Application of Magnetic NDT Methods to Evaluating the Stress-Strain State of the Individual Zones of Welded Joints

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Abstract
An extensive network of trunk pipelines, existing and under construction, working under hard environmental conditions necessitates the development of non-destructive testing techniques to be applied to diagnosing a current state of pipes and welded joints in the process of production and use. This paper reports on the results of the microstructural analysis and the study of the mechanical and magnetic properties of the different zones of welded joints (base metal, heat-affected zone material and weld material) in tube steels X70 and X80 made by controlled rolling. The effect of various loading conditions on the magnetic characteristics of the metals of the three zones is studied. Magnetic parameters uniquely characterizing the variation of the stress-strain state of the individual zones of a welded joint (the weld, the heat-affected zone, the base metal) in a certain range of applied stresses have been ascertained.

Keywords: Pipe steels, welded joint, stresses, strain, magnetic testing, coercive force, residual induction, maximum magnetic permeability.

Introduction
New long-distance oil and gas pipeline branches keep being laid, which will work at low temperatures under severe environmental conditions of the Yamal peninsula, Eastern Siberia, marine oilfields in northerly latitudes. A large part of them are pipelines made of now widespread pipe steel X70, which is produced with the application of controlled rolling. The current practice requires that trunk pipelines have a higher capacity with lower specific quantity of metal, and this necessitates an increase of the operating pressure in a pipeline (from 75 to between 100 and 200 atm for gas pipelines and from 55 to between 75 and 100 atm for oil pipelines) and thinner pipe walls. Besides, for flats used in pipe making, it is easier to impart better properties to thinner walls. This makes it promising to change over to pipes made of steels of strength grade X80 and higher. The use of highly strong offers a lower specific quantity of metal in pipeware, lower a laboriousness of construction-and-assembly work (especially welding) and lower costs of metal transportation. The strength properties of low-carbon economically alloyed pipe steels undergoing controlled rolling can be enhanced by changing over from steels with a ferritic-pearlitic structure to steels with a bainitic structure.

It is well known that welded joints, particularly the heat-affected zone, more often are fracture nuclei in metalworks, including trunk pipelines. The violation of the strength of welded joints in pipelines is caused, firstly, by defects that may arise during welding due to various deviations from the standards and engineering specifications and, secondly, by the effect of stresses, both residual and operating [1, 2].

As a rule, there are several zones in welded structures. They are the base metal, the weld and the heat-affected zone (HAZ). The difference in the structures of the zones, their physical-mechanical properties and the level of residual stresses accounts for the fact that the materials of the different zones of welded structures respond differently to the action of applied loads in making and use. This makes the development of methods for evaluating the variation of the stress-strain state in the different zones of welded steel structures in the stages of production and use an urgent challenge for non-destructive testing. The first stage in solving this problem is the determination of the physical parameters uniquely characterizing the variation of the
structural and stress-strain state of the individual zones of a welded joint (the weld, the heat-affected zone and the base metal).

This paper studies the structure and physical-mechanical properties of the different zones in welded joints of steels X70 and X80 under applied stressing in order to determine the applicability of magnetic techniques to evaluating the changes occurring in the material of welded large-diameter pipes in the course of production and operation.

**Materials and experimental procedure**

The studies were made on specimens cut out along the direction of rolling, i.e. along the weld, from different zones (the base metal, the HAZ material and the weld) of longitudinally welded pipes made of control-rolled steel of strength grades X70 (Ø1420×157 mm) and X80 (Ø1420×21.6 mm), according to the API standard. The chemical compositions of the base metal, the HAZ and weld materials of the specimens studied are given in Table 1.

