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STRUCTURE FORMATION OF ALUMINUM ALLOY D16 WHILE ROLLING BARS IN THE RADIAL SHEAR MILL

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This article presents a new method of obtaining bars from aluminum alloys D16 with ultrafine-grained (UFG) structure. The ultrafine-grained structure is obtained by implementing severe plastic deformation developed by a radial-shear mill (RSM). This paper investigates the stress-strain state (SSS) of the workpiece during rolling in a radial-shear mill. The (FEM) and the MSC Super Forge program allowed us to obtain quantitative data and establish the main laws of the distribution of SSS and temperature while modeling the rolling in the RSM. The rational technology of rolling aluminum alloy D16 was developed and tested in laboratory conditions. Particular attention is paid to the analysis of the effect of rolling conditions in the RSM on the formation of UFG structures in the aluminum alloy D16.

Keywords: aluminum alloys, rolling on a radial-shear mill, temperature, intensity of stresses and strains, ultrafine-grained structure.

INTRODUCTION

In recent years, methods of intense plastic deformation (IPD) [1] have been widely used as various types of equal-channel angular pressing; accumulated rolling; screw extrusion; broadening extrusion; comprehensive forging, etc., which made it possible to us to sharply crush the structure of metals and alloys and regulate their properties [2]. The IPD methods are carried out with a high level of accumulated deformation ($\varepsilon \geq 4 - 8$). The experimental and theoretical studies which were carried out so far on the deformation behavior of metals and alloys have clearly demonstrated the positive role of IPD. Using these unconventional methods, it is possible to deform the workpiece without changing the cross-section and shape, and achieving the necessary high degrees of deformation as well as preparing the structure for further grinding the grain using shape-forming plastic deformation at temperatures below the recrystallization temperature of the material which is being processed. It should be noted that macro-shear deformations cause changes in the metal structure due to trans-grain slip, which is independent of the crystalline orientation of the grains [3].

This allows us to obtain metals and alloys with ultrafine-grained (UFG) structure, having grain sizes in the sub microcrystalline range (from 0,1 to 1 mic$_*$m), or a nanocrystal line structure with dimensions of structural objects < 100 nm. The grain boundaries of such materials are saturated with dislocations to such extent that the coefficient of grain-boundary diffusion is much greater than the coefficient of the bulk diffusion [4]. In this state, the fundamental characteristics, physical and working properties of materials are fundamentally different from similar properties, which are characteristic to the same metals and alloys with a coarse-grained structure [5]. The authors of the paper believe that the radial-shear rolling (RSR) is considered to be the most universal method of increasing plasticity in nanostructured and UFG materials. The formation of non-equilibrium grain boundaries with high-angle disorientation, providing the processes of intergranular slippage under plastic deformation occurs while using this method of rolling. Extensive theoretical and experimental studies conducted in the paper [6] clearly showed the fundamental differences between the RSM process and traditional deformation methods. First of all, these differences include powerful shear deformations of the metal, which are developed in combination with intense radial reductions. The development of the metal structure and its properties are improved due to the above mentioned factors. The aim of the present paper is to investigate the effect of the stress-strain state (SSS) on the formation of structures arising during the RSM, and to develop a technology that allows us to obtain rods with a UFG structure made of aluminum alloy D16.

MATERIALS AND RESEARCH METHOD

In this paper, the authors used a radial-shear mill (RSM) of a new design to produce UFG structures in

