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TAILORING THE GRADIENT ULTRAFINE-GRAINED STRUCTURE IN LOW-CARBON STEEL DURING DRAWING WITH SHEAR

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Conventional drawing and drawing with shear were conducted on the rods of low-carbon steel. Deformation by simple drawing forms basically a homogenous structure and leads to a uniform change in microhardness along the billet volume. A comparative analysis of the models of these processes showed that shear drawing of steel at room temperature reduces energy characteristics in half, normal forces on the die – by 1,8, and enhances the strain intensity from 0,5 to 1,6. During drawing with shear, strain-induced cementite dissolution occurs and a gradient structure is formed, which increases the microhardness of the surface layer up to values close to 7 000 MPa.

Keywords: low-carbon steel, drawing with shear, gradient structure, severe plastic deformation

INTRODUCTION

Severe plastic deformation (SPD) is one of the most effective techniques to enhance the physical and mechanical properties of metallic materials via refining the structure to obtain the ultrafine-grained (UFG) and nanocrystalline (NC) states. For the formation of UFG and NC structures, complex deformation schemes are usually used: high-pressure torsion, equal-channel angular pressing, twist extrusion, etc. [1-3]. Despite the differences in loading conditions, all these schemes have one thing in common – the structure is refined due to active shear deformation of the metal under the combined effect of compression and tension. Further development of SPD techniques implies the elaboration of combined loading schemes with a mandatory use of shear deformation.

The most well-known and widespread scheme of simple shear is free torsion [4]. Combining the scheme with reduction may be

promising to disperse the structure and, as a result, to enhance mechanical properties.

In recent years the methods of surface deformation treatment have been provoking interest. Among them are the known methods of forging [5], surface friction [6], ultrasonic treatment [7], and others, and also the methods developed not so long ago – ECA broaching and shear drawing [8, 9].

In this regard, in the present paper there was set a task to study the influence of two different loading schemes – conventional drawing and shear drawing – on the change in the deformation intensity and corresponding transformation of the structure that occurs in low-carbon steel under this treatment, and also to determine the relationship between these changes and mechanical characteristics.

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THE MATERIAL AND METHOD

In order to solve this problem, we propose to perform an assessment of the severe plastic deformation intensity using numerical modeling, which would allow comparing the calculation results with the observed changes in the structure and properties.

As the material for research, we used low-carbon as-received steel 10 (with ~ 0,1 % C) in the form of a calibrated bar of 10 mm in diameter according to GOST 10702-78. In the development of a numerical model the rheological properties of steel 10 were chosen as recommended in [10].

The application package DEFORM™3D was used to implement numerical simulation. In order to conduct modeling in the application package DEFORM™3D, three-dimensional models were created in the software product Kompas-3D.

Conditions accepted for modeling.

1) The billet material in the initial state is isotropic and has no initial stresses
2) The temperature was taken as fixed 20 ºC;
3) The tool is an absolutely rigid body,
4) The billet is a plastic body;
5) 150 steps were taken for modeling that register a full pass of the bar;
6) The number of finite elements is 55000;
7) The friction between the tool and the billet was taken as 0,12;
8) The drawing rate – 0,95 mm/s;
9) The degree of deformation per one pass during drawing is 15 ... 20 %;
10) The rate of the drawing die rotation is 500 min^{-1};

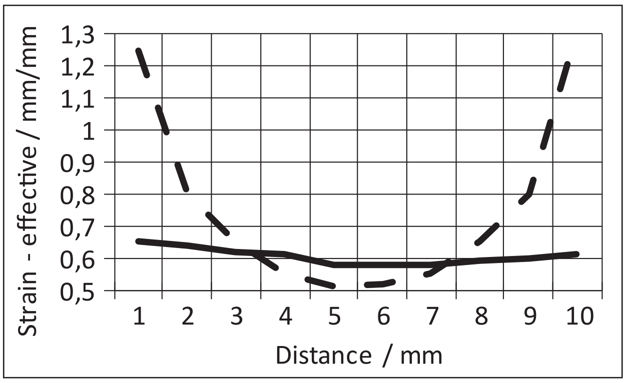

Figure 1 Distribution of strain intensity in cross section: —— conventional drawing, – – – drawing with shear

11) The degree of deformation per one pass is 15 ... 20 %.

For the tests we used a drawing machine capable of conducting shear drawing through the drawing nozzle.