<table>
<thead>
<tr>
<th>Strength grade</th>
<th>Zone of the joint</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Nb</th>
<th>V</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>X70</td>
<td>Base metal and HAZ</td>
<td>0.14</td>
<td>0.48</td>
<td>1.61</td>
<td>0.012</td>
<td>0.004</td>
<td>0.071</td>
<td>0.150</td>
<td>0.222</td>
<td>0.030</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>X80</td>
<td></td>
<td>0.083</td>
<td>0.21</td>
<td>1.77</td>
<td>0.009</td>
<td>0.001</td>
<td>0.101</td>
<td>0.243</td>
<td>0.144</td>
<td>0.040</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>X70</td>
<td>Weld metal</td>
<td>0.12</td>
<td>0.35</td>
<td>1.92</td>
<td>0.017</td>
<td>0.004</td>
<td>0.091</td>
<td>0.031</td>
<td>0.018</td>
<td>0.043</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>X80</td>
<td></td>
<td>0.077</td>
<td>0.35</td>
<td>1.66</td>
<td>0.011</td>
<td>0.002</td>
<td>0.079</td>
<td>0.286</td>
<td>0.338</td>
<td>0.02</td>
<td>0.003</td>
<td></td>
</tr>
</tbody>
</table>

The mechanical properties of the metal in different zones of welded joints were determined under uniaxial tension on an Instron 8801 testing unit. Uniaxial tensile testing was made on cylindrical specimens, with heads, 7 mm in gauge diameter. Hollow cylindrical specimens, 12 mm in the external diameter and 9 mm in the internal one, were used for torsion and combined loading tests. The tension and torsion tests were performed to fracture, the combine loading tests (tension/compression with torsion) being made only in the elastic strain region. The tests were performed at room temperature on a universal testing machine with a maximum tensile force of 50 kN and a maximum torsional moment of 200 N×m. The process of loading was suspended at a certain amount of strain, without relief, and magnetic hysteresis loops were recorded by a Remagraph C-500 magnetic measurement unit. The magnetic measurements were made in a closed magnetic permeameter-type circuit. A magnetic field of 500 A/cm was applied along the specimen axis. The values of the coercive force $H_c$, residual induction $B_r$ and magnetization in the maximum applied field $M_{\text{max}}$ (approximately equal to saturation magnetization) were determined from the magnetic hysteresis loops. The measurement error for the field and induction did not exceed 3 %. Maximum magnetic permeability $\mu_{\text{max}}$ was determined from the principal magnetization curve. The specimen was demagnetized before and after each magnetic measurement. By differentiating the descending magnetic hysteresis branches, the field dependences of differential magnetic permeability $\mu_{\text{dif}}$ were obtained (In what follows, the figures show only those portions of the field dependences of $\mu_{\text{dif}}$ where there are maximum permeability values).

Metallographic sections were made on the cross sections of the specimens in order to conduct microstructural studies. Etching was performed with a 4 % alcohol solution of HNO$_3$. The microstructure was studied with the use of a Neophot 21 optical microscope. Microhardness $HV_{0.05}$ in the cross-section of the specimens was determined by a Leica microhardness tester.

**Results and discussion**
The results of the metallographic studies are presented in fig. 1. The structure of the base metal of the X70 steel pipe consists of polygonal ferrite and pearlitic colonies, fig. 1a. It is obvious from fig. 1 that this structure is characterized by a slight “stringiness” of the pearlitic colonies. The structure of the HAZ of the X70 steel pipe is a mixture of ferrite, the martensite-austenite constituent and lath bainite (fig. 1c) having thin and long laths gathered into large clusters of a relatively equiaxial shape. Similar HAZ structures with big-size grains were studied in [3]. The reason for the appearance of a coarse-grained structure adjacent to the fusion line is heating to temperatures of the dissolution of the most carbide particles, which are effective barriers inhibiting grain growth [3]. The material of the weld of the X70 steel pipe (fig. 1e) has acicular bainite, ferrite and a martensite-austenite constituent in its structure.

