Measurement of the strain induced $\alpha'$-martensite content by eddy current method in the presence of elastic stresses of austenitic stainless steels

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Abstract. The effect of elastic and plastic deformation on the added voltage of eddy current probe under step loading of austenitic steel AISI 321 is investigated. The effect of mechanical stress on the added voltage significantly depends on the amount of residual plastic deformation is shown. This is due to an increase in the volume fraction of the strain induced $\alpha'$-martensite content. The added voltage decreases at loading in the elastic region. At loading beyond the yield point, the added voltage of eddy current probe increases sharply. Under measuring the strain induced $\alpha'$-martensite content by eddy current method it is necessary to take into account the influence of mechanical stresses is shown. An algorithm is proposed to reduce the measurement error of the magnetic phase fraction by taking into account the stress-strain state of the material.

1. Introduction
The eddy current method has powerful ability to characterize physical properties of metal alloys and composites [1-8]. This method is based on the interaction of the external electromagnetic field with the electromagnetic field of the eddy currents induced by the exciting coil in the investigated object. One of informative parameters of eddy current nondestructive testing is added voltage of the eddy current probe. In general, the added voltage of the eddy current probe depends on electrical conductivity, magnetic permeability, frequency of excitation current, continuity, size and shape of an investigated object and other parameters in a complex way. However, it may be that the frequency of the excitation current and other test conditions remains constant, and object dimensions change slightly in the course of experimenting. In this case, the added voltage of the eddy current probe changes due to the electrical conductivity and the magnetic permeability only. The eddy current investigations of deformation behavior of metastable austenitic steel have specificity, because both the electrical conductivity and the magnetic permeability change at the same time.

During plastic deformation of metastable austenitic steel, two different phases, paramagnetic $\varepsilon$-martensite and ferromagnetic $\alpha'$-martensite, can be formed from paramagnetic $\gamma$-austenite existing in the initial state [9-13]. The type of phase transformation can be one of such $\gamma \rightarrow \varepsilon \rightarrow \alpha'$, $\gamma \rightarrow \varepsilon$ or $\gamma \rightarrow \alpha'$. In general, the specific type and the extent of phase transformation as well as the mechanism of deformation depend on chemical composition, temperature, stress-strain state, grain size and stacking fault energy [9-19]. Hexagonal $\varepsilon$-martensite is formed if the stacking fault energy of austenite is low enough [20]. The stacking fault energy decreases with decreasing temperature, and hence the volume
fraction of ε-martensite should increase during plastic deformation of metastable austenitic steel at low temperature [21]. As a rule, ε-martensite is not formed at room temperature unlike α'-martensite [14]. But also it may be that ε-martensite is an intermediate phase formed during deformation [20]. The volume fraction of α'-martensite steadily increases during deformation, which leads to a considerable change in the magnetic properties and an increase in the deformation hardening [14, 22].

In the literature [23-25] the comparison of the calibration curves between the Ferritescope and actual α'-martensite contents was presented. However, the study does not take into account that the magnetic permeability of the material depends not only on the volume fraction of the magnetic phase, but also on the magnitude of mechanical stresses. This is due to the displacement of the domain boundaries during elastic deformation, which in turn affects the magnetic characteristics of the steel [26].

Based on the above, it is possible to the eddy current instrument readings $F$ as a function of partial derivatives of the phase content $\nu$ and mechanical stress $\sigma$ in the material:

$$\Delta F(\nu, \sigma) = \frac{\partial F}{\partial \nu} \Delta \nu + \frac{\partial F}{\partial \sigma} \Delta \sigma \quad (1)$$

As a rule, the measurement of the magnetic phase content is carried out on the unloaded material. However, in some cases it is impossible to unload the material of constructions. In this case, the measurement of the magnetic phase content is made with an additional error associated with the action of mechanical stresses in the elastic region.

To determine the error value, we investigated relationship between the eddy current instrument readings, the yield stress and the content of strain-induced α'-martensite during static deformation of metastable austenitic steel AISI 321.

The eddy current studies were supplemented with X-ray diffraction analysis and microstructural analysis.

