Estimating the Stress-Strain State of the “Stainless Steel – Structural Steel” Two-Layer Composite by Magnetic Measurements

Evgenia A. TUEVA, Eduard S. GORKUNOV, Sergey M. ZADVORKIN, Larisa S. GORULEVA, Irina A. GOLUBKOVA, Ivan S. KAMANTSEV

Institute of Engineering Science, Russian Academy of Sciences (Urals Branch), Ekaterinburg, Russia; tuevaevgenya@mail.ru

Abstract
One of the ways to reduce metal consumption in structures and to enhance their service properties is the use of composite materials, in particular, multilayer ones. In order to develop methods for diagnosing the state of these composites and their components, the effect of deformation by rolling and uniaxial tension on the structure, magnetic and mechanical properties of a two-layer composite produced by explosion welding of austenitic stainless steel and mild steel, as well as its individual components, has been studied. It has been shown that magnetic characteristics can be used to estimate the amount of deformation by rolling, the phase composition and mechanical properties, as well as the stress-strain state in the practically important elastic strain region.

Keywords: cold rolling, uniaxial tension, two-layer composite, differential magnetic permeability, coercive force, saturation magnetization, maximum magnetic permeability

Introduction
An urgent challenge for modern industry is to reduce metal consumption with simultaneous improvement of the service properties of structures and enhancement of their lifetime. One of the solutions to this problem is to use multilayer composite materials (CM), including those produced by explosion welding with subsequent rolling. Under external effects, the materials used as CM components sometimes fail to retain their structure and properties on the necessary level. For instance, as a rule, the most frequently used stainless austenitic steels have a deformationally unstable structure where force effects may cause phase transformations with the formation of ferromagnetic α’-phase particles in the paramagnetic matrix. This results in lower resistance to intercrystalline corrosion [1, 2]. Therefore it is necessary to diagnose the condition of machine parts and structural members made of these materials while in production and use.

In order to select informative parameters for estimating the condition of laminated composite materials and their components in the stage of production and while in use, studies have been made into the changes occurring in the phase composition, mechanical and magnetic properties of a “steel 08Kh18N10T – steel St3” two-layer CM produced by explosion welding with subsequent cold rolling.

Experimental details
Test specimens were cut out commercial sheet steels St3 and 08Kh18N10T (3.9 mm and 1.9 mm thick respectively), the chemical composition being given in table 1. The “steel 08Kh18N10T – steel St3” composite material was made by explosion welding under factory conditions. Rectangular sheets 200×20 mm were cut out of CM and of separate sheets of steels St3 and 08Kh18N10T.

Table 1. The chemical composition of steels St3 and 08Kh18N10T
The figures show the results and discussion of the magnetic permeability and magnetization characteristics of the specimens. The specimens were rolled to the following amounts of strain: for steel St3, ε_{rol} = 0, 0.11, 0.20, 0.34, 0.49, 0.63; for steel 08Kh18N10T, ε_{rol} = 0, 0.19, 0.27, 0.36, 0.45, 0.57. The value of ε_{rol} for CM specimens was determined in metallographic studies by changes in the cross section area, and it is indicated in Table 2. Note that the amount of strain for separate components in CM differs from ε_{rol} for the CM as a whole. As a rule, in the composite material the amount of the rolling strain of the 08Kh18N10T steel layer exceeded that of the St3 one.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>St3</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>0.48</td>
<td>0.19</td>
<td>-</td>
<td>0.005</td>
<td>0.01</td>
</tr>
<tr>
<td>08Kh18N10T</td>
<td>0.07</td>
<td>17.3</td>
<td>8.5</td>
<td>0.5</td>
<td>0.74</td>
<td>0.4</td>
<td>0.005</td>
<td>0.03</td>
</tr>
</tbody>
</table>