RESULTS AND DISCUSSION

Investigation of the nature of strain intensity distribution showed that after drawing this distribution is relatively uniform (Figure 1). At the same time, after shear drawing the strain intensity is distributed non-uniformly, it reaches $\varepsilon \approx 1,6$, which indicates of a more intense deformation impact on the specimen during shear drawing. The highest metal deformation, associated with the geometry of drawing dies and the method of their rotation about the drawing axis, is observed in the near-surface layer of the billet.

Graphs in Figure 1 show that per one cycle of drawing with shear it is possible to obtain a substantially higher strain intensity and, consequently, increase the productivity of the manufacturing process of high-strength elongated articles due to effective submicrocrystalline structure formation. The modeling results lead to the following conclusions: during drawing with shear the accumulated strain intensity reaches 1,6. At the same time, the drawing forces are reduced almost in half, the deformation non-uniformity increases significantly and normal forces on the tool decrease by 1,8 times.

Rods made of steel 10 were subjected to two types of deformation treatment – conventional drawing and drawing with shear. During the investigation, the effectiveness of the deformation impact on the structure during conventional drawing and drawing with shear was compared. The loading schemes were selected so that in the future there would be a possibility to analyze structural and strength changes in the implementation of two different deformation types – compression with shear (during drawing) and compression with shear and rotation (during shear drawing).

The conventional drawing was carried out in several passes on the drawing machine with a force of 30 KN with a diameter decreasing stepwise from 10 mm to 7 mm. The shear deformation was also conducted on a drawing machine with an attachment for the die rotation.

The deformation by drawing was calculated using the formula –

$$\varepsilon = [(S_o - S_1)/S_o] \times 100\ \%,$$

where S_o is the cross-sectional area of the rod prior to drawing, S_1 - after drawing [11-12].

To determine the features of the material's microstructure in the initial and strained states, a metallographic analysis was performed on a light and scanning electron microscopes. The average grain sizes, the features of the ferrite cellular and dislocation structure were determined, the size and distribution of Fe_3C particles were estimated. Besides, the HV microhardness was measured at a load of 1 N and a holding time of 10 s in the cross section of the rods before and after straining. The measurement error did not exceed 8 %.

In the cross section of the rods of the alloy in the initial state, mainly equiaxed ferrite grains with relatively straight-line boundaries and average sizes of $d \approx$ 12 – 13 μm are observed. Along the boundaries of ferrite grains, chaotically distributed are globular, often somewhat elongated into chains, particles of Fe_3C cementite (degenerate pearlite [13]) of an indefinite shape with sizes of $d_{Fe3C} \sim 0,2 – 3,0$ μm (Figure 2a). The density of particle distribution in the cross section of the rods is relatively non-uniform, and amounts to ~ 1,2 particles per 100 μm^2, their volume fraction lying within a range of 2,5 ÷ 3 %.

In the process of deformation, significant structural changes take place in steel 10, which have essential differences depending on the type of deformation processing. While studying the structure in the cross section of the processed billets after 5 passes of deformation by simple drawing, it was established that the alloy's structure is relatively homogeneous, the grains (of ferrite) are non-equiaxed, often bent, the boundaries are tortuous, the grain sizes are equal to $d_{g.} \sim 7,5$ μm. The Fe_3C particles, like in the initial state, are located mainly along ferrite grains and their shape and sizes practically have not changed. In the central and peripheral regions of the processed rods, the alloy's microstructure is, on the whole, identical.

While after conventional drawing the alloy's microstructure is practically homogeneous throughout the whole volume of the rod, after drawing with shear there is obvious non-uniformity in the distribution character and morphology of ferrite grains and Fe_3C particles in the cross section of the rod.

In the near-surface, heavily deformed region of the rod (zone L_1 in Figure 2b), numerous finely-dispersed Fe_3C particles with sizes of, mainly, 0,1 ÷ 0,4 μm with an extremely non-uniform distribution density are observed.

In the so-called transition zone with a fibrous structure consisting of strongly elongated twisted ferrite grains (zone L_2 in Figure 2b), the distribution density and quantity of cementite particles approach zero.

