S. A. MASHEKOV, G. A. SMAILOVA, A. M. ALSHYNOVA, A. ZHAUYT, N. S. SEMBAEV, M. R. MAULENOVA

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INVESTIGATION OF THE FORMATION EVOLUTION OF ALUMINUM ALLOY 1050 STRUCTURE DURING ROLLING IN THE SPIRAL ROLLERS AND THE LONGITUDINAL WEDGE MILL

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This article presents a new methodof obtaining the sheet steel with ultrafine-grained structure. The ultrafine-grained structure is obtained by implementing severe plastic deformation developed by a spiral roller. This paper investigates the stress-strain state (SSS) of the workpiece during rolling in a spiral roller and a longitudinal wedge mill (LWM). A rational technology of rolling aluminum alloy 1050 was developed and tested under the laboratory conditions. It was proved that the system achieves an equilibrium state by diffusion along the grain boundaries accelerated by the flow of vacancies formed during the deformation. It has been established that rolling aluminum alloy 1050in the spiral rollers and LWM leads to an increase in the strength and plastic properties of the sheet metal.

Keywords: aluminum alloys, rolling, ultrafine-grained structure, strength, ductility.

INTRODUCTION

Nowadays, obtaining materials with ultrafine-grained (UFG) structure is one of the new and promising ways of improving the properties of the final product, such as foil [1]. For instance, they are able to maintain a high level of plasticity by possessing increased strength compared to the conventional crystalline materials. An equal-channel angular pressing and torsion under high pressure are considered to be the methods of severe plastic deformation (SPD) used for obtaining ultrafine-grained materials. Compared to the commonly used technologies of deformation processing of materials (such as rolling and extrusion), the SPD methods allow us to obtain the bulk nanostructured materials that cannot be produced by conventional thermomechanical processing. However, the patterns of the diffusion effect on the processes accompanying SPD are not still fully understood. The aim of this paper is to study the formation patterns of the structure and properties of aluminum alloy 1050 during SPD.

The paper presents a developed tool consisting of rollers with spiral working surfaces [2]. The opposing spiral protrusions and valleys of the upper and lower rolls in this tool are respectively made according to the left and right helix. This tool develops SPD without changing the geometric dimensions of the original billet and allows us to obtain the ultrafine-grained structure in the billets of metals and alloys.

MATERIALS AND RESEARCH METHODS

This paper also presents a developed five-stand longitudinal wedge mill (LWM) used for rolling strips [3]. The five-stand longitudinal wedge mill for rolling sheets from steels and alloys contains electric motors, gearboxes, gear stands, universal spindles, couplings, stands with working and back-up rolls. At the same time, two support rolls were installed in the first three stands there, and four support rolls were installed in the last two stands. The rotation of working rolls occurs through the bearing stands with five gear motors with angular speed of $\omega = \upsilon \cdot R$ (where υ is the rolling speed in each mill stand; R is the radius decreasing in the direction of rolling of the working rolls of each mill stand).

The stress-strain state (SSS) of the workpiece was studied during rolling in a spiral roller, as well as on the longitudinal wedge mill with the purpose of developing the technological process allowing usto distribute the accumulated deformation evenly, i.e. to obtain thin strips of high quality aluminum alloy 1050, as well as to determine the optimal value of a single reduction.

The specialized standard program MSC Super Forge was used for calculating the SSS. A three-dimensional geometric model of the workpiece and rollers was built in the Inventor CAD program and imported into the

S. A. Mashekov, (mashekov.1957@mail.ru) M. R. Maulenova, Kazakh National Technical University, Almaty, Kazakhstan
G. A. Smailova, Kazakh Agrarian University, Almaty, Kazakhstan
A. M. Alshynova, Almaty Technological University, Almaty, Kazakhstan
Zhauyt, Almaty University of Power Engineering and Telecommunications, Almaty, Kazakhstan
N. S. Sembayev, Pavlodar State University, Pavlodar, Kazakhstan

CAE program MSC Super Forge. A three-dimensional volume element CTETRA (four-node tetrahedron), implemented to model three-dimensional bodies, was used for creating a finite element model of the workpiece and rolls.