2. Experimental procedure

The studies were carried out on the sheet-type specimens of metastable austenitic stainless steel AISI 321. The chemical composition of steel is given in table 1. Dimensions of the flat specimen were 100×20×6 mm. An electromechanical testing machine Tinius Olsen H100KU was used for tension testing. Uniaxial tension with a strain rate of $10^{-3}$ s$^{-1}$ was carried out at room temperature in 6 stages.

| Table 1. Chemical composition of the investigated material (%) |
|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| C       | Ni   | Cr   | Ti  | Mn  | Si  | Cu  | S   | P   |
| 0.02    | 9.16 | 17.76| 0.32| 0.74| 0.43| 0.23| 0.00| 0.03|

A multifunctional eddy current instrument MVP-2M (SPC “Kropus”, Russia) was used for the eddy current studies. This instrument can measure the added voltage of eddy current probe $F$ and the percentage content $F_{\text{meas}}$ of the magnetic phase. The eddy current probe was attached to the specimen as shown in figure 1 for in-situ measuring of the added voltage during tension testing. The percentage content of the magnetic phase was measured after each stage of plastic deformation.
A metallography microscope ALTAMI MET 3M was used for microstructure observation. Surface of the specimen was first mechanically polished and then electrolytically etched in a 10% water solution of oxalic acid for a few minutes to reveal microstructure. A diffractometer DRON-3M with a Cu-Kα tube was used for X-ray diffraction analysis.

3. Results and discussion
Stress-strain curves for step-by-step static tensile testing are shown in figure 2.

![Figure 2. Stress-strain curves for tensile testing of steel AISI 321.](image)

Microstructure of steel AISI 321 is shown in figure 3. Parallel shear bands are observed inside some grains in the initial state (figure 3a). With the residual strain 3%, the number of the shear bands increased and also the intersecting shear bands appeared (figure 3b). With the residual strain 54%, the shear bands are "destroyed" and create a pronounced relief inside a grain (figure 3c). According to [23, 27], strain-induced α'-martensite is very finely dispersed and formed on the intersections of the shear bands inside the austenite grains.

![Figure 3. Microstructure of steel AISI 321: initial state (a), residual strain 3% (b) and 54% (c).](image)
The results of X-ray diffraction analysis are presented in figure 4 and table 2. On the X-ray diffraction pattern obtained in the initial state, only γ-austenite peaks (111), (200) and (220) are observed. At the residual strain 3%, α'-martensite peak (110) was detected. At the residual strain 54%, γ-austenite peaks (200) and (220) decreased, γ-austenite peak (111) as well as α'-martensite peak (110) increased, and α'-martensite peak (200) appeared. It is to note that ε-martensite peaks are not observed. Changes in the intensity of different peaks are associated not only with the phase transformation, but also with changing the crystallographic texture due to plastic deformation [28, 29]. The lattice parameter of γ-austenite is 3.6 Å. The lattice parameter of α'-martensite is 2.9 Å.

![X-ray diffraction patterns of steel AISI 321: initial state (a), residual strain 3% (b) and 54% (c).](image)

**Figure 4.** X-ray diffraction patterns of steel AISI 321: initial state (a), residual strain 3% (b) and 54% (c).

| Specimen                | Double Bragg's scattering angle (°) | Interplanar distance (Å) | (hkl) | Phase |
|-------------------------|-------------------------------------|--------------------------|-------|-------|
| initial state           |                                     |                          |       |       |
|                         | 43.26                               | 2.095                    | (111) | γ     |
|                         | 50.23                               | 1.818                    | (200) | γ     |
|                         | 74.29                               | 1.276                    | (220) | γ     |
| residual strain 3%      |                                     |                          |       |       |
|                         | 43.36                               | 2.089                    | (111) | γ     |
|                         | 44.05                               | 2.056                    | (110) | α'    |
|                         | 50.35                               | 1.814                    | (200) | γ     |
|                         | 74.27                               | 1.276                    | (220) | γ     |
| residual strain 54%     |                                     |                          |       |       |
|                         | 43.00                               | 2.106                    | (111) | γ     |
|                         | 44.18                               | 2.050                    | (110) | α'    |
|                         | 50.23                               | 1.818                    | (200) | γ     |
|                         | 64.30                               | 1.449                    | (200) | α'    |
|                         | 74.95                               | 1.268                    | (220) | γ     |

