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MICROMECHANICAL PROPERTIES OF CRYO-ROLLED (CR) ALUMINUM ALLOY Al0,6Mg0,35Si

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The present study is devoted to the effect of cryorolling (– 150 °C) in mill rolls implementing shear alternating severe plastic deformation (SPD) on the microstructure and mechanical properties of the alloy. Comparison of the processes of cryorolling (CR) and rolling at room temperature (RTR) is given. The study of the microstructure of the samples and the mechanical properties showed that CR ensures the production of ultra-fine grained (UFG) material with an average grain size of 350 ÷ 500 nm, as well as an increase in hardness by 162,2 % (118 ± 2 HV) and R_m by 106,34 % (293 ± 5 MPa).

Keywords: Al0,6Mg0,35Si alloy, mechanical properties, cryorolling, transmission electron microscopy (TEM), UFG

INTRODUCTION

Such characteristic properties of aluminum alloys as lightness, strength, ductility, good formability, high thermal conductivity, corrosion resistance due to the antioxidant film Al_2O_3, non-toxicity make it an almost ideal structural material. [1]. Recently, to obtain the optimal combination of strength, plasticity and toughness in aluminum alloys, which is very difficult to achieve [2], the processes of severe plastic deformation (SPD), based on the transfer of high levels of deformation to the material [3] and cryogenic deformation processes [4], based on active strain hardening of the material at ultralow temperatures. The processes make it possible to obtain nanocrystalline and ultrafine-grained (UFG) materials with excellent mechanical properties primarily due to intensification of deformations and activation of grain-dislocation factors. There are scientific and experimental reports on Al-Mg-Si alloys subjected to cryorolling with and without SPD implementation which have shown improved mechanical properties [5, 6]. However, in the available literature there are no reports on Al-Mg-Si alloys subjected to cryorolling with the implementation of SPD to obtain rolled sections, for example, round, square, rhombic, reinforcing sections and oriented to large-scale production in existing rolling shops. The present study is aimed at obtaining a UFG structure by cryorolling the Al–0.6Mg–0.35Si alloy. The effect of cryorolling on the microstructure and mechanical properties of the alloy is estimated. A comparison of the micromechanical properties of the Al0,6Mg0,35Si alloy during cryorolling (CR) with the results obtained during rolling at room temperature (RTR) is given.

MATERIALS AND METHODS

RTR and CR were carried out in the rolls of duo 250 and duo 150 rolling mills with alternating non-diagonal rhombic and traditional square passes to realize alternating shear SPD and forming passes (Figure 1). The design of the non-diagonal rhombic pass was developed on the basis of the previous scientific works of the authors of this study with the conversion of the shear upsetting process on the rolls, and the roll pass design was calculated and developed in accordance with the relevant basic principles [7].

In non-diagonal rhombic passes, severe shear deformation (or shear strain) is realized through the implementation of alternating shear deformation, simultaneously with this, high-altitude compression (reduction) of the metal occurs. Since rhombic passes alternate with square passes, where high-altitude metal compression also occurs, the process carries out an alternating intense shear.

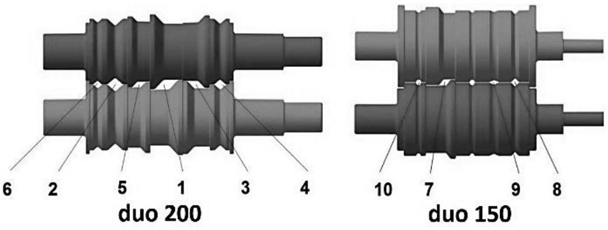

Figure 1 Sketches of roll passes: 1, 3, 5, 7 - non-diagonal rhombic passes for alternating shear deformation; 2, 4, 6, 8 - square passes for reduction; 9 - oval pass; 10 - round pass

