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EFFECT OF ASYMMETRIC ROLLING WITH CONE-SHAPED ROLLS ON MICROSTRUCTURE OF LOW-CARBON STEEL

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Effect of asymmetric rolling with cone-shaped rolls (ARCSR) on the evolution of microstructure of low-carbon steel was investigated. Steel containing 0,15 % C (wt. %) billet with initial grain size of 60 μm was deformed up to thickness of 5 mm with diameters ratio of 1,5, as well as in cylindrical rolls. Rolling was conducted at three different temperatures: 900 °C, 1 000 °C and 1 100 °C. Final thickness is obtained through four passes of ARCSR with total reduction of 61,7 %. It has been shown during ARCSR at 900 °C grain size is relatively smaller (0,092 μm – surface layer and 0,112 μm – middle layer).

Key words: rolling, steel, microstructure, properties, asymmetric

INTRODUCTION

Ultrafine grain (UFG) size in metals and alloys is known for its positive effect on their mechanical properties. Severe plastic deformation (SPD) has been employed during several last decades to impose intensive shear strains at relatively low temperature but mainly was limited by small dimensions of specimens used in processes such as equal channel angular pressing (ECAP) [1], high-pressure torsion (HPT) [2] etc. Asymmetric rolling is well-known SPD process for its potential to induce intensive shear strain throughout the thickness of the specimen of unlimited length [3] so that it allows formation of uniform UFG structure. Special attention should be given for asymmetric rolling in cone-shaped rolls [4] that imposes different roll diameter ratio throughout the length of the rolls. Authors [4] used rolling in cone-shaped rolls to deform 1070 aluminium sheet. Distinguishing feature of this technique is the shear strain distribution character across the width of the specimen rolled when inserts introduced in left and right portion of the specimen after deformation inclined in inverse direction to one another depending on locations of maximum and minimum diameters.

Most of the results of investigation on low-carbon steel were obtained with asymmetric rolling using cylindrical rolls with different diameters [5 - 9].

In this paper the formation of UFG structure in low-carbon steel deformed in cone-shaped rolls with a roll size ratio of 1,5 was investigated.

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EXPERIMENTAL PART

Equipment and tools

In this study two-high rolling mill with one-shaped rolls was used. The specification of the rolling mill and technological scheme of rolling and heating processes are given in Tables 1 and 2.

Table 1 **Specification of the rolling mill**

Type	Two-high
Motor power	7 kW
Roll dimensions	Max. dia. 50 mm Min. dia. 33,3 mm Av. dia. 41,65 mm Body length 105 mm
Roll material	41Cr4
Roll surface	Notched

Table 2 **Rolling and heating conditions**

Rolling	Asymmetric; Symmetric
Number of passes	3
Total reduction	61,7 % (10 mm - 5 mm)
Heating temperature	900 °C; 1 000 °C 1 100 °C
Specimen turning	180 ° after first pass - 180 ° after second pass

Materials and methods

The chemical composition of low-carbon steel used in this study is given in Table 3. A 10 × 45 × 100 mm as - received hot - rolled billet with initial grain size of about 60 μm was asymmetrically rolled at 900 °C, 1 000 °C and 1 100 °C in cone-shaped rolls with roll diameter ratio of 1,5 and reduction ratios of 18,7 %, 20 % and 23 %. The final thickness of 5 mm was reached after 3 passes with interim heating the specimens. According to [4] the specimen was rotated and reversed after each pass to keep the shear strain unidirectional. For comparison purpose the specimen rolled with cylindrical rolls was deformed in the same conditions. Shear strain introduced across the thickness in the rolling direction (RD) was measured by the inclination of inserts screwed parallel to the normal direction (ND) (Figure 1).

Table 3 **The chemical composition of the low-carbon steel / wt. %**

C	Si	Mn	Ni	S	P
0,151	0,210	0,556	0,231	0,011	0,015
Cr	N	Cu	As	Fe	
0,217	0,0012	0,186	0,032	Bal.	

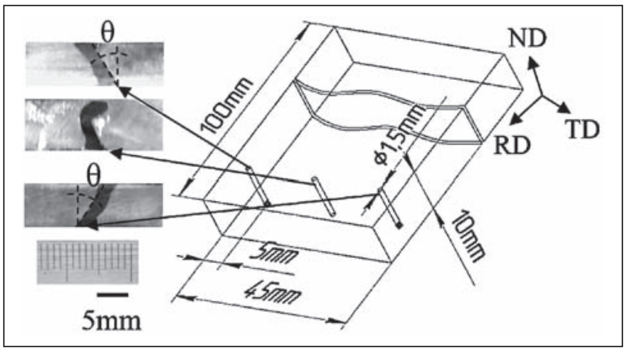

Figure 1 Schematic illustration of the initial shape of the specimen with inclined inserts after three passes of rolling: θ – shear angle; ND, TD, RD – normal direction, transversal direction and rolling direction respectively

In order to observe the microstructure of the specimen Optical Microscopy and Scanning Electron Microscopy were used. The metallographic samples were taken from the specimen in transverse direction TD and ND-RD plane.

