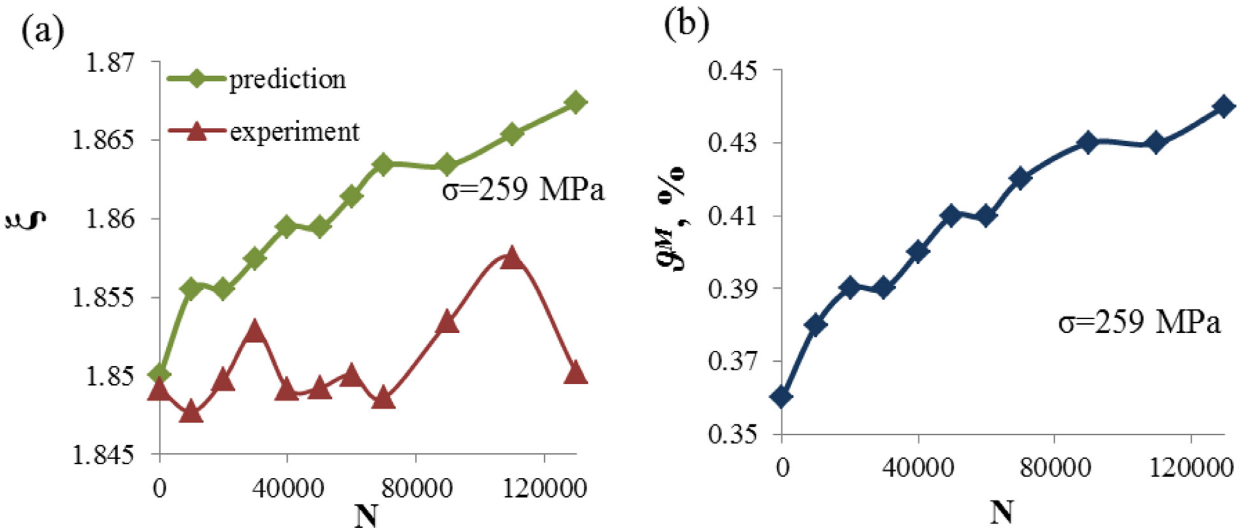

Fig. 6. Same as Fig. 4. Stress amplitude $\sigma = 259\ MPa$.

- The data exhibit substantial fluctuation. This can be attributed to the general fluctuation of fatigue data observed in a variety of materials. More specifically, it can be related to the fact that growth of the α'-phase and of damage (that produce opposite effects on ξ)–proceed at different rates at different stages of lifetime.
- The values of $\Delta\xi^{\phi}$ at failure at three stress amplitudes are summarized in Table 2. They can be judged to be relatively close, with the account of the usual variability of fatigue data. These data, albeit limited and hence viewed as preliminary, appear to support the criterion (5), i.e. approximate constancy of $\Delta\xi^{\phi}$ at the failure point.

5. Conclusions

Monitoring of damage growth, as well as estimation of lifetime of construction elements made of austenitic steel under cyclic loading, is developed. Cyclic loading causes growth of the martensitic phase and development of damage (diffused microcracking) in the austenitic phase; These two factors produce opposite effects on the overall Poisson's ratio ν–and hence on the ratio ξ of the longitudinal and shear wavespeeds. The methodology of separation of the two effects is developed, based on a combination of the acoustic and eddy current measurements. We suggest the criterion of failure as corresponding to the critical level of damage, as assessed from the critical level of the part $\Delta\xi^{\phi}$ of the overall change $\Delta\xi$ that corresponds to damage growth.

The proposed methodology is compared with experimental data and the agreement is found to be reasonable. The experimental data is rather limited, though, so that conclusions made in the present short paper should be viewed as preliminary ones.

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