Rectangular samples with the size 6 × 100 × 200 mm in the cross section were used for calculations. The material of the rolls and the material of the rolled stock were assigned from the material database. The Johnson-Cook elastoplastic model was chosen for simulating the plasticity of the material. The contact between the roller and the workpiece is modeled by Coulomb friction and the friction coefficient was adopted as 0,3.

Rolling is carried out in the following mode: heating to a temperature of 400 °C, rolling up to four passes in a spiral roller to a thickness of 5,9 mm and rolling at a temperature of 400 °C onthe longitudinal wedge mill to a thickness of 1,5 mm. The 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. The developed technology of rolling strips of aluminum alloy 1050 was tested under laboratory conditions. While testing the technology, the initial billet of aluminum alloy with a thickness of 8 mm was heated to a temperature of 400 °C, held for 30 minutes and rolled in four, eight and twelve passes in a spiral roller (SR) to the thickness of, respectively, 7,9, 7,7 and 7,0 mm. The final rolling of the strips with a thickness of 1,5 mm was carried out on LWM at a temperature of 400 ^{o}C. Metallographic analysis was performed using an energy-dispersed spectrometer JNCAENERGY (England) installed on a JEOL electron probe micro analyzer with an accelerating voltage of 25 kV. The range of magnifications of the device JEOL ranges from 40 to 40 000 volumes. The structural features of the deformed samples were also examined using a JEM-2100CX electron transmission microscope (ETM) at 200 kV accelerating voltages [4]. The chemical composition of the aluminum alloy 3003 was determined using the micro analyzers with an electronic probe JXA-8230 of the company JEOL using a standard technique. X-ray structural analysis (XSA) was performed by using an automated standard D8 Advance diffractometer (Brokers, Germany). Monochromatic Cu – K_{α} radiation with a wave length λ = 1,5406 Å was used in the process of analysis. The voltage of the X-ray tube was equal to 40 kV, the current strength was 30 mA, and the scanning step for survey radiographs was 0,05 2θ (for clarification, 0,01 2θ). The obtained diffract gram data were processed and theater planar spacing’s were calculated by using the EVA software. The samples were deciphered and the phases were searched according to the program Search/match, using the base of powder diffractometric data PDF-2. The micro hardness of the samples was measured by the Vickers method on an automated micro hardness tester of the American company INSTRON with a working load of 2,942 N and with the exposure time of 10 seconds for this load. The mechanical properties of aluminum alloy 1050 were determined after rolling the billet in a spiral roller and LWM. The samples were subjected to heat treatment consisting of quenching and subsequent aging before conducting the mechanical testing. The heating temperature for quenching was 450 °C, and the exposure time at this temperature was 2 hours.

RESULTS AND ITS DISCUSSION

Based on the results of numerical simulation, it was established that:

1) the seizure of the workpiece with spiral rollers leads to the formation of a minimum-sized tensile of $\sigma_{11}$and σ_{22} in the deformation zone, as well as σ_{33} compressive stresses;

2) the further rolling of the spiral rollers leads to the formation of normal stresses σ_{11}, σ_{33} and σ_{22} in the deformation zone, varying in the range: σ_{11} from 13,798 to 19,852 MPa; σ_{33} - from – 30,243 to 4,133 MPa; σ_{22} - from – 18,264 to 12,188 MPa;

3) at the initial moment of rolling, the intensity of stresses and strains are localized in the contact zones of the workpiece with the working surfaces of the rolling protrusions;

4) an increase in a single crimp leads to the transfer of an emphasis of the intensity of stresses and strains from the contact zones to the zones of the strip located under the inclined working surfaces of the protrusions as well as the roller troughs;

5) in the process of rolling in the spiral rollers, the zones of contact of the tool with the strip are cooled, while the temperature rises slightly in the zones of action of bending deformation;

6) in the second, third and fourth rolling passes in spiral rollers, the magnitudes of the intensity of stresses and strains increase under the inclined sections of the protrusions and troughs of the rolls;

7) the developed method of rolling the strips in spiral rollers provides intensive alternating deformation of the strip with a slight reduction;

8) maximum possible shift is realized when the ratio of the protrusion width to the depression width is 0,8... 0,9.

