Abstract: The paper presents the results of investigations of transformation plasticity of heat resistance and stainless steel during quenching. A special device was used to evaluate transformation plasticity and determine the maximum normal bending stress, modulus of transformation plasticity for high alloyed and high corrosion resistance steel. Other targets of experiments were to determine relations between magnitude of normal bending stresses and plastic deformation of test pieces, to examine influence of hardening temperature on the transformation plasticity, to calculate modulus of transformation plasticity \(E_{tr}\). Key words: Transformation plasticity, martensitic transformation, elastic and plastic deflection.

1. INTRODUCTION

Transformation induced plasticity (TRIP) effect is used for production of steels with high strength and high formability. The remarkable strength to ductility balance results form strain-induced transformation of retained austenite to martensite during plastic deformation \([1,2]\). The transformation of austenite to martensite is fundamental to the hardening of carbon steels. This transformation plays an important role for the mechanical behaviour of low-carbon ferrous alloys containing about 10 vol. % retained austenite. Results show \([3]\) that a homogeneous microstructure and the absence of initial blocky martensite ensure long deformation paths. At the same time, tensile data reveal only a small influence of deformation parameters on the ultimate strength.

Other authors suggested a microstructure-based computational model \([4]\), which can describe the transformation induced plasticity accompanying the mechanically induced martensitic transformation in metastable austenitic steel. The martensitic transformation kinetics was assumed as a nucleation-controlled phenomenon. The probability, which the nucleation site would really act, was derived for each martensitic variant as a function of the interaction energy between externally applied stress state and lattice deformation. The increase of nucleation site in the austenite due to the plastic deformation was formulated as the increase of the shear-band intersection.

The strain-induced martensitic transformation, however, strongly depends on the temperature and strain rate imposed, and an appropriate improvement of mechanical properties is realized under quite restricted circumstances. To obtain the required mechanical properties, a constitutive model which can suitably predict the deformation behaviour including transformation under a wide range of deformation rate and temperature has been developed by employing Olson and Cohen’s model for strain-induced martensitic transformation kinetics \([5]\). The possibility of the improvement of such mechanical properties of material as strength, ductility and toughness has been individually discussed \([6]\).

Experimental results show that the presence of austenite typically enhances the ductility and strength of steel \([7]\). They
use a recently developed model to analyze in detail the contribution of the martensitic transformation to the overall stress-strain response of a specimen containing a single island of austenite embedded in a ferrite-based matrix. Results show that the performance of the material depends strongly on the lattice orientation of the austenite with respect to the loading direction.

In the present work we study transformation plasticity, abnormality of steel plasticity during martensitic transformation. The main purpose of this work is to investigate kinetics of transformation plasticity behaviour.

2. EXPERIMENTAL

Tensile properties of stainless steels at low temperatures are strongly influenced by the plastic strain-induced martensitic transformation. As a result of the transformation, the initially homogeneous γ-phase looses its homogeneity due to the progressive development of the harder martensite phase. The martensite platelets embedded in the soft austenitic matrix provoke local stress concentration and block the movement of dislocations. Therefore the existence of martensite induces additional strain hardening [8]. Transformation plasticity is inverse deformation during phase transformation under low loading. During the heat treatment, accompanying with the complicated thermo-mechanics processes, transformation plasticity has great influence on the distortion and distributing of the residual stress in workpiece, so it is essential to research the transformation plasticity of the materials [9].

The tests of the transformation plasticity were accomplished by bending the steel test pieces. The load makes the elastic-plastic deflection in the specimens. The deflection of the test pieces, the content of retained austenite, and the self-deformations after tempering were measured during the investigation.

Bending test pieces (6x8x100 mm) prepared from the heat resistance and stainless steel was used for transformation plasticity analysis. Chemical composition of steel (grade according to Russian standard GOST) is given in the Table 1.

| Steel grade*  
14Cr17Ni2 | Alloying elements, % |
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>C</td>
<td>0.11-0.17</td>
</tr>
<tr>
<td>Cr</td>
<td>16-18</td>
</tr>
<tr>
<td>Ni</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Si</td>
<td>≤0.8</td>
</tr>
<tr>
<td>Mn</td>
<td>≤0.8</td>
</tr>
</tbody>
</table>

*Steel grade according to Russian standard GOST

Temperature of the test pieces were measured using weld thermocouple made of chromel-alumel; a deflection of the test pieces was tested with 0.01 mm accuracy using indicator and was recorded at choice intervals of the time. The test piece after holding in the furnace at the hardening temperature for a certain time carries out into the testing device and in 30 s loads applying bending stress.

3. RESULTS

On rising hardening temperature, temperature of beginning of martensitic transformation $M_s$ decreases, rate of plastic deformation decreases as well.

Test pieces were preheated in the electric furnace up to the temperatures 950 °C, 1000 °C, 1025 °C, 1050 °C and 1075 °C, after holding at certain temperatures test pieces were carried out into special transformation plasticity testing device. When test pieces cooled until the 600 °C – 550 °C they were loaded by defined force (normal bending stresses: 10 N/mm², 80 N/mm², 120 N/mm², 150 N/mm²) and were cooled to the room temperature (cooling rate for investigated steel was sufficient to ensure martensitic transformation). Until room temperatures test pieces cool during 12 – 15 min. In the austenitic state test pieces were bended elastically and remain in this state until reaches temperature of martensitic transformation. At the beginning
of the transformation the test piece plastically bends intensively till transformation goes on. Variation of test piece deflection was measured at the accuracy of 0.01 mm every 15s. Kinetics curves of test pieces deflection are given in the Fig. 1 and Fig. 2.