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A billet of the Al0,6Mg0,35Si alloy was manufactured by radial shear rolling [8] and had the chemical composition Al0,6Mg0,35Si /Wt. %. Initial samples with a diameter d_0 = 38 mm and a length l_0 = 80 mm (cross-sectional area F_0 = 1 133,5 mm^2) were rolled in n = 10 passes to obtain a round profile with a diameter d_{10} = 10 mm (F_{10} = 79,61 mm^2) Hence, the total elongation coefficient was λ_t = 14,24, and the mean elongation coefficient was λ_m = 1,30, which is optimal for the pass system [7]. The rolling speed is 0,4 m/s (constant). Before rolling, the samples were preliminarily heat treated (solution treatment) at 450 °C for 3 hours. Before the first pass of cryorolling, the initial samples were immersed in liquid nitrogen (– 150 °C) for 30 min, and before the rest of the passes for 20 min to reach saturation temperature. Further, a study of hardness (Vickers hardness test), ultimate tensile strength (R_m), yield strength (R_v) and elongation θ/% was carried out. Optical metallography of the original sample in cross-section was examined on an inverted microscope model Leica DM IRM etched in Keller's reagent (95 ml H_2O, 2.5 ml HNO_3, 1.5 ml HCl, 1 ml HF) for 15 – 20 seconds. TEM analysis of cut ultrathin samples after RTR and CR followed by annealing was performed at an accelerating voltage of 120 Kv on a JEOL JEM 1400 Plus microscope.

RESULTS AND DISCUSSION

The optical micrograph of the original sample is shown in Figure 2 (a). The structure contains an α–Al matrix with intermetallics. The average grain size is in the range of 50÷60 μm. The grains have a hexagonal morphology with triple Y-shaped grain boundaries. Grain boundaries are highlighted in white.

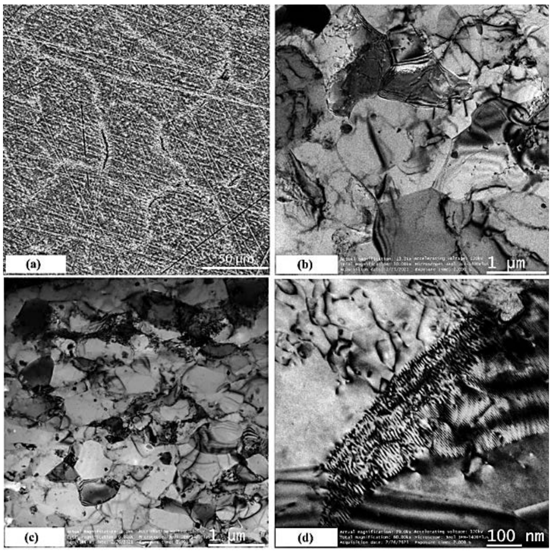

Figure 2 Micrographs of the Al0,6Mg0,35Si alloy: (a) optical micrograph of the initial sample, (b) TEM micrograph of the sample after RTR, (c) TEM micrograph of the sample after CR, (d) TEM micrograph of the dislocation structure after CR

Figure 2 (b), (c) and (d) shows TEM micrographs of the Al0,6Mg0,35Si alloy after RTR and CR. It can be seen from TEM micrographs that, after both rolling cases, strongly fragmented equiaxial grains of hexagonal morphology with low-angle grain boundaries prevail in the material structure. The average grain size after RTR and CR is, respectively, in the range of 1 – 2 μm and 350 – 500 nm. Samples after CR also show highly fragmented grains with an average size of 200 – 220 nm. In contrast to RTR, in the alloy after CR, strongly deformed nonequilibrium and diffusion grains, dislocation cells, entangled dislocation tangles, and dislocation walls are observed.

When rolling according to the proposed scheme (see Figure 1), a favorable stress-strain state is created in the zone of plastic deformation. Thus, the high values of stress intensity observed during rolling according to the proposed scheme, causes an intensive refinement of the grain structure throughout the entire volume of the metal.