The calculation and SSS analysis of the workpiece during the rolling of strips on the LWM shows that:

1) small tensile σ_{11}, compressive σ_{33} and σ_{22} stresses occur in the deformation zone during the seizure of the workpiece by the first, second, third, fourth and fifth stand of the longitudinal wedge mill;

2) further rolling of the workpiece on the longitudinal wedge mill leads to the occurrence of absolute values of small normal compressive and tensile stresses σ_{11}, σ_{33} and σ_{22} in the deformation zone;

3) while rolling in the first the longitudinal wedge mill stand, the intensities of stresses and strains are localized in the zones of metal capture by rolls;

4) the magnitude of the intensity of stresses and strains increases in the center and along the edges of the deformable workpiece with an increase in compression;

5) continuous rolling of the billet in subsequent the longitudinal wedge mill stands allows us to transfer areas of concentrated deformation gradually from the center to the zone of contact of the rolls with the rolled billet;

6) gradual transfer of sections with localization of deformation from the center to the surface leads to a more uniform distribution of accumulated deformation;

7) the most uniform distribution of the total intensity of stresses and strains over the height and length of the rolled strip was obtained by rolling with a single compression in the first stand of 20 %, the second stand of 18 %, the third stand of 13 %, the fourth stand of 15 %; and the fifth stand of 12 %.

It should be noted that most of the plastic zone is under a comprehensive non-uniform compressionunder any conditions of rolling in the spiral rollers and the longitudinal wedge mill. However, small tensile stresses appear in a size of a small section of strips, located under the inclined working surfaces of the protrusions and depressions of the spiral rollers, as well as at the edges of the strips rolled on the longitudinal wedge mill [5].

The study of the original microstructure of the workpiece showed that alloy 1050 contains a heterogeneous microstructure. This structure owned large grains. The average grain size in the longitudinal direction was 51 microns, while in the transverse direction it equaled to 73 microns. Fine grains with the size of 8 – 17 microns were located along the boundaries of large grains.

A typical strip structure with an internal substructure was formed during the hot rolling process in four-pass spiral rollers. Inside the band, there are sub grains with the size of 4 microns separated by low-angle boundaries. A low dislocation density and uniformly distributed precipitations of the $FeAl_3$ and Fe_3SiAl_{12} phases with an average size of 80 - 90 nm are observed inside the sub grains.

It was established that a mixed UFG structure is formed in the alloy 1050 during the deformation with eight passes. This structure consists of crystallites with a high density of lattice dislocations and “diffuse” non-equilibrium high-angle boundaries, as well as a small number of fragmented initial sub grains separated by low-angle boundaries [6]. With an increase in the number of passes up to twelve, the metal grains are cleared from dislocations; higher-angle, thinner and equilibrium boundaries with well-distinguished extinction contours are formed throughout the entire volume. These observed changes in the structure indicate relaxation of the stressed state of the lattice. The analysis of the dark-field images of microstructures showed that a dispersed UFG structure with an average grain size of 400 – 600 nm is formed throughout the entire volume of sheet metal while rolling in spiral rollers with twelve passes.

The results of the study of the microstructure of strips rolled on the longitudinal wedge mill showed that it undergoes dynamic polygonization in the process of deformation. Dislocations are redistributed inside the sub grains, forming bulk dislocation networks. Thus, the sub-boundarieswith a large disorientation formed in this way has an increased curvature and mobility and they become the centers of recrystallization. The processes of polygonization accompanied by fragmentation of sub grains. Dynamic recrystallization proceeds in a parallel way, therefore it is difficult to separate the degree of realization of each of these processes from their contribution to the resulting structure. Nevertheless, the observed facts occurring in the bands after deformation such asequiaxed grains, “clean” from dislocations, and grains with uniformly distributed single dislocations and with dislocation networks of increased density can serve as confirmation of the last recrystallization.The latter is surrounded by non-equilibrium diffuse boundaries; the contours of extinction are observedin the region of the borders of less defective recrystallized grains. According to the ETM data, the degree of structure deficiency increases, particularly, the number of grains with higher density of dislocations increases more than those in the bands after rolling with twelve passes in a spiral roller.This is also evidenced by the increase in the level of micro distortion of the lattice, determined by the broadening of the x-ray line. Such structure is similar to the mixed UFG structure formed by rolling in spiral-shaped rollers with eight passes. The average crystallite size does not change and it equals to 400 - 600 nm, as well as while rolling in a spiral roller with twelve passes.However, according to the constructed histograms, the nature of the distribution of crystallite size is changed by the quantity: the proportion of small grains increases, while large grains with a size of more than 900 nm occur in the structure. The distribution is close to bimodal, which is characteristic of a recrystallized structure.

Summing up all the experimental data described above, it can be assumed that the formation of the UFG structure occurs mainly by the mechanism of fragmentation, dynamic polygonization and recrystallization during rolling in spiral rollers with twelve passes and on the LWM.

In accordance with the data of diffract grams, in the structure of an alloy 1050, iron phases such as Al_3Fe,Al_6Fe, Al_8Fe_2Si, Al_5FeSi and Al_4FeSi are contained both in the initial and deformed state in the spiral rollers and in the LWM. The particles with the size of 4 – 8 nm are evenly distributed over the volume of the material in the thin stripes deformed with twelve passes in spiral rollers and LWM.

It is known that the solubility of silicon in aluminum is noticeable, and iron is practically insoluble [7]. Therefore, the decomposition of the supersaturated solid solution during deformation of the alloy 1050 in a spiral roller and the longitudinal wedge millis carried out due to the grain boundary diffusion of silicon [8]. An increase in silicon and a decrease in the Fe/Si ratio to 1,5 or less lead to the formation of Al_8Fe_2Si equilibrium stable ternary phase and eliminate the appearance of a structural defect during dynamic recrystallization. All the mentioned above leads to an increase in the plastic properties of aluminum alloy 1050.

The initial samples had an increased micro hardness, while their value varied from 320 MPa to 410 MPA. Increased micro hardness values may be associated with solid solution hardening due to the fixation of the supersaturated aluminum solid solution with the main alloying elements [9].

According to the results of micro hardness measurements, depending on the number of rolling passes in the spiral rollers, it was found that the greatest increase in the micro hardness of the alloy is observed during rolling with four passes (920 MPa). The hardness decreases with the subsequent increase in the number of passes, and it practically stabilizes near the value of ~ 660 MPa.

It is established that the mechanical properties of an alloy 1050, subjected to rolling in a spiral roller and the longitudinal wedge mill, are much higher than its initial values. In particular, the temporary tensile strength σ_v increases by 20 %, and the plasticity is one and half times higher than the corresponding parameter of the initial samples. Such combination of sufficient strength (σ_v = 235 MPa) and good plasticity (δ = 14 %) opens up wide possibilities for using this material in practice [10].

CONCLUSIONS

1. Intensive plastic deformation of aluminum alloy 1050 in a spiral roller leads to a strong decrease to the size of aluminum grains and particles of intermetallic phases. As a result of the deformation, the supersaturated solid solution of aluminum decomposes, and the system evolves to a state corresponding to the equilibrium phase diagram.

2. the most likely mechanism for the system to achieve an equilibrium state is diffusion along the grain boundaries accelerated by the flow of vacancies formed during the deformation.

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