For steel 08Kh18N10T, the quantity of deformation α′-martensite resulting from rolling was determined by X-ray diffraction analysis with the application the homologous pair method. Monochromated Kα-radiation of chromium was used to obtain X-ray patterns. The Vickers hardness of the specimens was determined under the load on the indenter of 49N. To perform uniaxial tension tests, flat tensile specimens with heads were cut out of pre-rolled St3 and 08Kh18N10T steel sheets and of the “steel St3 – steel 08Kh18N10T” composite material. The long specimen axis coincided with the direction of rolling. The specimens were tensioned at room temperature with simultaneously recorded magnetic characteristics. A magnetic field was applied along the specimen tension axis (along the direction of rolling), the axis of the induction pick-up coil being also parallel to the axis of tension. The specimen was demagnetized before and after each step of magnetic measurements. Specimen elongation under tension was determined contactlessly by a La Vision video extensometer. The values of conventional yield stress σ_{0.2} and ultimate strength σ_u were found from the stress-strain diagrams.

The magnetic characteristics of the specimens were measured after rolling and under uniaxial tension in a permeameter-type magnetic circuit. A magnetic field of strength H up to 550 A/cm was applied along the direction of stress. Coercive force H_c, residual induction B_r and magnetization M_{max} in the maximum applied field were found from magnetic hysteresis loops. The field and induction measurement error did not exceed 3 %. Maximum magnetic permeability μ_{max} was determined by the basic magnetization curve. Field dependences of differential magnetic permeability μ_{diff} (the figures show only those portions of the field dependences μ_{diff} that have permeability peaks) were obtained by differentiating the ascending branches of the magnetic hysteresis loops.

### Results and discussion

Explosion welding is impact-wave loading, with the pressure reaching the order of several GPa within the order of μs [3]. Sheets or plates while being welded deform plastically in the...
contact area, so that the interface between the CM components is an undulating surface [3]. The undulating nature of the interface has been revealed by a metallographic study. As the amount of rolling deformation increases, the interface undulation decreases, and, according to [4], this increases material strength in the contact area. The same is evidenced by our measurements of the hardness of both CM components: their hardness increases with the amount of rolling deformation (fig. 1), the hardness near the weld being higher than on the external specimen surfaces.

![Hardness distribution through the cross section of the composite material at different amounts of rolling deformation](image)

Figure 1. Hardness distribution through the cross section of the composite material at different amounts of rolling deformation

Figure 2α shows the magnetic behaviour of steel St3 as dependent on the amount of rolling deformation. The coercive force increases with $\varepsilon_{\text{rol}}$, the maximum magnetic permeability being halved. Obviously, this behaviour is due to increasing dislocation density $N$ (according to [6], $H_c \sim N^{1/2}$). The saturation magnetization of steel St3 remains unchanged with varying $\varepsilon_{\text{rol}}$ ($M_{\text{max}} \approx 1.67 \times 10^4$ A/cm), and this bears witness to the stable phase composition of the material being deformed.

According to the X-ray diffraction studies, the initial 08Kh18N10T steel structure contains only austenite. The lack of ferromagnetic phases in the structure of the steel is confirmed by low maximum magnetization (about 16 A/cm in the field of 550 A/cm).

It follows from fig. 2b that, in the entire range of strains, the maximum magnetization and maximum magnetic permeability of steel 08Kh18N10T increase monotonically with $\varepsilon_{\text{rol}}$, and this implies an increase in the ferromagnetic phase. Note that the maximum magnetization increases linearly from 0 to 720 A/cm, and, according to [7], this points to a linearly increasing quantity of $\alpha'$-martensite. The quantity of $\alpha'$-martensite formed at the maximum amount of rolling deformation, which is determined by an X-ray diffraction analysis, reaches 85 %. The calculations of the quantity of deformation martensite made by the magnetization of the specimens in view of their chemical composition have demonstrated a smaller quantity of the $\alpha'$-phase. For instance, as calculated by $M_{\text{max}}$, the specimen with the maximum amount of rolling deformation contains about 60 % martensite. The difference in the results on the content of deformation martensite in steel 08Kh18N10T that were obtained in two different ways may result from the fact that the X-ray method analyzes only the surface layer, which deforms more severely during rolling than the material bulk [8].
Figure 2. The magnetic behaviour of steel St3 (a), steel 08Kh18N10T (b) and the composite material (c) as dependent on the amount of rolling deformation. For steel 08X10H10T and the composite material, the quantity of $\alpha'$-martensite determined by the X-ray phase analysis method is also shown.

