Diagnostics of heat-resistance steel hardening and dislocation structure evolution after plastic deformation

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Abstract: The properties of heat-resistance 15Kh13MF steel in conditions of application simulation of technological plastic deformations is analysis. The study steel is assigned for continuous caster rolls. Steel chemical conceptions, physical and mechanical aspects of properties controlled, and the control checking of hardness and structure evolution are analyzed. Influence of high temperature plastic deformation conditions on mechanical and plastic 15Kh13MF steel properties are reviewed.

Key-Words: - steels; hardness test; tension test; transmission electron microscopy (TEM)

1 Introduction

Bimetals, consisting of different constitutive materials are an interesting family of materials because they are capable of arresting propagating cracks under service loading [1]. The 15Kh13MF steel is extensively used in metallurgical plants and in many bimetallic caster rolls and understanding of their mechanisms of plastic deformation is extremely important. High strength properties and good draw ability of 15Kh13MF steel sheets are the function of strengthening mechanisms controlled by technological production parameters [2] such as temperature, strain, strain rate, time and chemical composition.

During the low-cycle fatigue, a cyclic deformation of steel occurs, which results in the ultimate hardening of the material with the maximum increase in the microhardness and density of dislocations within the low-angle boundaries [3]. Later on, due to the exhaustion of the material plasticity, the formation of microcracks and growth of the main crack through the whole of its section occur. It is known that the ultimate hardening of the material under cyclic loading with one-sided accumulation of strains and under static loading has the same value [2]. Hardening under plastic deformation is associated with changes in the types of the material structures that are responsible for the fracture resistance [3].

The aim of this work is to study the effect of tensile plastic deformation on the variation in the microstructural parameters of steel 15Kh13MF.

2 Materials and Investigation procedure

Specimens of 5×6×30 mm in size were cut out along the axial direction from a bimetallic body of a roll produced by centrifugal casting with alternating flowing of the layers. Steel 15Kh13MF was used as a protective layer of the continuous casting rolls, Fig. 1.

Fig. 1. Specimen cutting scheme

Chemical composition and mechanical properties of these steel at the temperatures of +20 and +600 °C are presented in Tables 1 and 2.

Table 1. Chemical composition of steel, %

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>15Kh13MF</td>
<td>0.15</td>
<td>0.6</td>
<td>0.65</td>
<td>12.2</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of 15Kh13MF steel

<table>
<thead>
<tr>
<th>Steel</th>
<th>T, °C</th>
<th>E×10^5 MPa</th>
<th>σYS, MPa</th>
<th>σUS, MPa</th>
<th>δ5, %</th>
<th>ψ, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>15Kh13MF</td>
<td>20</td>
<td>1.81</td>
<td>338</td>
<td>456</td>
<td>6.0</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>1.31</td>
<td>242</td>
<td>334</td>
<td>24.2</td>
<td>56.6</td>
</tr>
</tbody>
</table>
Specimens were subjected to uniaxial tension loading at a temperature of +600 °C. Tests were performed on a STM-100-type servo-hydraulic machine equipped with an IBM computer. The longitudinal strain of the specimen and force were measured during the experiment.

The specimen microstructure was studied on a TEM-125K-type transmission electron microscope using the thin-foil method. Objects for microstructural studies were cut out from specimens in the longitudinal direction. The final thinning of the objects was achieved by the method of jet electrolytic polishing of foils in the electrolyte composed of 10% of HClO₄ +90% of CH₃COOH at a voltage of 140 V and current of 90 mA. According to the analysis of microdiffraction patterns, the change in the dislocation density within the low-angle boundaries under conditions of tensile deformation was calculated. At least 25-30 microdiffraction patterns were analyzed for each of the points. For the objects cut out of neck areas of the specimens fractured under tension, the actual necking \( \psi \) was calculated according to the formula [6]:

\[
\psi = \ln\left(\frac{F_0}{F_k}\right)
\]

where \( F_0 \), \( F_k \) are the initial and current cross-section areas, respectively.

3 Effect of Plastic Deformation on the Changes in the Dislocation Structure of the Material

Steel 15Kh13MF of the protective layer belongs to ferritic-martensitic steels. The microstructure of steel 15Kh13MF is a lath dislocation martensite (Fig. 2a), which also contains a great part of the ferrite, “massive” inclusions and carbide precipitate (Fig. 2b) and dispersed precipitate (Fig. 2c). The presence of the extinction contours on the electronic-microscopic pictures (Fig. 2a,b,d) is indicative of the presence of dislocations of the same sign that cause a local bending of the foil [2, 6].

Breakdowns in the extinction contour lines (Fig. 2d) testify to jump-like changes in the local orientation of the crystal lattice [7].

