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THE STUDY EVOLUTION OF THE STRUCTURE FORMATION OF THE FOIL WORKPIECE DURING ROLLING SCREW ROLLERS AND LONGITUDINAL-WEDGE MILL (LWM)

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The article presents the results of studies of the influence number of passes and single crimps during rolling strips, respectively, in helical rolls and longitudinal-wedge mill on the parameters of the microstructure of aluminum alloy 2017. Comparative assessment grain sizes of ultrafine-grained structure after rolling strips with different passes in the helical rolls and deformation of the longitudinal-wedge mill at a deformation temperature of 400 °C. It is shown that the aluminum alloy sheet material 2017 provides the formation of a homogeneous ultrafine grain structure with a grain size of about 240 nm, which leads to an increase strength and plastic properties of the alloy.

Key words: aluminum alloy 2017, rolling, sheet, structure, temperature

INTRODUCTION

Recently, the production of materials with ultrafine-grained (UG) and nanocrystalline (NC) structure is one of the new and promising ways to improve the properties of the final product. For instance, increased in comparison with conventional large-crystal materials strength, they are able to maintain a high level of plasticity. Among the methods of obtaining UG or (NC materials are methods of severe plastic deformation (SPD), such as equal-channel angular pressing and torsion under high pressure, etc. In comparison with the commonly used processing technologies, SPD methods allow to form a nanoscale fine, homogeneous, isotropic, equiaxial grain with predominantly large-angle boundaries and low density of dislocations in its body, which cannot be produced by conventional thermo mechanical processing [1]. However, the known methods of SPD are difficult to use to obtain NC or UG structures in sheet materials. Therefore, to obtain NC or UG structure in sheet metal many new designs of rolls have been proposed.

These rolls are not widely used in production due to the complexity of their manufacture or the difficulty of installing them on rolling mills. The purpose of this work is to study the evolution formation of the structure of foil billet of aluminum alloy 2017 with SPD in a helical roll (HR) and rolling in a longitudinal wedge mill (WM).

MATERIALS AND METHODS

The work has developed a tool consisting of rolls with helical working surfaces [2]. This tool does not change the geometric dimensions of the original billet, implements SPD and allows you to obtain blanks from metals and alloys with nanostructures. It should be noted that the opposite located helical projections and depressions of the upper and lower rolls are made on the left and right helical lines, respectively. We have also developed a five-square WM for rolling strips of steel and alloys. This mill contains electric motors, gearboxes, gear stands, universal spindles, couplings, stands with working and support rolls. In the first three stands are installed two and in the last two stands – four support rolls. In the laboratory, we tested the developed technology of rolling strips of aluminum alloy 2017. Testing of the technology initial billet of aluminum alloy 2017 with a thickness of 8 mm was heated to a temperature 400 °C, has stood for 30 minutes and rolled four, eight and twelve passes in the HR to a thickness of 7,0 mm. In this case, after each of four passes, the billet was heated to a temperature of 400 °C. The final rolling of the strip to a thickness of 1,5 mm was carried out on the WM at a temperature of 400 °C. Cold rolling was carried out on a sheet-rolling mill DUO 155 to a thickness of 0,1 mm, with the last pass was carried out on polished rollers from a double billet. A metallographic analysis was performed on an NEOPHOT 32 microscope (Karl Zeiss, Jena) (Germany), as well as a JN-CAENERGY energy dispersive spectrometer (England) mounted on a JEOL electron probe micro analyzer with an accelerating voltage of 25 kV.

When processing the data, a standard Tango filter was used. In this case, non-indexed points were sequentially

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attached to neighbors with a gradual decrease in their number from 8 to 3. At the final stage «single» points - grains, surrounded on all sides by points with excellent orientation were removed. Small – angle (mug) boundaries with a disorientation of more than 2 º, high-angle (HA) - more than 15 º were referred to small-angle (SA). The size of the sub grains was determined by secant method in the same program along and across the rolling direction. The number of grains and sub grains in both methods in the calculation was not less than 500, which provided a measurement error of not more than 5 % with a confidence probability of 0,9. The micro hardness of the samples was measured by the Vickers method on an automated micro hardness tester of the American firm INSTRON with a working load of 2,942 N and a holding time for this load of 10 seconds. Strength characteristics (conditional yield strength and strength limits, R_m and R_v / MPa) and plasticity (relative elongation, δ / %) were determined in accordance with GOST 11701-84 according to the results of stretching of flat samples with the size of the working part 0,7 × 3 × 9 mm. Before the mechanical test, the samples were subjected to heat treatment (HT), consisting of hardening and subsequent aging [3]. The heating temperature for quenching was 450 °C, holding at this temperature 2 h, cooling in oil. Aging was carried out at a temperature of 120 °C for 5 hours.