The structure of the base metal of the X80 steel pipe is a mixture of fine quasi-polygonal ferrite, acicular and globular bainite, see fig. 1b. It was shown in [4] that, for steel with this morphology to be generated, fine austenitic grain must be formed, which results from microalloying with niobium, vanadium and titanium. These elements form carbides favoring dispersion hardening. Steels of the X80 to X100 strength grades are characterized by a finely dispersed bainitic (ferritic-bainitic) structure, which enables high strength and good cold-resistance to be achieved even for thick rolled products. The formation of the ferritic-bainitic structure is based on the following aspects: low carbon content (0.04 to 0.08 %); doping with Mn, Mo, Ni, Cr, Cu, which decrease the temperature of polymorphic $\gamma \rightarrow \alpha$ transformation and inhibit pearlitic transformation; complex microalloying with Nb, Ti, V; lower content of harmful admixtures ($\leq 0.002$ % S; $\leq 0.010$ % P); the use of rapid cooling after rolling under controlled conditions.

The HAZ material of the both steels is characterized by the presence of an area with coarser grain; however the sizes of the structural constituents in this area is much smaller (see fig. 1d) than in steel X70. Besides lath bainite, in the structure there are precipitates of acicular and globular bainite. The weld material (fig. 1e) in steel X80 is characterized by higher dispersion as compared to the base metal and the HAZ material, as well as to the weld material of steel X70, and has acicular bainite, ferrite and a martensite-austenite constituent in its structure. Due to higher dispersion and distinctions in the chemical composition (see table 1) of the weld materials of the steels of the both grades, the hardness of the weld material for the both steels exceeds the hardness of the base metal and HAZ material, see table 2.

Table 2 shows the mechanical and magnetic characteristics of the metal in the zones of welded pipes. The strength characteristics of the base metal and the weld material of the X70 steel pipe coincide within the measurement error. For the X80 steel pipe, the yield stress $\sigma_{0.2}$ and ultimate strength $\sigma_B$ of the weld metal is almost 10 % higher than these characteristics of the base metal. The ratio $\sigma_Y/\sigma_U$ characterizing the strain-hardenability of a material is generally specified by the normative documentation for the material. For the HAZ material of the X70 steel, the value of this ratio is higher than for the base metal and the weld material. It follows that the HAZ material is less strain-hardenable than the base metal and the weld material; consequently, it is in this zone of the pipe that the probability of brittle fracture increases. The different zones of the X80 steel pipe have practically the same values of $\sigma_Y/\sigma_U$, and this is indicative of the strength balance of the welded joint for this material. However, the values of $\sigma_Y/\sigma_U$ for all the three zones of the welded joint of steel X80 are higher than for steel X70, and this testifies to a decrease in the plasticity margin of the former. Besides, this is vindicated by the values of relative elongation $\delta$; namely, for the base metal and the weld material, the X80 values are 15 % lower than the X70 ones for the same zones, the difference for the HAZ material being 27 %.
Table 2. The mechanical and magnetic properties of the metal from the different zones of welded large-diameter pipes made of steels X70 and X80

<table>
<thead>
<tr>
<th>Strength grade</th>
<th>Zone of the joint</th>
<th>σ_Y, MPa</th>
<th>σ_U, MPa</th>
<th>δ, %</th>
<th>σ_Y/σ_U</th>
<th>HV_{0.05}</th>
<th>H_c, A/cm</th>
<th>B_n, T</th>
<th>μ_max</th>
<th>M_{max}, kA/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X70</td>
<td>Base metal</td>
<td>505</td>
<td>635</td>
<td>17.2</td>
<td>0.079</td>
<td>280</td>
<td>5.3</td>
<td>0.922</td>
<td>788</td>
<td>16.0</td>
</tr>
<tr>
<td>X80</td>
<td>Base metal</td>
<td>595</td>
<td>650</td>
<td>14.7</td>
<td>0.91</td>
<td>260</td>
<td>7.1</td>
<td>1.125</td>
<td>744</td>
<td>16.24</td>
</tr>
<tr>
<td>X70</td>
<td>Weld metal</td>
<td>490</td>
<td>640</td>
<td>17.5</td>
<td>0.77</td>
<td>305</td>
<td>8.9</td>
<td>0.58</td>
<td>342</td>
<td>15.6</td>
</tr>
<tr>
<td>X80</td>
<td>Weld metal</td>
<td>640</td>
<td>710</td>
<td>14.8</td>
<td>0.90</td>
<td>320</td>
<td>10.6</td>
<td>1.063</td>
<td>544</td>
<td>15.76</td>
</tr>
<tr>
<td>X70</td>
<td>HAZ metal</td>
<td>525</td>
<td>615</td>
<td>19.5</td>
<td>0.85</td>
<td>260</td>
<td>6.2</td>
<td>0.86</td>
<td>670</td>
<td>16.4</td>
</tr>
<tr>
<td>X80</td>
<td>HAZ metal</td>
<td>600</td>
<td>680</td>
<td>14.2</td>
<td>0.88</td>
<td>235</td>
<td>7.1</td>
<td>1.127</td>
<td>760</td>
<td>16.32</td>
</tr>
</tbody>
</table>

Figure 2 shows the field dependences of differential magnetic permeability of the material from the individual zones of a welded joint for all the specimens tested.
It is obvious that the heights and positions of the peaks on the field dependences of the differential magnetic permeability of the X70 steel specimens cut out from the base metal, the weld and HAZ are different, this being due to the different structures and the levels of the physical-mechanical properties. As distinct from steel X70, the peaks from the HAZ material and the base metal in the X80 steel pipe are found in one and the same fields, since they have practically equal strength properties and their coercive forces are equal ($H_c$ in fig. 2 is shown by dotted lines). The peak for the X80 weld material on the field dependence of differential magnetic permeability lies in stronger fields, possibly, owing to a higher degree of alloying and dispersion of the structure of this material. Thus, the use of the field dependences offers information on the state of the individual components of the welded joint, whereas, when measuring the coercive force, we obtain an integral characteristic from the entire volume analyzed.

The normal stress dependences of the coercive force $H_c$, residual induction $B_r$ and maximum magnetic permeability $\mu_{\text{max}}$ for all the specimens are presented in fig. 3. It is obvious from fig. 3 that the values of the magnetic characteristics of the HAZ material and the base metal for the both steels are at about the same level. The coercive force values for the weld metal and steels X70 and X80, both in the initial state and in the whole range of applied stresses, exceed the coercive force values for the base metal and the HAZ material. This may be due to the higher dispersion of the structural constituents of the weld zone in a welded joint. On the dependences of all the magnetic characteristics corresponding to the weld material in steel X70 there is a drastic difference in the values in the initial range of tensile stresses. This may be owing to a partial compensation of the internal stresses by external loads.

The saturation magnetization of the different zones in the both steels is practically the same, and this is indicative of the stable phase composition of the materials.
On the dependences $H_c(\sigma)$, $B_r(\sigma)$ and $\mu_{\text{max}}(\sigma)$ for all the specimens studied there are extrema near $\sigma \approx 150–250$ MPa. The experimentally obtained nonmonotonic dependences $H_c(\sigma)$, $B_r(\sigma)$ and $\mu_{\text{max}}(\sigma)$ in the elastic region can be represented as resulting from the action of a number of factors. Particularly, the tension of specimens in the elastic region induces the formation of the magnetic texture of stresses, which is also termed induced magnetic anisotropy [5]. This phenomenon was discussed in detail in [6]. Thus, the magnetic characteristics studied for all the materials tested vary uniquely at the values of normal stresses ranging between $-200$ and $+200$ MPa, and these parameters can be used for the magnetic inspection of normal stresses and elastic strains in trunk pipelines. Note that the above-mentioned range of applied stresses several times exceeds the working pressure for present-day pipelines, which, according to [7], is 10 to 15 MPa.

The magnetic behaviors of the base metal, the weld and HAZ materials in the both steels under the effect of tangential stresses is shown in fig. 4.

It is obvious from fig. 4a that, for steel X70, the values of the residual induction of the base metal and the HAZ material are at about one and the same level, and they considerably exceed the values for the weld material. When tangential stresses range between 100 and 230 MPa, the $B_r$ values of the weld material grow by 15 % for steel X70. The maximum magnetic permeability of the HAZ in steel X70 varies within the error, the variations of this parameter for the base metal and the weld material being 5 and 10 %, respectively.

