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# Gradient structure formation in the process of severe plastic deformation of carbon steels under the conditions of the effect of dynamic strain aging

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**Abstract**. The formation of a gradient structure during the severe plastic deformation (SPD) by high-pressure torsion (HPT) of low- and medium-carbon steels under the influence of dynamic strain aging (DSA) is studied. Deformation mechanisms under various regimes of deformation processing are analyzed. The temperature ranges of the DSA effect during the ECAP processing of steel 10 and the fact of the formation of a gradient structure during the HPT processing under these conditions are established. It is shown that the deformation of carbon steels in the DSA temperature range enables controlling the structure of the deformed state.

## 1. Introduction

In recent years, a new field of research has emerged and is being developed – the study of gradient structural states in metallic materials. Research results demonstrate that the presence of a gradient structure enables rendering new, unprecedented properties to a material [1-5]. This structure combines a hard corrosion- and wear-resistant surface and a relatively «soft» core, which enables redistributing the loads and relaxing the stresses [5-6].

In this work, we make an attempt to study the features of the formation of a gradient structure under conditions of dynamic strain aging (DSA) during severe plastic deformation (SPD) of low- and medium-carbon steels by high-pressure torsion in the temperature range of DSA.

## 2. Material and experimental procedure

As materials for the study, we selected low-carbon steels 10 and 20, and medium-carbon steel 45, having standard chemical compositions [7]. Samples of the steels in the form of disks with a diameter of 10 and 20 mm and a thickness of 0.5 mm were subjected to high-pressure torsion (HPT) under a pressure of 6 GPa at temperatures of 20, 250 and 400 °C. For this purpose, a die-set similar to that described in [8, 9] was used,

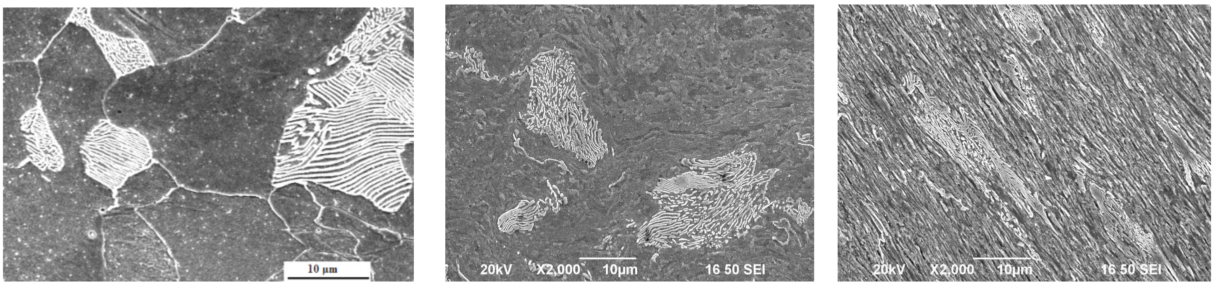
HPT processing was performed for 5 revolutions, and the logarithmic strain in the middle of the radius was $\varepsilon \approx 3.45$. After processing, the microhardness of these samples was measured, and their microstructure was studied using light and electron microscopes. Samples of steel 10 were subjected to severe plastic deformation by HPT at 20, 250 and 400 °C, and samples of steels 20 and 45 were subjected to HPT at 20 and 400 °C.

After processing, the microhardness of all samples was measured, and their structure was studied using light and electron microscopes.

## 3. Experiment results

### *3.1. HPT processing of steel 10*

The structure of steel 10 in the initial state represents ferrite grains with sizes of ~ 9-13 μm and pearlite grains with sizes of ~ 1=5 μm. Figure 1 shows the microstructure of steel 10 in the initial state and after 5 revolutions of HPT. As can be seen, the pearlite grains in the central region of the samples retain the equiaxed shape, but in the peripheral regions both the ferrite and pearlite grains are severely elongated along the direction of metal flow, and the strongest structure refinement takes place. Cementite plates in pearlite are, as a rule, fragmented in both the central and peripheral regions of the samples.




(a) (b) (c)

**Figure 1.** Microstructure of steel 10: a – initial state, b, c – 5 revolutions of HPT at 20 °C, b – central region of the samples, c – peripheral region. SEM.

Figure 2 shows the microhardness distribution along the diameter of the samples of steel 10 after HPT at different temperatures. It can be seen that the microhardness of the steel after HPT at 20 °C is lower than that after HPT at 250 and 400 °C. HPT processing at 250 °C leads to a more profound strengthening of the material in the peripheral region of the sample, while HPT processing at 400 °C results in a nearly uniform strengthening of the steel along the sample diameter. The microhardness in the central region of the sample (with a diameter not exceeding 2 mm), processed at 400 °C, is higher than that after processing at 250 °C.