![Plastic deflection vs. time for different hardening temperatures](image1)

**Fig. 1.** Influence of hardening temperature on the kinetics of plastic deformation

The deflection due to transformation plasticity is similar to that due to elastic deformation, and simple relationships are also derived between the ratio of the maximum deflection to the elastic deflection and material constants (transformation plasticity coefficient K and Young's modulus E) \[10\].

An intensity of transformation plasticity and size of plastic deformation depend on hardening temperature.

Heated up to the 1000 °C test pieces at first deforms in opposite direction to the bending force direction. It shows, that martensitic transformation begins in the compressed part of the test piece, resulting increasing of the volume.

When used lowest normal bending stresses 10 N/mm², obtained magnitude of plastic deflection was from 0.13 mm to 0.18 mm (Fig. 3).

![Plastic deflection vs. stress for different temperatures](image2)

**Fig. 2.** Influence of normal bending stresses on the plastic deformation kinetics of the test pieces

![Plastic deflection vs. stress for different temperatures](image3)

**Fig. 3.** Dependence of plastic deflection from the magnitude of normal bending stresses

It shows, that during martensitic transformation supposed yield point \(\delta_{TV}\) is much lower than 10 N/mm² (design of
device and a friction between test piece and support during bending do not allow to determine yield point precisely. When hardened the same steel and tempered at the temperature of 630 °C and held for 6h, yield point at the 300 °C remains relatively high – 630 MPa \(^{[1]}\). On rising the hardening temperature from 950 °C up to 1050 °C, plastic deflection increases, because austenite enriches in carbon, when carbide Cr\(_{23}C\)\(_6\) dissolves (Fig. 4).

When hardening temperature was 1075 °C plastic deflection started decrease again: much more retained austenite compose in the structure.

Modulus of transformation plasticity \(E_{tp}\) as an indicator of steel plasticity under the given conditions of transformation was calculated according to expression:

\[
E_{tp} = \frac{P \cdot l^3 \cdot 9.81}{48 \cdot I_x \cdot y_{tp}}
\]  

(1)

where \(P\) is the load acting to the centre part of the test piece, N; \(l\) is the distance between bending supports, mm; \(I_x\) is the inertia momentum of the test piece, mm\(^4\); \(y_{tp}\) is the deflection of transformation plasticity during second martensitic transformation, mm.

Modulus of transformation plasticity defines the relation between acting load \(P\) and plastic deflection of double supported beam for the given materials and under the given condition.

Elastic-plastic state of the material under the given condition characterizes modulus of the elastic-plastic state \(E_{ep}\) that can be expressed:

\[
E_{ep} = \frac{P \cdot l^3}{48 \cdot I_x \cdot (y_e + y_{tp})}
\]  

(2)

where: \(P\) is the load acting to the centre part of the test piece, N; \(l\) is the distance between bending supports, mm; \(I_x\) is the inertia momentum of the test piece, mm\(^4\); \(y_e\) is the elastic deflection of the test piece, mm; \(y_{tp}\) is the deflection of transformation plasticity during second martensitic transformation, mm.

Elastic deflection of the test piece can be calculated using expression:

\[
y_e = \frac{P \cdot l^3}{48 \cdot E_T \cdot I_x}
\]  

(3)

where: \(l\) is the distance between bending supports, mm; \(E_T\) is Young’s modulus at temperature of 420 °C, N/mm\(^2\); \(I_x\) is the inertia momentum of the test piece, mm\(^4\); \(P\) is the load acting to the centre part of the test piece, N.

Using Young’s modulus of heat resistance and stainless steel we can calculate elastic deflection of the test piece \(y_e\). Plastic deflection of the test piece at the moment of the loading can be calculated:

\[
y_p = y_{ep} - y_e
\]  

(4)

where: \(y_{ep}\) is the elastic-plastic deflection of the test pieces on loading, mm; \(y_e\) is the elastic deflection of the test piece, mm.

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{Temperature, °C} & \textbf{Plastic deflection, mm} \\
\hline
950 & 22000 \\
1000 & 24000 \\
1050 & 26000 \\
1100 & 28000 \\
1150 & 30000 \\
1200 & 32000 \\
\hline
\end{tabular}
\end{center}

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{Modulus, N/mm²} & \\
\hline
2000 & 0.8 \\
4000 & 1 \\
6000 & 1.2 \\
8000 & 1.4 \\
10000 & 1.6 \\
12000 & 1.8 \\
\hline
\end{tabular}
\end{center}

\[\text{Fig. 4. Plastic deflection and modulus of transformation plasticity as a function of hardening temperature}\]

4. CONCLUSIONS

1. Heat resistance stainless steel during martensitic transformation is in a state of transformation plasticity. Supposed yield point \(\sigma_{ty}\) is lower than 10 N/mm\(^2\).
2. Transformation plasticity of heat resistance stainless steel depends on hardening temperature.
3. Magnitude of plastic deflection has a linear dependence on the magnitude of normal bending stresses.

5. REFERENCES


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