RESULTS AND DISCUSSION

The microstructure of the initial billet was coarse-grained, and mainly consisted of highly elongated fibers (S_f) 150 - 260 microns thick and ~10 % equiaxed recrystallized fine-grained grains (D_g) ~6 μm in size [4]. Inside the fibers, there was a polygonized structure with the same (~ 6 μm) sub grain size (D_s) and a low density of lattice dislocations ($\rho = 0{,}7 \times 10^{12}$ m^{-2}). Due to the presence of the substructure, the distribution of boundary misorientations was bimodal with an average angle (Θa) ~ 21º and a fraction of high-angle boundaries (N_h / N) ~ 36 %. Analysis of the obtained data showed that, after rolling with four passes in the explosives a predominantly fibrous structure is formed, i.e. the structure of the original billet is retained in the microstructure of aluminum alloy 2017. As a result of rolling, metal fibers in the HR acquire a banded shape and against the background of increasing their length and reducing the thickness to 50 - 80 μm, their partial fragmentation was noted - division into parts by new transverse high-angle boundaries. Judging by the TEM, SEM and XRD data, a relatively heterogeneous cellular structure with a high dislocation density was formed inside the fibers ($\rho = 7{,}8 \times 10^{14}$ m^{-2}) and a relatively non-uniform grid of low-angle boundaries. In this case, it was possible to clearly distinguish extended, continuous SA, which is located across the rolling direction dividing the fibers into blocks and individual sub grains as well as "dangling" SA inside these sub grains. According to the SEM data, the sub grain size was about 1,2 μm, and the cell size in the TEM measurements was 0,3 – 0,5 μm smaller. In addition, the substructure of TEM images looked more homogeneous than on EBSD cards. Including the distribution inside the fibers of the borders of slightly disoriented cells was relatively homogeneous. Interesting was the fact that the dislocation density recorded in a rolled alloy was of the same order as in nanocrystalline metals and alloys obtained by cold (at room temperature) intense plastic deformation [5]. Despite this, only four grains ~ 260 nm in size with a TEM contrast characteristic of strongly deformed, non-equilibrium nanostructures, obtained, for example, by high-pressure torsion at room temperature were found in the structure of an aluminum alloy after four passes in rolling [2]. From the obtained materials it can be seen that rolling in explosives did not qualitatively change the spectrum of border misorientations - it remained bimodal. However, unlike the initial state, the share of HA in it decreased to ~ 21 % with a corresponding decrease in the average misorientation angle to 6 º. The above-described structural changes first of all, the formation of a developed cellular structure with an increased density of crystal defects caused by the suppression of their redistribution and annihilation (dynamic return), led to an increase in the level of microstressing of the crystal lattice to 0,18 %. Such a magnitude of microstresses does not exceed the level normally found in materials deformed by SPD at room temperature. For example, in copper subjected to torsion under high pressure, it was only 0,21 %. Rolling in HR with twelve passes led to qualitative changes in the structure of the alloy. Against the background of even more thinned (thickness was only 4 - 8 μm) and fragmented fibers, a mixed structure consisting of equiaxial sub grains ~ 220 nm in size and areas consisting of new, small grains of the same size, whose share amounted to ~ 53 %. At the same time, the dislocation density did not change and the grain and sub grain boundaries on the TEM images became even clearer and thinner. Judging by the EBSD maps, these areas alternated and were arranged form of stripes stretched across the rolling direction. The share of HA in such a structure reached 83 %, and the average misorientation angle of the boundaries is ~ 36 º. At the same time, the distribution spectrum of boundary misorientations became close to the theoretical random distribution with a maximum of about 48 º. Thus, it can be concluded that in 2017 aluminum alloy, as a result of its rolling into HR with twelve passes, a mixed nano (sub) grain structure is formed, with crystallite size ~ 120 - 360 nm and coherent scattering areas ~ 70 - 80 nm. Similar structures with a nanometric crystallite size were obtained in a number of studies of treatments involving SPD torsion under high pressure at room temperature [3]. Considering, taking into account the data of these and other works, the processes responsible for the formation of a nanocrystalline structure in alloy 2017 in the conditions of rolling in HR. The process of transformation alloy structure with increasing degree of its deformation during rolling in explosives can be represented as follows. As the results of EBSD analysis show, in the early stages of rolling in explosives, a network of low-angle boundaries forms in the material, which with increasing degree of deformation increases the misorienta-