Martensitic areas of the structure are the dislocation lath martensite wherein “massive” inclusions, carbide precipitate and dispersed precipitate are observed. Parallel laths of martensite form the martensite plates. The plated structure is characterized by a system of parallel laths of various sizes. The angle of disorientation between the neighboring laths of the martensite in a plastically nondeformed material determined by the microdiffraction method is roughly 3°.
e) microcracks and pores \((\times 40000\) magnification); f) microdiffraction.

Inside the martensite laths, a high density of dislocations takes place. These dislocations being taken individually hardly differ and have a spotty contrast. The areas of the martensite laths with a lower dislocation density appear brighter in the photographs. At a high magnification \((\times 80000\) magnification), Fig. 2c shows the area of the dislocation structure with a spotty contrast and dispersed precipitate. Here, the image contrast due to dislocations is difficult to differ from that due to dispersed precipitate. Such contrast that is responsible for a blurred image of dislocation lines is likely to be due to the presence of the considerable concentration of impurity atmospheres on dislocations [8]. Thus, the peculiar features of the image are indicative not only of the considerable density of dislocations but also of their essential pinning by impurity atmospheres and the processes of redistribution of alloying elements as well, which results in the formation of precipitates. The presence in the ferrite of carbide inclusions that are the effective barriers on the way of dislocation movement also affects the mechanical properties of steel 15Kh13MF (Fig. 2b).

Thus, the mechanical properties of steel 15Kh13MF in the initial state are conditioned by the presence of dislocation boundaries of the lath martensite, a considerable density of dislocations in plates, pinning of dislocations by impurity elements and dispersed precipitates, blocking of dislocation movement by inclusions.

After tensile deformation, certain changes in the morphology of the dislocation structure were detected, which consist in the increase of the nonparallel alignment of dislocation subboundaries and decrease in the distance between the subboundaries (Fig. 2d). The martensite grain size reduction and increase in the fragmentation of laths of the dislocation martensite were revealed. The presence of numerous reflections and their blurring in the microdiffraction pattern are indicative of the decrease in the distance between low-angle boundaries (Fig. 2f). An increase in the width and angle of disorientation of diffraction reflections with respect to the central reflection was observed, which is indicative of the disorientation of subboudaries of the ferritic-martensitic structure and laths of the dislocation martensite as compared to the initial state of the material. With an increase in the plastic strain (necking \(\psi\)), the angular disorientation between diffraction reflections increases and accordingly the dislocation density within the low-angle boundaries increases [9].

At high \(\psi=0.30\), the formation of microcracks and micropores was observed near inclusions due to separation of the inclusion from the matrix or as a result of breakdown of inclusions, which are the result of the accumulation of the limiting dislocation density and exhaustion of the material plasticity (Fig. 2 e). Since the dislocation density increases in the process of plastic deformation and inclusions are effective barriers on the way of dislocation movement, the dislocation density in local volumes reaches the boundary value, which results in the separation of inclusions from the matrix or the breakdown of inclusions and formation of microcracks and pores.

### 4 Evaluation of Hardening of Steels Using the Methods of Hardness (Microhardness)

The increase in the hardness of steels due to strain hardening is explained mainly by two reasons: the formation of the intragranular substructure that fulfils the role of additional barriers and the increase in the disorientation of the boundaries of the structure components existing in the initial state of the material [10].

Thus, the effect of the tensile plastic deformation
of the steels under investigation at a microstructural level consists in the increase of the density of dislocations within the low-angle boundaries, increase of disorientation of the subgrain structure, decrease in the distance between the low-angle boundaries (structural element size reduction). The above factors give rise to the distortion of the crystal lattice of the material and result in the formation of substructural barriers to dislocation movement, which intensifies the process of metal hardening, table 1.

Table 1. Parameters of hardening

<table>
<thead>
<tr>
<th>Steel</th>
<th>Actual necking, ( \psi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>15Kh13MF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>( H_p ) MPa</td>
<td>2080</td>
</tr>
<tr>
<td>HRB</td>
<td>74</td>
</tr>
</tbody>
</table>

Plastic deformation causes an increase in the number of dislocations in the material; the resistance to their migration increases. The engineering evaluation of the hardening processes can be made using the method of hardness (microhardness) which also characterizes the deformation capacity of the material [11]. The data on the hardness (microhardness) measurements for steel 15Kh13MF at various levels of plastic strain (the actual necking \( \psi \) of specimens) is presented in Table 1.

Conclusions

The effect of the tensile plastic deformation at a temperature of +600 \(^\circ\)C on the microstructure, dislocation density within the low-angle boundaries, hardness and microhardness of steel 15Kh13MF after deformation was investigated.

It has been found that in the ferritic-martensitic steel 15Kh13MF under conditions of plastic deformation, the out-of-parallelism increases and the distance between the subboundaries of the dislocation structure decreases, laths of the dislocation martensite are divided and fragmented. This is caused by the insufficient plasticity of laths of the lath martensite that serve as additional barriers capable of retarding the movement of dislocations.

Acknowledgement

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References: