A new combined SPD technique to improve mechanical properties and electrical conductivity of long-sized billets

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Abstract. As a result of computer simulation carried out using the DEFORM 3D software package, the influence of the shape of the extrusion die-set, combined with equal-channel angular pressing with parallel channels (ECAP-PC), on the stress-strain state of cylindrical billets of an aluminum alloy was established. The obtained data made it possible to manufacture an experimental die-set for extrusion, combined with ECAP-PC, and to produce in it a cylindrical long-sized UFG billet from the 6063 alloy. It was established that one cycle of direct extrusion combined with ECAP-PC in the matrix with a non-axisymmetric deforming section for direct extrusion leads to a significant microstructure refinement and an improvement of mechanical properties of the alloy.

1. Introduction

Equal channel angular pressing (ECAP) has been the most common method of severe plastic deformation (SPD), which enables producing billets in the form of bars with an ultrafine-grained (UFG) structure from metallic materials including those based on aluminum for structural and electrical purposes [1]. Simple shear is realized, as the billet passes through the conjugation zone of channels with equal cross-sections, made in special equipment, while the diameter retains. This tool shape allows repeatedly deforming the billet and achieving ultra-high strain values (e≥4), which is a prerequisite for the UFG structure formation and, accordingly, for enhancement of mechanical and service properties of the billet material.

The development of the ECAP method is ECAP-PC [2], which, in comparison with ECAP, provides a decrease in processing cycles due to shear occurring in two deformation zones corresponding to two consecutive zones of intersection of channels in the tool. But even such a number of processing cycles of ECAP-PC is difficult to be used in batch industrial production.

Direct extrusion combined with ECAP-PC of a cylindrical billet is a promising development of the ECAP-PC method, focused primarily on improving the productivity of processing UFG material by three or more times. A distinctive feature of direct extrusion combined with ECAP-PC is the feasibility of shear in three deformation zones, in two mutually perpendicular planes - during direct extrusion in the die with a non-axisymmetric deforming section and ECAP-PC in two intersecting tool channels. In this case, the deformation of the billet according to the scheme described above can reach e~3.5 and more, which makes it possible to provide a significant refinement of the microstructure of the processed material already in one processing cycle and, accordingly, enhance the mechanical
properties. In this work, experimental evaluation of the obtained simulation results of the processing by direct extrusion combined with ECAP-PC of a cylindrical billet was carried out using the example of a commercial heat-hardened aluminum alloy 6063 of the Al-Mg-Si system.

2. Experimental
In the course of research, computer simulation of direct extrusion combined with ECAP-PC using the DEFORM 3D software package and a full-scale experiment were carried out. In computer simulation, the following conditions and assumptions were accepted: the tool – an absolutely rigid body (3D models of the tool were previously created in "KOMPAS 3D 8V"); temperature - constant equal to 100 °C; the thermal effect of deformation was neglected due to the low strain rate; billet of the 6063 alloy – a plastic body; the diagram of deformation of the alloy \( \sigma_i = 219 \ln(e_i + 1) + 68 \) constructed upon the results of mechanical tests of the samples, was introduced when preparing the database in the form of a table function; the friction coefficient was introduced when preparing the database in the form of table function ( \( f_\sigma \) ) (\( \tau = f_\sigma \sigma_s / \sqrt{\lambda} \)) of the modulus of compressive, normal contact stress \( \sigma_{n1} \); the number of finite elements - 80,000; deformation velocity - 5mm/s; time step 0.1s; the number of simulation steps is 100...400.

Before experimental direct pressing combined with ECAP-PC, the initial cast billets were annealed in a SNOL electric furnace at a temperature of 530 °C.

The direct extrusion combined with ECAP-PC of the billets was carried out in the die-set mounted on a hydraulic press with a nominal force of 600 kN. The press was equipped with a measuring unit including an analogue digital converter and a computer with the "IMADET 5.0" processing program. To study the strained state changing in the billet during deformation, the channel for direct extrusion was designed as axisymmetric and non-axisymmetric (figure 1).

Electron microscopic studies of the materials under study were carried out on a JEOL JEM 2100 transmission electron microscope. Static tensile tests of cylindrical specimens with a gauge length of 15 mm and a gauge diameter of 3 mm were carried out in an Instron 8862 machine at room temperature. Specific electrical conductivity (\( \mu \)) of the samples was determined using an eddy current meter for electrical conductivity of non-ferrous metals and alloys with a relative error of ± 2%.

3. Results and discussion
3.1. Simulation results
In the simulation, the relative length of the original cylindrical billet and the die shape (L/d) were varied. The deformation zone of the billet was investigated during direct extrusion in the die with axisymmetric and non-axisymmetric deforming sections. The deformation pattern during extrusion was estimated by the Lode coefficient (\( \mu_L \)), which was calculated for 80 points uniformly taken over three sections of the deformation zone.