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rods of aluminum alloy D16. The rolling process in the RSM is carried out in the deformation zone formed by three working rolls and a die. Working rolls, deployed at the angles of feed and rolling, are located through 120 ^{0} around the deformable workpiece. Due to the reversal of the rolls at the feed angle, the rotational motion of the rolls is transmitted to the workpiece as a rotational-translational motion through the deformation zone [7]. The technological basis of the RSM consists of large feed angles (up to 18 ^{0}) in combination with a special geometry of the deformation zone, based on the configuration of the work rolls and the die. A specialized standard program MSC Super Forge was used for calculating the SSS. A three-dimensional geometric model of the workpiece and rolls was built in the Inventor CAD program and imported into the CAE program, MSC Super Forge. A three-dimensional volume element CTETRA (four-node tetrahedron) which is used to model three-dimensional bodies was used while creating a finite element model of the workpiece and rolls. The round samples in the cross section with a diameter of Ø 40 × 60 mm were used to calculate the SSS. The material of the rolls and the rolled stock was designated from the materials database. The Johnson-Cook elastoplastic model was chosen to simulate the plasticity of the material. The contact between the roller and the workpiece is modeled by Coulomb friction, where the friction coefficient was adopted as 0,3. Rolling the workpiece on the RSM was carried out in the following mode: heating the workpiece to the temperature of 300 °C, and rolling it on a radial-shear mill to a diameter of 14 mm. Program “MSC Super Forge” was launched. The components of the strain tensor and stress, as well as the temperature distribution over the volume of the workpiece were calculated by the step method. At the same time, the technical characteristics proposed for RSM were used for calculating these indicators. The power of the electric motor was equal to 15 kW, and the frequency of rotation of the rolls was 70 rotations per minute. Rolling was performed with an angle of feed equal to $\beta = 15°$ and an angle of rolling - $\alpha = 8$ °. In this paper, the formation of UFG structure of rolling blanks in the bars was produced in the following modes [8]. The initial coarse-grained billet of the D16 alloy (the average grain size of the annealed samples was 162 microns and the billet diameter was 60 mm) was subjected to RSM at a temperature of 300 °C and 400 °C to a diameter of 8 mm. The samples of aluminum alloy D16 were subjected to heat treatment before the mechanical testing which consists of quenching and subsequent aging. The heating temperature for quenching was 475 °C; then it should be held at this temperature for 2 hours, cooled in oil. Aging was carried out at a temperature of 120 ^{o}C for 5 hours. The metallographic analysis was performed by using an energy-dispersed JNCAENERGY spectrometer (England) installed on a JEOL electron probe micro analyzer (Joel) with an accelerating voltage of 25 kV. The range of magnifications of the device JEOL is from 40 to 40 000 times. The principle of the micro analyzer: high-energy (25 kV) narrow (1 mic$_*$m) electron beam is directed to the sample, where it turns into a raster (frame), scanning the sample; at the same time the secondary electrons emitted by the sample are recorded [9]. The structural features of the deformed samples were also examined using a JEM-2100CX electron transmission microscope (ETM) at accelerating voltages of 200 kV. Quantitative analysis of the parameters of the defective substructure was carried out by using the standard methods. The sections for metallographic examination were prepared according to the traditional method on grinding and polishing wheels. A concentrated solution of nitric acid in ethyl alcohol was used for etching the samples. The grain size (D_3, mic$_*$m) was determined by the secant method (~ 300 grains by measurement). The strength and plasticity of the samples were determined at room temperature on an Intron 5882 installation.

RESULTA AND ITS DISCUSSION

On the basis of the program “MSC Super Forge” of the obtained results of numerical simulation of the rolling process of aluminum alloy D16, it has been established that:

1) small stretching of the main stresses σ_{11} appear on the surface of the workpiece;
2) each element is affected by compressive main stresses of σ_{22} and σ_{33} in the outer layer;
3) when the RSM is deformed in the deformation zone, the metal flows along a helical path with different speeds of the outer layer as well as the inner layer;
4) the movement of the metal flows at different speeds causes intense shear displacements in the volume of the workpiece, which lead to a significant increase in strain intensity (Figure 1, a) and stresses (Figure 1, b); at the same time this contributes to a significant grinding of grains and obtaining of an ultrafine grain structure.