RESULTS AND DISCUSSION

Equivalent strain

The equation for asymmetric rolling derived by the authors [10] is used for measuring the equivalent strain:

$$\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_{yy}^2 + \frac{1}{4}\gamma_{yz}^2}\,, \qquad (1)$$

where: ε_{yy}^2 - compressive strain in ND / $\varepsilon_{yy} = \ln\left(\frac{H_1}{H_0}\right)$; H_1 and H_0 – final and initial thicknesses / mm; γ_{yz}^2 - shear strain in ND-RD plane / $\gamma_{yz} = \frac{\lambda}{H_1} = \tan\theta$; λ - adjacent side; θ - inclination angle of the insert after asymmetric rolling in cone-shaped rolls / grad.

According to the inserts inclination angle (Figure 1) the equivalent strains distribution throughout the thickness in three sections of the specimen is calculated using the Equation 1 and summarized in Figure 2.

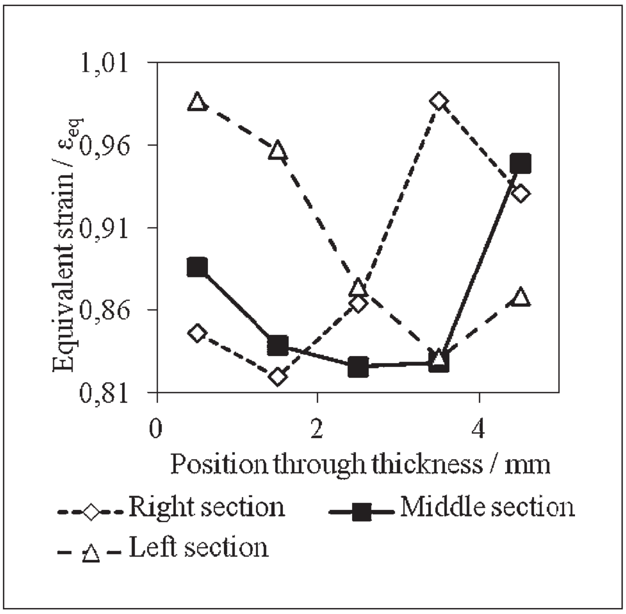

Figure 2 The equivalent strain distribution across the thickness of the specimen

As it can be seen from Figure 2 shear strain imposed in the lateral sides of the specimen by the rolls with different diameters is higher than that of the middle plane (solid line in Figure 2) where the rolls diameter is equal. However, in case of right and left planes the shear strain is decreasing toward the smaller diameter side and conversely increasing toward the larger diameter side. In the middle plane the strain character is comparable with rolling in cylindrical rolls with lower degree of shear strain in the central layer.

Microstructure

Figure 3 shows micrographs of specimen after three passes of asymmetric rolling in cone-shaped rolls at different temperatures.

As it is shown in Figure 3 the finest grain size – 0,092 μm in surface region and 0,112 μm in the central region obtained at temperature of 900 °C. While two other temperatures of 1 000 °C and 1 100 °C grains are also refined but less intensively in comparison with 900 °C. This can be explained by higher tendency to dynamic recrystallization at higher temperatures above 1 000 °C.

The graphic of grain size evolution during asymmetric rolling in cone-shaped rolls at different temperatures is plotted in Figure 4.

Figure 4 demonstrates that at the reduction of 20 % (2nd pass) the grain size in central region dramatically decreased up to 64 % from original size to 17,1 μm at temperature of 1 000 °C and to 50 % to 20 μm in surface region respectively. The smallest grain was observed in surface region after reduction of 23 % at 900 °C (0,092 μm).

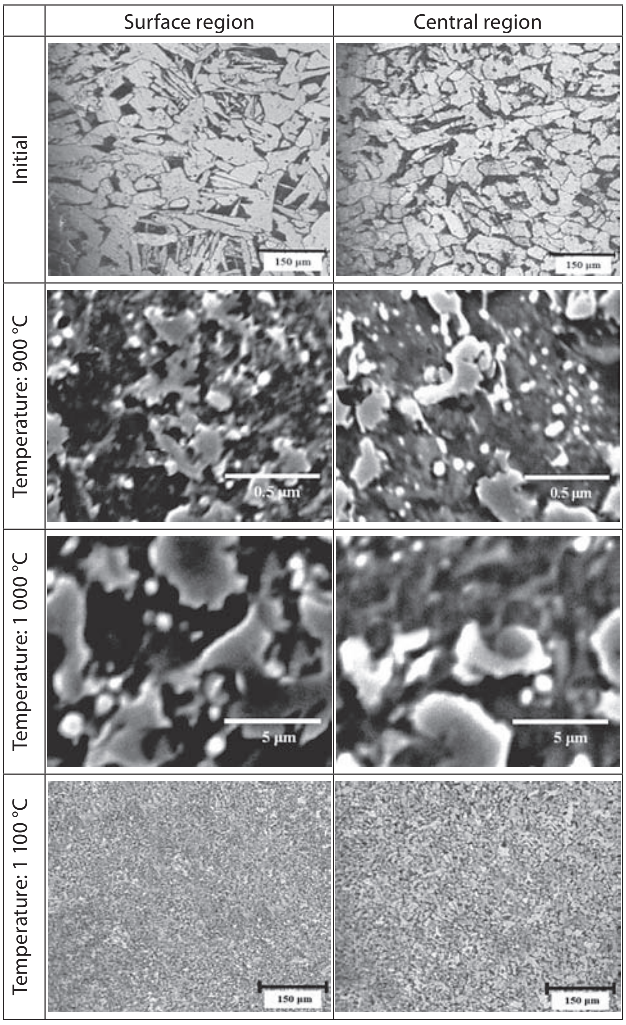

Figure 3 Microstructure of low-carbon specimen after three passes of asymmetric rolling in cone-shaped rolls at different temperatures

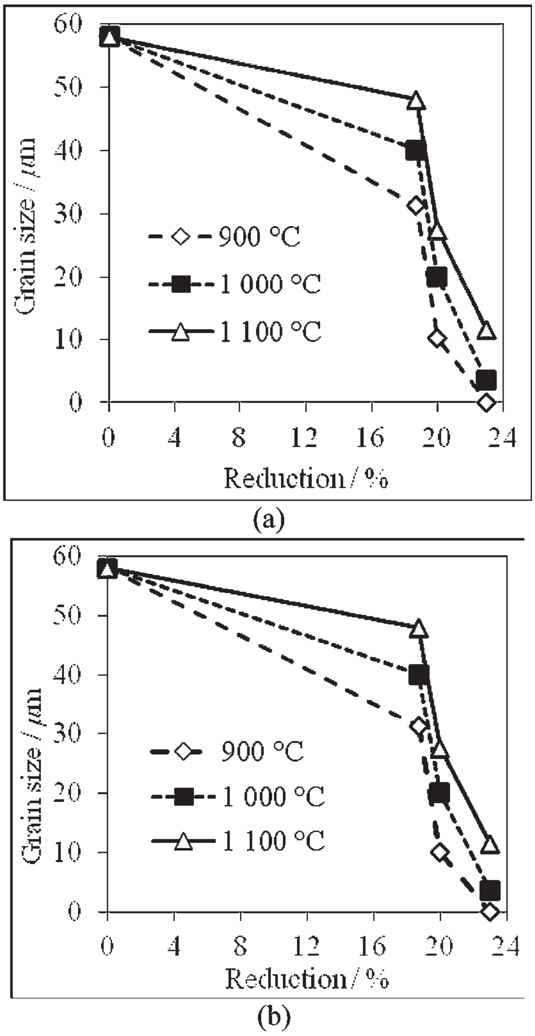

Figure 4 Grain size evolution during asymmetric rolling in cone-shaped rolls at different temperatures in (a) central region and (b) surface region

Non-uniform distribution of grains during the asymmetric rolling may have been resulted by the unidirectional shear straining when the specimen rotated and reversed to initial position around the ND axis to 180 ° so that the shear imposed to the specimen intensively developed pass after pass that lead to formation of this non-uniformity at the central region.

Noteworthy that at relatively low temperature of 900 °C the grain is severely refined up to UFG level.

CONCLUSIONS

In the present study, microstructure and tensile properties of low-carbon steel plate deformed in cone-shaped rolls were investigated. The results are summarized as following:

– The equivalent strain measurement using inserts introduced in the body of the specimen and finally inclined after being rolled in cone-shaped rolls demonstrated intensive shear strain across the thickness of the specimen on the left and right side and less intensive shear strain in the middle section of the specimen. Furthermore, the direction of inserts inclination on both sides is inverse which is mainly concerned with the diameter ratio.

– Microstructural observations revealed the non-uniformity of grain size distribution across the thickness of the specimen with larger grains in the central region of the specimen during asymmetric rolling in cone-shaped rolls and smaller grains up to UFGs in surface region. Effect of temperature on microstructural development was also investigated and it was shown that at 900 °C the grain size is 0,092 μm which is in the range of UFG size.

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