The authors believe that at CR, the liquid nitrogen temperature effectively suppresses dynamic recovery processes, in contrast to RTR, where dynamic recovery has a significant effect on the microstructure. The authors also believe that due to the presence of particles of the strengthening binary Mg_2Si phase in the alloy, the motion of dislocations and the migration of atoms is inhibited leading to the accumulation and compaction of dislocations, which is consistent with similar conclusions [5]. Due to a decrease in the temperature of the alloy to cryogenic temperatures, a decrease in the volume of the alloy occurs, causing an increase in the energy of compression deformation and accumulating deformations with each subsequent rolling pass.

Mechanical properties during tensile testing and Vickers hardness data of the Al0,6Mg0,35Si alloy of the initial sample and at different rolling modes are given in Table 1.

Table 1 **Mechanical properties of Al0,6Mg0,35Si alloy at different processing methods**

Process	HV	R_v/MPa	R_m/MPa	θ/%
Initial sample	45 ± 2	78 ± 5	142 ± 5	15 ± 1
RTR	92 ± 2	233 ± 5	251 ± 5	11 ± 1
CR	118 ± 2	258 ± 5	293 ± 5	9 ± 1

It is noticed that, compared with the hardness of the original sample (45 ± 2 HV), the hardness after RTR and CR increased by 104,4 % (92 ± 2 HV) and 162,2 % (118 ± 2 HV), respectively. The hardness of the alloy after CR increased by 28,26 % compared to RTR. The R_v of the samples increased from 78 ± 5 MPa (initial sample) to 233 ± 5 MPa in the RTR sample (an increase of 198,72 %) and to 258 ± 5 MPa in the CR sample (an increase of 230,77%). R_v of alloy after CR compared to RTR increased by 10,73 %. The R_m of the samples increased from 142 ± 5 MPa (the original sample) to 251 ± 5 MPa in the RTR sample (an increase of 76,76 %) and to 293 ± 5 MPa in the CR sample (an increase of

106,34 %). Alloy R_m after CR increased by 16,73 % compared to RTR. Based on the decrease in the elongation values at RTR and CR (by 26,67 % and 40 %, respectively), we can conclude about a decrease in ductility. Low temperature annealing can be performed to increase ductility with little change in mechanical properties.

Improvement of mechanical properties is mainly associated with strain hardening or Hall-Petch strengthening, intensification of shear strains in the passes of a rolling mill, grain refinement, dislocation factors, and precipitation of hardening solid dispersed secondary phases [5]. At CR, the effect of suppressing dynamic recovery is added to these factors, which contributes to an increase in the density of dislocations, thereby also the mechanical properties.

The grain size refinement is attributed to grain-boundary strengthening or Hall-Petch strengthening. The mechanism of this hardening can be explained as follows. Before plastic deformation, there are dislocations in the grains of the material in a certain amount. During plastic deformation, these dislocations and newly formed dislocations (for example, dislocations created by Frank-Read sources) will move through the crystalline lattices of the grains to the grain boundaries, where these boundaries and their disorder impede the movement of dislocations. and they accumulate along grain boundaries.

It is important to note that recent experimental studies of nanocrystalline aluminum materials [9] have shown that the Hall-Petch relationship is not always effective; upon reaching a certain critical grain size (on the order of several tens of nanometers), a further increase in the yield stress is not observed: the yield stress remains constant or decreases (the material softens) even if the grain size decreases. This paradox is called the inverse Hall-Petch effect. Despite the fact that recently a lot of experimental and research works devoted to this effect in nanocrystalline materials have been carried out, the nature and mechanisms of this phenomenon remain insufficiently studied and require further, more in-depth studies.

CONCLUSIONS

Thus, the implementation of a full cycle of cryorolling in new gauges ensures uniform and intensive processing of the metal over the entire section, refinement of the structure to the UFG state, which is reflected in obtaining higher quality products. The cryorolling process proposed by the authors has shown its effectiveness in achieving the UFG structure. For further grinding of grains to a nanocrystalline state with an average grain size of less than 100 nm, the authors are currently developing combined methods of cryorolling with extrusion or pulling [10] to obtain long billets and with deformation in a closed die to obtain spherical billets.

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