As applied tangential stresses grow, the coercive force values for the materials of all the specimens vary within the error. The exception is the coercive force values for the specimen cut out from the weld of an X80 steel pipe; namely, they increase a little in the whole range of applied stresses. The coercive force values for the weld material exceed those for the base metal and the HAZ material by 50 %. The maximum magnetic permeability of the weld...
material is 35 % lower than $\mu_{\text{max}}$ of the other two zones of the welded joint. For steel X80, the $B_r$ values of all the three zones of the welded joint are about equal.

It follows from a comparison between figs. 3 and 4 that, firstly, the tangential stresses have a smaller effect on the magnetic characteristics of the materials than the normal stresses, and, secondly, when there are tangential stresses, the magnetic characteristics of the both steels vary uniquely in the whole range of applied loads. This may be attributed to the fact that, in torsion, as distinct from tension and compression, the following two types of magnetic texture are simultaneously formed in a material: 1 – easy magnetization axis, which coincides with the direction of applied loading and facilitates magnetization along the specimen axis; 2 – easy magnetization plane, which is perpendicular to the specimen axis and complicates magnetization along the specimen axis. The effect of normal stresses offers conditions for the formation of only one type of magnetic texture, namely, the “easy magnetization axis” type. With reference to fig. 5 it can be seen that, under combined loading of specimens cut out from different zones of a welded joint in steel X70, there is a unique dependence of the coercive force in the range of applied normal stresses from −200 to 200 MPa and tangential stresses from 0 to 200 MPa.

Fig. 4. The magnetic characteristics of the base metal (■), the weld material (▲) and the HAZ materials (○) as dependent on tangential stresses: steel X70 (a), steel X80 (b).
Fig. 5. The normal stress dependences of the coercive force of the base metal, the HAZ and weld materials for steels X70 and X80 at various levels of tangential stresses.

In fig. 5 there are no dependences of residual induction and maximum magnetic permeability, however, the behavior of the curves is similar to those for the dependences shown in fig. 3. For steel X80, the applied normal stresses at which the magnetic characteristics vary uniquely range between −200 and 150 MPa, the tangential stresses ranging between 0 and 145 MPa. This enables $H_c$, $B_r$ and $\mu_{\text{max}}$ to be used in the said range of applied stresses as parameters for evaluating the changes in the stress state of the individual zones of a welded joint (the weld, the HAZ and the base metal) in X70 and X80 steel pipes made by controlled rolling. The range of stresses tested can be extended due to the application of multiparametric testing. However, the introduction of an additional parameter will result in greater labor and time expenditures, thus making the test object more expensive.

**Conclusion**

1. It has been demonstrated that the weld material of the both steels studied is more dispersive than the base metal and, all the more, than the HAZ material where a coarse-grain structure is
formed. In terms of the level of the strength properties, the welded joint in steel X80 is more full-strength than in steel X70, this being evidenced by the $\sigma_Y/\sigma_U$ ratio. Higher values of $\sigma_Y/\sigma_U$ for the HAZ material in steel X70 suggest the highest probability of the occurrence of brittle fracture here.

2. The obtained experimental results on the effect of various loading conditions (tension/compression, torsion and combined loading) on the magnetic characteristics have shown a decrease in the sensitivity of the latter under applied tangential loads. At the same time, at the level of normal stresses ranging between $-200$ and $200$ MPa, not exceeding 0.4 of yield stress, the coercive force, residual induction and maximum magnetic permeability behave uniquely, and this enables them to be used as parameters for evaluating the stress-strain state of the individual zones of welded joints in large-diameter pipes.

3. It has been found that the values of the field of maximum differential permeability on the field dependences correlate with the different structural states and levels of the physical-mechanical properties of the individual zones of welded joints. This can be a base for the further development of techniques for diagnosing the deviation of the structure and level of the physical-mechanical properties of a material from the required state and detecting the most dangerous welded joint zones in terms of the probability of brittle fracture.

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