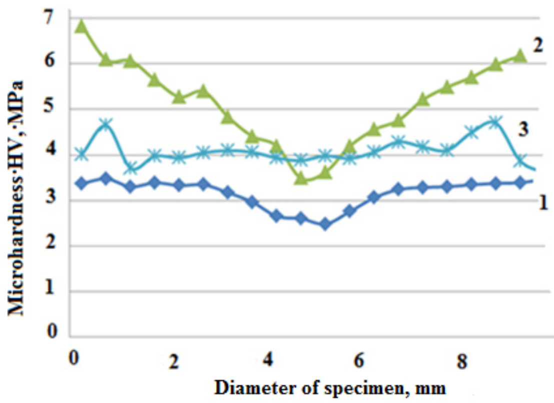


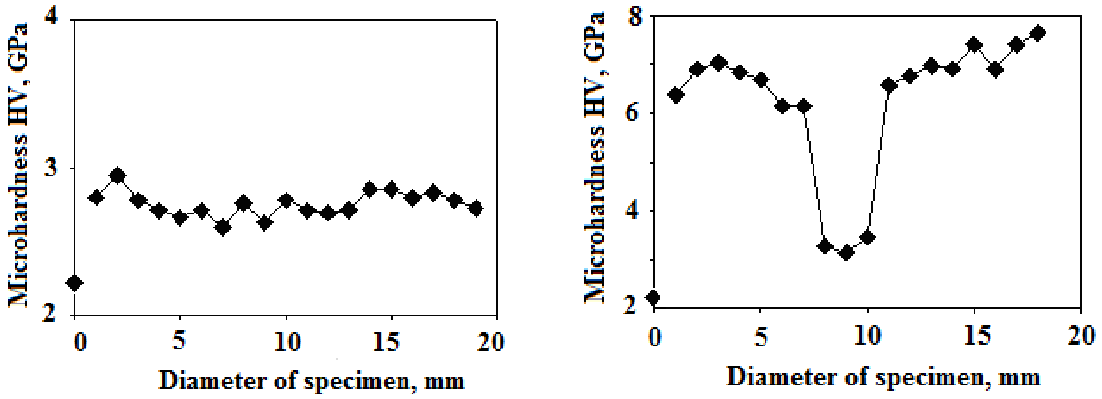

**Figure 2.** Microhardness of steel 10 along the diameter of disk-shaped specimens after 5 HPT revolutions: 1 – 20 °C, 2 – 250 °C, 3 – 400 °C.

This combination, observed in the studied samples, of the ultrafine-grained structure in the peripheral regions of the samples and the relatively coarse-grained structure in the central region after the HPT processing is in essence the gradient structure [10-14].

### *3.2. HPT processing of steel 20 and steel 45*

The structure of the steels in the initial state consists of ferrite grains with a size of ~ 15-25 μm and pearlite grains with a size of ~ 0.5-20 μm. The volume fraction of a pearlite in the investigated steels 20 and 45 is, respectively, ~ 25% and 60%. The average microhardness value of steels 20 and 45 in the heat-treated condition was 2200 and 2450 MPa, respectively.

Figure 3 displays the HV microhardness values along the diameter of the steel 20 samples. A similar microhardness distribution along the sample diameter is also observed in steel 45.




(a) (b)

**Figure 3.** Microhardness distribution along the diameter of the steel 20 specimens after HPT at 20 °C (a) and at 400 °C (b).

Microstructural analysis shows that after the HPT processing of steels 20 and 45 at a temperature of 20 °C there is observed a slight grain refinement, which is more noticeable at the periphery of the samples. The shape of grains at the periphery is close to equiaxed. The microhardness distribution along the diameter of the samples is rather non-uniform and increases after HPT processing approximately by 20% as compared to the initial state, amounting to 2.7 GPa.

Thus, severe plastic deformation of low- and medium-carbon steels in the temperature range of dynamic strain aging results in an increase in the yield stress and the strain hardening parameters, primarily owing to the decrease in the size of structural elements, as well as the additional influence of the second-phase particles. This contributes to the formation of the gradient structure and properties in the investigated steels.

## 4. Conclusions

1. We considered the features of the gradient structure formation during the processing by high-pressure torsion of steel 10, steel 20 and steel 45 in the conditions of the effect of dynamic strain aging. We analyzed the role of activation of diffusion processes during the SPD processing.

2. We studied the structural changes occurring in the steels during the processing by high-pressure torsion in the temperature range of the effect of dynamic strain aging and, correspondingly, the formation of a gradient structure in the steels. The formation of the gradient structure is promoted by the activation of the DSA effect.

3. As a result of the DSA effect, in the process of severe plastic deformation, there occurred a further structure refinement in the alloys and, consequently, a larger increase in the yield stress and microhardness, as compared to the samples processed at room temperature.

4. We analyzed the mechanisms of plastic deformation leading to the formation of a gradient structure during the processing of steel 10 by high-pressure torsion – this is the shear strain leading to the activation of dislocation slip and the interaction of dislocations with impurity atoms, as well as the development of rotational deformation modes and the diffusion processes of carbon atoms redistribution.

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