Figure 2b shows also measurement results on the coercive force of steel 08Kh18N10T as dependent on the amount of rolling deformation. It is obvious that $H_c$ is characterized by a non-unique $\varepsilon_{rol}$ dependence. Before $\varepsilon_{rol} = 0.19$ there is an almost 12-fold increase in $H_c$ as compared to the initial state. Firstly, this may be due to higher dislocation density in rolling. Secondly, in the first stages of plastic deformation, the size of ferromagnetic phase precipitations in Fe-Cr-Ni alloys ($\alpha'$-martensite in our case) is much smaller than the critical particle size of the single-domain state of iron-based alloys (about 8 nm [9] and 50 nm [10] respectively). Single-domain state is characterized by high coercive force values, which are often commensurable with the field of magnetocrystalline anisotropy (400 A/cm for pure iron [11]). When $\varepsilon_{rol} > 0.19$, the coercive force values decrease, and this can be attributed to the growing number and size of the ferromagnetic phase precipitations, so that the multi-domain state of these precipitations becomes energetically advantageous.

The magnetic behaviour of the composite material as dependent on $\varepsilon_{rol}$ is shown in fig. 2c. The saturation magnetization increases nonlinearly with the amount of rolling deformation, and this is indicative of the $\gamma \rightarrow \alpha$ phase transformation in the 08Kh18N10T steel layer. However, the dependence $M_{\text{max}}(\varepsilon_{rol})$ is close to logarithmic, whereas the content of the $\alpha'$-phase grows practically linearly with $\varepsilon_{rol}$. This is due to the fact that the volume fraction of the 08Kh18N10T CM component determined in the metallographic studies by the change in the specimen cross section decreases from 34 % to 28 % as the amount of rolling deformation increases. The curve $\mu_{\text{max}}(\varepsilon_{rol})$ varies with a peak near $\varepsilon_{rol} \approx 0.40$. The initial growth of $\mu_{\text{max}}$ may be caused by the increasing quantity of $\alpha'$-martensite, the subsequent decrease being caused by higher defect density.

When $\varepsilon_{rol} = 0$, the coercive force of the CM exceeds considerably the values of $H_c$ for the St3 and 08Kh18N10T specimens (fig. 2). The higher value of $H_c$ for the composite material is attributable to material work hardening during explosion welding. The increase in the amount
of rolling strain to 0.28 does not cause any significant changes in $H_c$ of the composite, though the coercive forces of the components increase in this range of $\varepsilon_{rol}$. This can be explained by the increasing magnetic permeability of steel 08Kh18N10T during rolling due to the formation of deformation martensite, which facilitates the magnetization reversal of the two-layer material as a whole. The increase in $H_c$ of the composite at $\varepsilon_{rol} > 0.28$ is caused by increasing defect density in the crystalline structure of the metal rolled [8].

Figure 3 presents field dependences of differential magnetic permeability for the CM and the constituting materials before rolling and at different amounts of rolling deformation. For the St3 steel and the composite material, at $\varepsilon_{rol} = 0$, on each field dependence of differential magnetic permeability (fig. 3a) there is one peak corresponding to ferrite in steel St3. The magnetic permeability of steel 08Kh18N10T is close to 1. Rolling (fig. 3b, c) affects the dependences $\mu_{dif}(H)$ for all the three materials. The peak height on the field dependence of $\mu_{dif}$ for steel St3 decreases almost 3 times. The decrease in differential permeability with the increasing amount of rolling deformation is attributable to increasing dislocation density, i.e., to the same reason as the change in the coercive force and maximum magnetic permeability.