The Lode coefficient values for the points of the deformation zone of a billet deformed in the die with a non-axisymmetric section for extrusion satisfy the inequality: -0.65≤\( \mu_L \)≤0.38. The inequality for the die with an axisymmetric deforming section for extrusion is -0.9≤\( \mu_L \)≤-0.25. The average values of the Lode coefficient are -0.14 and -0.57 respectively. The deformation schemes of the points of the billet deformed in the die with a non-axisymmetric deforming section for extrusion are close to shear. In the case the die has an axisymmetric deforming region, the scheme is close to stretching. From the obtained modeling data, it can be noted that a more uniform strain distribution in the billet deformed in the die with a non-axisymmetric deforming section for direct extrusion is due to a relatively greater strain heterogeneity in the section of a part of the billet deformed only by direct extrusion.

The study of the dependence of the deforming force on the punch displacement during pressing of a cylindrical billet 30 mm in diameter and 40 mm in length showed that the deforming force in all cases of simulation reaches its maximum value at the moment of completion of the plastic deformation.
centers formation. The maximum values of the deforming forces do not differ significantly - by 5%, and are 462 kN (axisymmetric deforming section,) 436 kN (non-axisymmetric deforming section). The lower value of the deforming force during pressing in the die with a non-axisymmetric deforming section for direct extrusion is possibly due to the influence of the deformation pattern close to shear realized during pressing.

Figure 2 shows a graphical dependence of the maximum extrusion force combined with ECAP-PC in the die with a non-axisymmetric deforming section for direct extrusion on the relative length of the original cylindrical billet. It can be seen that the dependences of the force and stress on the relative length of the initial cylindrical sample are close to linear dependences. For a relative length L/d of 18, the force reaches P=1100 kN, the maximum contact stress is 2000 MPa, which is close to the initial flow stress of tool steels in the hardened state at room temperature (2500...3000 MPa).

3.2. Experimental results

Experimental pressing of the 6063 alloy billets with a diameter of 30 mm and a length of 40 mm was carried out on the basis of the results of computer simulation. As a result of deformation processing, defect-free billets were obtained that did not contain surface defects and cracks. The maximum force value obtained by experimental measurement during experimental pressing in the die with a deforming section for direct extrusion was 421.8 kN and differed by 3.4% from the force value obtained by numerical simulation.

The specimens were made from deformed ingots to determine the mechanical properties and electrical conductivity and to assess the hardening effect of the 6063 alloy achieved after processing according to the extrusion scheme combined with ECAP-PC (table 1). For comparison of the obtained level of properties of alloy ingots after processing according to the extrusion scheme combined with ECAP-PC, table 1 shows the properties of this material subjected to standard hardening treatment T6, as well as properties after processing by ECAP-PC. It has been found that the long-sized billets subjected to processing in the die-set, made in accordance with the schemes shown in figure 1, demonstrated higher strength than the billet after special hardening heat treatment T6. The strength of the ingots obtained in various dies for extrusion does not differ significantly, however, there are noticeable differences in the uniform (before necking) deformation of samples obtained from the
billets pressed in the die with a non-axisymmetric deforming section for direct extrusion. An increased value of uniform deformation after ECAP indicates the formation of a more homogeneous UFG structure, which is also very important for enhancement of fatigue properties of materials [4].

Table 1. Mechanical properties and electrical conductivity of the 6063 alloy

| Treatment | \(\sigma_{0.2}\), MPa | \(\sigma_{\text{B}}\), MPa | \(\delta_p\), % | \(\delta_{\text{R}}\), % | \(\mu\), MS/m |
|-----------|----------------------|----------------------|----------------|----------------|-------------|
| Direct pressing in the die with axisymmetric deforming section + ECAP-PC at 100 °C | 203±5 | 224±3 | 3,0±0,3 | 12,0±0,3 | 29,98±0,3 |
| Direct pressing in the die with non-axisymmetric deforming section + ECAP-PC at 100 °C | 210±6 | 230±3 | 6,0±0,3 | 11,0±0,3 | 30,01±0,2 |
| ECAP - PC, 4 cycles at 100 °C [3] | 256±2 | 264±2 | - | 12,5±0,3 | 30,04±0,2 |
| T6 | 145±5 | 195±3 | - | 8,0±0,2 | 30,16±0,2 |

The values of specific electrical conductivity of the billets after one cycle of processing by the new combined method and four cycles of ECAP-PC are practically the same. This indicates that already in one processing cycle, along with the formation of a developed substructure, dynamic aging occurs in the material, accompanied by a decrease in the concentration of alloying elements in the aluminum solid solution, to a level comparable to that achieved after multi-cycle deformation processing.

The conducted electron microscopic studies of the microstructure of the billet showed that after direct pressing combined with ECAP-PC the initial coarse-grained structure transformed into a lamellar-type structure (figure 3), which had a pronounced orientation relative to the shear direction. The average transverse size of the formed (sub)grains was 430 nm, and the longitudinal size was up to 1500 nm, respectively. Thus, it is the significant refinement of the initial microstructure of the alloy achieved during processing that ensured the achievement of a strength level in the 6063 alloy that exceeds the strength of course grained material after standard hardening treatment and acceptable electrical conductivity.

Conclusion
1. Processing the aluminum alloy 6063 using a new technique by direct extrusion combined with ECAP-PC was studied by computer simulation and full-scale experimental characterization.
2. It was shown that a single cycle of direct extrusion combined with ECAP-PC provided a noticeable increase in strength and ductility of the 6063 alloy as compared with the standard hardening heat treatment (T6). This indicates that the proposed technique is promising for processing of aluminum alloys.

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