Large shear deformations are accompanied by heating of the metal. The temperature effect of heating is up to 200 - 300 ^{o}C, which allows us to reduce the heating temperature before the rolling process, as well as allows one to significantly reduce and optimize the temperature range of processing. Thus, the stress state scheme, which is close to all-round compression, providing intensive compaction of the structure of various zones of the workpiece is implemented while using this particular method. Rolling blanks at a temperature of 300 ^{o}C and 400 ^{o}C on the mill of RSP leads to the formation of a structure with the size of UFG. As a result of the implementing the softening processes throughout the entire volume of rolled bars, a structure is formed in the range of UFG size and it equals to the range ranging from 420 to 960 nm. The structure obtained by the UFG is characterized by uniform grain sizes throughout the

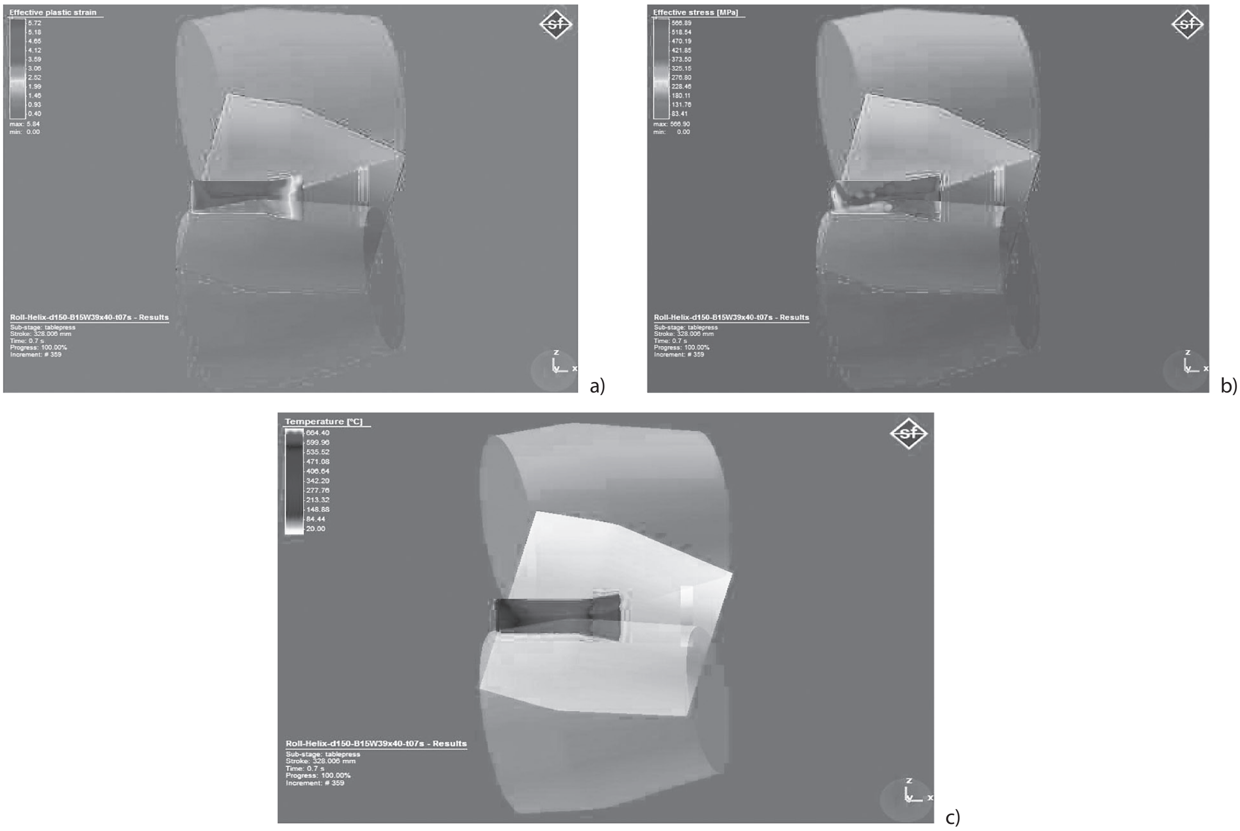

Figure 1 Picture of the distribution of strain intensities (a) and stress (b), as well as the temperature field (c) in the workpiece while rolling bars in the RSM (rolling temperature is 300 °C).

entire volume of the material. A distinct image of the grain boundaries was observed on the images of the microstructure after rolling on the RSM. The type of microstructure indicated the formation of grains with predominantly high angle boundaries [10].