For the 08Kh18N10T specimens, on the curves $\mu_{dif}(H)$ there appears a peak corresponding to deformation martensite resulting from rolling. The peak is localized in fields of 20…25 A/cm. In the same fields, another peak is formed on the field dependences of the differential magnetic permeability of the CM specimens, and this implies a phase transformation going on in the 08Kh18N10T steel layer of the CM. Curves $\mu_{dif}(H)$ for all the three materials rolled to maximum amounts of deformation are presented in fig. 3c. It is obvious that, on the $\mu_{dif}(H)$ curve for the CM rolled from $\varepsilon_{rol} = 0.62$ there are two distinct peaks corresponding to two ferromagnetic phases, namely, ferrite in steel St3 and martensite in steel 08Kh18N10T. The fields of the peaks of separate components approximately correspond to the values of their coercive forces: the peaks are localized in fields ranging between 2 and 6 A/cm for steel St3 and in fields ranging between 20 and 40 A/cm for steel 08Kh18N10T. Note that, at maximum rolling reduction, the peak on the dependence $\mu_{dif}(H)$ for steel St3 as a separate material is located in a stronger field than that for the St3 steel layer in the CM, since the maximum value of $\varepsilon_{rol}$ is 0.63 for the St3 steel specimen and 0.53 for the St3 steel layer in the CM, see table 2. As $\varepsilon_{rol}$ increases, the peak height corresponding to steel 08Kh18N10T grows with the $\alpha'$-phase content. Thus, the location of the peaks on the field dependence of differential magnetic permeability and their height are indicative of the values of the amount of rolling deformation both for the composite material as a whole and for its separate components.

Under uniaxial tension, the behaviour of $H_c$, $B_r$ and $\mu_{max}$ of the materials is non-unique. The obtained dependences are similar to those found earlier for the model three-layer material “steel 12Kh18N10T – Armco iron – steel 12Kh18N10T” [12]. The extrema observed on the dependences $H_d(\sigma/\sigma_{0.2})$, $B_r(\sigma/\sigma_{0.2})$ and $\mu_{max}(\sigma/\sigma_{0.2})$ for the specimens made of steel St3 and of CM (fig. 4a and 4b) in the elastic region of tension is attributable to the formation of a magnetic texture of stresses, which is also referred to as induced magnetic anisotropy [11]. The effect of stresses reaching and exceeding the yield stress causes a collapse of the magnetic texture of stresses [11,13-14], and the major factor affecting the coercive force in the plastic region is increasing dislocation density and dislocation clusters. The similarity of the magnetic behaviour of the CM and steel St3 may be due to the fact that, in the composite material under tension in the elastic and early plastic stages, the magnetic properties are affected by the St3 steel layer constituting a greater volume in the CM and having a higher magnetic permeability. A low ferromagnetic phase content prevents the 08Kh18N10T steel layer from having any tangible effect on the magnetic behaviour of the composite material.
The magnetic characteristics of steel 08Kh18N10T are shown in fig. 4b as dependent on applied tensile stresses. Deformation by uniaxial tension, as well as cold rolling, increases the quantity of the ferromagnetic phase in the structure of the corrosion resistant steel; however, the growth of the values of maximum magnetization is insignificant in the stage of elastic deformations for all the specimens. For the specimens with \( \varepsilon_{\text{rol}} \leq 0.27 \), i. e., with a considerable plasticity margin, an intensive growth of maximum magnetization is observed at stresses exceeding conventional yield stress, and this implies an increase in the content of deformation \( \alpha' \)-martensite in the steel. At stresses exceeding yield stress the coercive force of these specimens varies with a maximum. It may be due to the fact that plastic deformation favours the growth of deformation martensite particles caused by rolling and that they change from the one-domain state into the multi-domain one. In the specimens with a lower plasticity margin (\( \varepsilon_{\text{rol}} > 0.27 \)) fracture under uniaxial tension seems to occur before any noticeable deformation martensite has a chance to appear. As a result, the growth of the maximum magnetization of these specimens is insignificant, and the dependences \( H_c(\sigma/\sigma_{0.2}) \) vary without a maximum. It is also obvious from fig. 4b that the unique dependence of all the magnetic parameters for steel 08Kh18N10T is observed as far as \( 0.5\sigma_{0.2} \). This enables the level of applied elastic tensile stresses in products made of steel 08Kh18N10T to be estimated by magnetic parameters.
Figure 4. The magnetic characteristics of steel St3, steel 08Kh18N10T and the “steel 08Kh18N10T – steel St3” composite material as dependent on reduced applied tensile stresses.