Table 1 **The mechanical properties of the 2017 alloy at room temperature**

Treatment	R_m / MPa	R_v / MPa	A / %
Hot rolling with 12 passes in explosives + WM + cold rolling on WM + heat treatment (see above)	394	202	27
Standard hardening heat treatment of the original sample: annealing at a temperature of 540 °C and cooling in water at room temperature + aging at a temperature of 160 °C, 12 hours.	345	180	14

tion and transforms into high-angle boundaries leading to the formation of a new nanocrystalline structure. It is important to note that the proportion of recrystallized grains and the average misorientation angle in the structure developing in the rolling process increase with an increase in the number of passes.

The size of the new grains remains practically unchanged during the deformation process and when rolled into explosives with twelve passes, corresponds to the size of sub grains. At the same time, structural changes are accompanied by an increase and subsequent stabilization of the level of microstresses and the density of accumulated dislocations. The combination of such changes in the parameters of the alloy structure suggests that the formation of new grains is carried out in accordance with the mechanism of continuous dynamic recrystallization. In contrast to the intermittent mechanism associated with the formation and growth of embryos, continuous recrystallization is a «one-step» phenomenon i.e. it is carried out exclusively due to the dynamic generation of new grains without subsequent migration of high-angle boundaries [4]. According to the results of measurements of microhardness depending on the number of passes in the rolling HR found that the greatest increase in the microhardness of the alloy is observed when rolling with four passes. With the subsequent increase in the number of passes, the hardness changes little, practically stabilizing near the value of ~160 HV. This type of dependence of microhardness degree of deformation was repeatedly observed during deformation of aluminum alloys by various methods for example, during cryogenic deformation of aluminum alloy 2024 by ECAP, Al-4Zn-2Mg and 6063 by isothermal rolling [5]. Stabilization of microhardness values indicates the achievement of the ultimate hardening of the material as well as the grinding of its structural elements, such as the size of cells, sub grains and grains. The obtained strength values after the 2017 alloy processing by the method of rolling in HR and WM, as well as subsequent heat treatment, are in good agreement with the changes in hardness. Mechanical properties are shown in Table 1. It is important to note that with a significant increase in the strength characteristics after processing in HR and WM the material shows a very high plasticity. It is known that in conventional thermally hardened aluminum alloys as a rule heat treatment leads to an increase in strength and a decrease in ductility. In our study, it was found that the additional heat treatment of a UG alloy subjected to pretreatment in HR makes it possible to achieve a simultaneous increase in both strength and plastic characteristics. It can be noted that when rolling HR, reducing the duration of the deformation effect more than 4 times in comparison with traditional SPD methods, along with the formation of the UG structure, allows the super saturation of the solid solution to be maintained at a level that guarantees hardening during subsequent heat treatment due to dispersion hardening.

CONCLUSIONS

1. Oriented dislocation (cellular) strip structures with wide boundaries are formed. Then, their structure is improved, at the first stage of which the dislocation boundaries become narrower and more ordered due to a decrease in their thickness and an increase in the density of dislocations in them. Upon reaching a certain “critical” degree of deformation and accordingly, a high density of dislocation formations, the processes of dynamic return and dynamic recrystallization begin to be activated in the alloy. The nature of the change in the structure parameters of the alloy during the rolling process in explosives is evidence that the formation of new grains of nanometric size is carried out in accordance with the mechanism of continuous dynamic recrystallization;
2. Hot rolling in the HR with twelve passes of the initial billet from the alloy 2017 provide its nanostructuring with the formation of a mixed structure, with the size of recrystallized grains (~240 nm) with a characteristic electron microscopic contrast for the SPD materials;
3. Rolling aluminum alloy in HR 2017 leads to an increase in the dislocation density in the alloy matrix by 8 - 9 times to a level of ~ 8×10^{14} m^{-2}, more than a twofold decrease in the size of the CSR, accompanied by an increase in the micro-stresses of the crystal lattice. At the same time, the lattice parameter of the matrix changes non-monotonically: first, it decreases sharply and then increases, approaching the values in the unreformed alloy aged to maximum strength.

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