The Table 1 lists the results of microhardness measurements in the cross section of the rods from steel 10 in

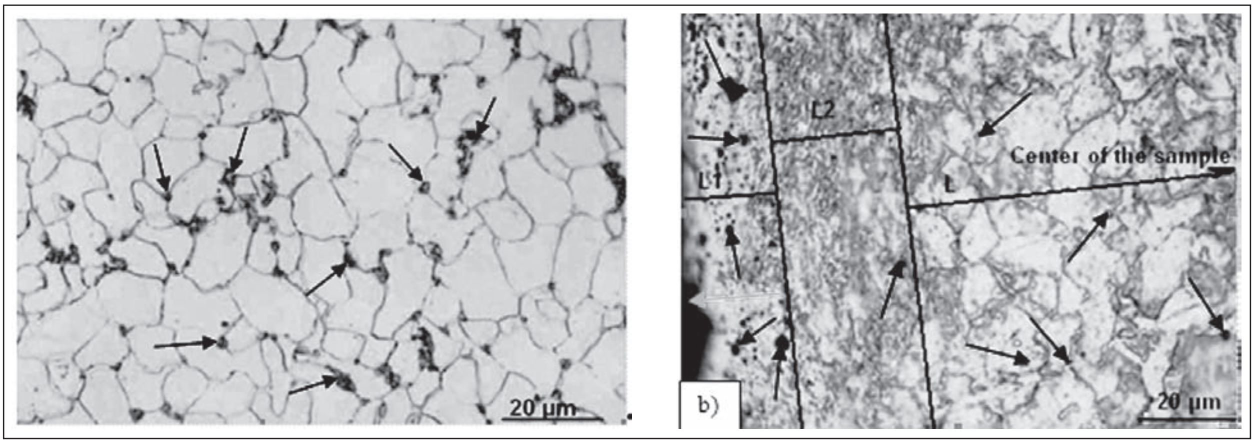

Figure 2 Microstructure of steel 10: a) initial state; b) gradient microstructure in the peripheral region of the sample after drawing with shear. L_1 is a heavily deformed near-surface region with a width of ≈ 25 µm; L_2 is the transition region with a width of ≈ 35 µm. L is a comparatively weakly deformed region with a width of ≈ 160 ÷ 220 µm. The zones with various deformation degrees (L_1, L_2, L) are conventionally divided by lines. The red arrows indicate the particles of Fe_3C cementite. The blue arrow indicates the lateral surface of the rod. Light microscopy

the initial and processed states. After conventional drawing, with increasing strain (number of passes) the HV values increase practically uniformly across the whole section of the rods.

Table 1 **Microhardness changes in the cross section after processing by different deformation schemes**

State of the sample	Microhardness HV MPa (cross section)	
	In the center	On the surface
Initial	1 900 – 2 000	1 900 – 2 000
Drawing 5 passes	2 650 – 2 750	2 650 – 2 750
Drawing with shear	2 700	6 960 ± 310

Both in the model and in the actual experiment, it was established that straining of the billet by drawing with shear leads to an essential structure inhomogeneity – the formation of the so-called gradient structure and, as a consequence, a gradient of the mechanical properties from the rod center to its surface.

The observed microstructural changes in the size and distribution character of cementite particles indicates the activation of diffusion processes of dissolution of Fe_3C particles, present in the alloy in the initial state, followed by the precipitation of new cementite particles in the near-surface heavily deformed region of the rod (zone L_1) during drawing with shear.

Similar processes of cementite dissolution during SPD processing were observed by the authors of the papers [14-18]. The given process is to a certain extent similar to the coagulation of second-phase particles in alloys, when larger precipitates increase due to the dissolution of smaller ones [13, 19]. It is evident that this «pumping out» of carbon atoms from the region L_2 to the region L_1 leads to a decrease in the concentration of dissolved carbon atoms to an equilibrium one, which eliminates the causes for formation of new cementite particles.

The abnormally high value of microhardness on the surface of the rods after drawing with shear is evidently conditioned by the presence of both a high density of dispersed cementite precipitates in the zone L_1 and a high density of structural defects (boundaries of grains, subgrains, dislocations, etc.).

CONCLUSIONS

– Deformation by simple drawing forms basically a homogenous structure and, accordingly, leads to a uniform change in microhardness throughout the billet volume.
– A comparative analysis of the models of shear drawing and conventional drawing has shown that shear drawing of steel 10 at room temperature reduces energy characteristics in half, normal forces on the die – by 1,8, and enhances the strain intensity from 0,5 to 1,6.
– During drawing with shear a gradient structure is formed, which increases the microhardness of the surface layer up to values close to 7 000 MPa. Also, strain-induced cementite dissolution of the initial dispersed cementite particles and formation of new ones occurs during cold plastic deformation of low-carbon steel.

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