Determined the quantitative characteristics of the structural components of the alloy by using the obtained microstructures, and found that a disperse structure with an average fragment size of 420 - 650 nm was formed on the RSR mill in mode 1 over the billet cross sections. While rolling on the RSP mill in mode 1, the dominant relaxation mechanism of elastic energy with increasing degree of deformation is fragmentation, whereas the small mechanism is dynamic recrystallization due to the high solid-solution hardening of the original Al matrix and the presence of dispersed hardening phases [11]. It was found that the fragmentation of the structure to the UFG level occurs due to the bending of the crystal lattice and rotational deformation modes, leading to the breaking of the sub grain structure and the transformation of the dislocation low-angle boundaries separating the original sub grain into the high-angle boundaries. The formation of a large number of high-angle boundaries is confirmed by the micro diffraction pattern of the ring type with a large number of discrete point reflexes. The ETM methods determined that the boundaries of the fragments are blurred, and the inhomogeneous contrast inside the fragments indicates a high level of internal stresses. An assessment of the dislocation structure and micro diffraction patterns allowed us to conclude that, as a result of the RSM, the formation of a UFG structure with high-angle non-equilibrium boundaries in the D16 alloy occurs as a result of a crystallographic shift carried out by the displacement of lattice dislocations, and a non-crushlographic shift when the grain-boundary dislocations move.

A different situation is observed in blanks deformed in RSM at a temperature of 400 °C. It was found that during the rolling in the RS, the strip structure is divided into deformation, intermediate and micro bands, consisting of sub grains separated by high-angle and low-angle boundaries. In this case, a further evolution of the structure occurs. Namely, the number of lattice and grain-boundary dislocations is reduced, clear extinction contours appear at the grain boundaries, i.e. all signs of dynamic recovery and dynamic recrystallization are manifested by a continuous mechanism. As a result of these processes, a UFG structure consisting of grains with a size of 720 – 960 nm is formed in the material [11].

Consequently, during rolling in mode 2, the relaxation of elastic energy in the D16 alloy is carried out by two mechanisms-small fragmentation and dominant dynamic recrystallization. It was also established that the fragmentation of the structure to the UFG level occurs due to the bending of the crystal lattice and rotational deformation modes, leading to the breaking of the sub grain structure and the transformation of dislocation of low-angle boundaries separating the original sub grain into high-angle boundaries. The formation of the UFG structure in the D16 aluminum alloy was reflected in their properties. It was established that in the UFG alloy D16, the temporary tensile strength increases by 32 %, and the yield strength is about 1,8 times compared with the initial state.

CONCLUSIONS

1. Rolling on the RSM leads to the localization of strain intensity and stress in the initial stage of rolling on the surface zones of the workpiece, and at the subsequent stages near the central zones of the workpiece.

2. The picture of the movement of the trajectories of different metal layers with different pitch and angle of elevation of the screw lines clearly proves that the process of RSM provides us with the a stratified, distinct orientation of the ground-up structure obtained by a certain way in addition to the cardinal grinding of the entire structure.

3. Research has established that it is possible to form uniform UFG structures with grain sizes about 340 - 730 nm in a bar material made of D16 aluminum alloy, which subsequently leads to an increase in strength and ductility properties, and wear resistance as well as a decrease in friction coefficient.

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Note: The responsible for England language is Aigerim Nauryzbayeva, Almaty, Kazakhstan