It follows from the results obtained that, to estimate the stress state of “steel 08Kh18N10T – steel St3” composite products (as well as St3 and 08Kh18N10T products) under uniaxial tension in the practically important elastic region ($\sigma < 0.5\sigma_{0.2}$), the quantities $H_c$, $B_r$ and $\mu_{\text{max}}$ can be used.

As the behaviour of the coercive force, maximum magnetic permeability and residual induction of the composite material is almost completely governed by the behaviour of the same characteristics for steel St3, they cannot be used to estimate changes occurring under uniaxial tension in the 08Kh18N10T steel layer in the composite. The field dependence of differential magnetic permeability can be a more informative parameter for diagnosing the condition of the separate components in the CM. As an example, fig. 5 shows the field dependences of differential magnetic permeability for specimens made of the composite material produced by explosion welding, when $\varepsilon_{\text{rol}} = 0$ and $\varepsilon_{\text{rol}} = 0.62$ at different applied tensile stresses.

The field dependences of $\mu_{\text{diff}}$ for the material that has not been deformed by rolling (fig. 5a) have only one peak corresponding to ferrite in steel St3, and the specimen fractures before the quantity of $\alpha'$-martensite sufficient for another peak to appear has managed to form. The field dependence of differential magnetic permeability for the specimen with $\varepsilon_{\text{rol}} = 0.62$ (fig. 5b) has two pronounced peaks corresponding to two ferromagnetic phases: ferrite in steel St3 and deformation $\alpha'$-martensite in steel 08Kh18N10T. The height of the $\mu_{\text{diff}}$ peak corresponding to
deformation martensite increases with applied tensile stresses, and this is indicative of an increasing quantity of the $\alpha$'-phase. The field of the $\mu_{\text{diff}}$ peak corresponding to deformation martensite varies with a minimum when tensile stresses are applied, and this is qualitatively similar to the variation of the coercive force of the composite material caused by tensile stressing. Similar field dependences of differential magnetic permeability were observed for all the specimens subjected to cold pre-rolling.

Figure 5. The field dependences of differential magnetic permeability for specimens made of the composite material at $\varepsilon_{\text{rol}} = 0$ (a) and $\varepsilon_{\text{rol}} = 0.62$ (b) at different levels of applied tensile stresses

Conclusions

1) As the amount of rolling deformation increases, the coercive force and maximum magnetic permeability of the St3 low-carbon steel specimens, both measured in a closed magnetic circuit, vary monotonically. The sensitivity of these magnetic characteristics enables them to be used as informative parameters for estimating rolling-induced changes in the strain state of products made of low-carbon steels.

2) The values of maximum magnetization and maximum magnetic permeability, both varying monotonically with the increasing amount of deformation can be used to estimate the structural changes and the strain state of products made of cold rolled stainless austenitic steel 08Kh18N10T. Due to a relatively small value of magnetization of steel 08Kh18N10T, to make the diagnostics of the condition of machine parts and structural members made of this material more reliable it is preferable to use combinations of the above-mentioned magnetic parameters.

3) The coercive force of the “steel 08Kh18N10T – steel St3” composite material varies uniquely as the amount of rolling deformation increases, and this enables it to be used for estimating the amount of plastic deformation in composite materials of the kind. The peak height and position on the field dependence of the differential magnetic permeability of the composite material can serve as parameters for estimating the amount of rolling plastic deformation both in the composite material as a whole and in its constituents.

4) In the practically important elastic region, at uniaxial tensile stresses of about $0.5\sigma_{0.2}$ and lower, the coercive force, maximum magnetic permeability and residual induction of the materials tested behave uniquely, and they can be used to estimate the variations of the stress-strain state of “steel St3 – steel 08Kh18N10T” composite products under uniaxial tension.

5) The peak height and position on the field dependence of the differential magnetic permeability of the composite can serve as parameters for estimating the amount of elastic-
plastic uniaxial tension deformation both of the composite material as a whole and its constituents.

The work was supported by RFBR (grant No 11-01-12126) and RAS Presidium Programme No 25.

References