The dependencies of the added voltage $F$ of the eddy current probe on the applied stress $σ$ for each stage of tensile deformation are shown in figure 5.
Figure 5. Curves obtained \textit{in-situ} for added voltage of eddy current probe vs applied stress. 1 - $\varepsilon=3\%$, 2 - $\varepsilon=9\%$, 3 - $\varepsilon=15\%$, 4 - $\varepsilon=25\%$, 5 - $\varepsilon=33\%$, 6 - $\varepsilon=54\%$.

The added voltage of the eddy current probe decreases linear in the elastic region at each stage of tensile testing. The $\alpha'$-martensite begins to induce beyond the yield point, which affects the sharp increase in the added voltage of the eddy current probe. When the load is removed, the added voltage of the eddy current probe increases slightly. On each stage of tensile testing, the minimum of the added voltage corresponds to the yield stress. The slope of curve angle $\tan(\alpha) = \Delta F / \Delta \sigma$ changes nonlinearly with increasing residual strain is found (figure 6). The increase $|\Delta F / \Delta \sigma|$ occurs at large plastic strains and is associated with an increase in content of strain-induced $\alpha'$-martensite.

Figure 6. Dependence of slope of curve angle $\tan(\alpha) = \Delta F / \Delta \sigma$ on residual strain

The content of strain-induced $\alpha'$-martensite $F_{\text{meas}}$ increase with the plastic strain as shown in figure 7, curve 1. The measurement was carried out at $\sigma = 0$. The dependence of the content of the ferromagnetic phase on the residual strain is sigmoidal. The initial content of the $\alpha'$-martensite was 0.4% and increased to 40.7% after plastic deformation 54%. The data for curves 2 - 4 in the figure 7 were obtained by converting the $F$ values to a percentage of the ferrite phase using calibration.
samples. The curve 2 correspond to eddy current instrument reading when $\sigma = 1/3\sigma_{ys}$, curve 3 – for $\sigma = 2/3\sigma_{ys}$ and curve 4 for $\sigma = \sigma_{ys}$.

Figure 7. Dependence of strain-induced $\alpha'$-martensite on residual strain, 1 - $\sigma = 0$, 2 - $\sigma = 1/3\sigma_{ys}$, 3 - $\sigma = 2/3\sigma_{ys}$, 4 - $\sigma = \sigma_{ys}$.

As can be seen from these curves, the presence of elastic deformations in the material significantly increases the measurement error of the ferrite phase. At the content of the strain-induced $\alpha'$-martensite of 28% and the presence of elastic stresses close to the yield stress, the relative error reaches 40%. To correct the eddy current instrument readings in the presence of information about the magnitude of the strain $\varepsilon$ and stress $\sigma$, you can use the expression:

$$F = F_{meas} + K_{1F}\sigma + K_{2F}\alpha\sigma,$$

(2)

where $K_{1F} = -0.005$, $K_{2F} = 0.0007$.

This approach on average reduces the relative measurement error of the strain induced $\alpha'$-martensite content to 7%.

4. Conclusion

The stages of austenitic steel AISI 321 deformation are displayed by the dependence of the eddy current instrument readings on the applied stresses. The added voltage of the eddy current probe decreases slightly at loading in the elastic region and increases sharply at loading beyond the yield point.

The X-ray diffraction analysis and the eddy current investigations indicate that $\alpha'$-martensite is formed during plastic deformation of austenitic steel AISI 321 at room temperature. After 54% plastic deformation, which led to the destruction of the specimen, about 40% of $\alpha'$-martensite was formed which increased the yield stress since 320 to 580 MPa.

When measuring the content of martensite by eddy current method it is necessary to take into account the influence of mechanical stresses was shown. An algorithm is proposed to reduce the measurement error of the ferrite phase fraction by taking into account the stress-strain state of the material.

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