

THE ROLE OF SEVERE PLASTIC DEFORMATION IN THE FORMATION OF HIGH ELECTRICAL PROPERTIES OF ALUMINUM ALLOY

РОЛЬ ИПД ПРИ ФОРМИРОВАНИИ ПОВЫШЕННЫХ СВОЙСТВ ЭЛЕКТРОТЕХНИЧЕСКОГО АЛЮМИНИЕВОГО СПЛАВА

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Abstract: At present time there is considerable interest in extending the application area of low-alloy and rather inexpensive heat-hardenable aluminum Al-Mg-Si alloys in the automotive industry, aviation, construction and electrical engineering. In this regard, the topical problem is to enhance strength and electrical conductivity of such materials, which would subsequently reduce the weight of products made of structural and electrical Al-Mg-Si materials. Severe plastic deformation is one of the promising methods of obtaining a significant increase in properties. In this paper a new SPD method is investigated – Multi-ECAP-Conform, characterized by the fact that per one processing cycle the accumulation of true strain is provided up to $\epsilon > 2.5$. In order to study the stress-strain state effect on the mechanical properties of the aluminum Al-Mg-Si alloy, mathematical and physical modeling with the modern software Deform-3D were applied, as long as the well-established techniques of assessment of materials mechanical characteristics after plastic processing. The obtained results demonstrate the adequacy of using mathematical and physical modeling to estimate the stress-strain state by Multi-ECAP-Conform.

KEYWORDS: ALUMINUM ALLOYS, SEVERE PLASTIC DEFORMATION METHODS, ULTRAFINEGRAINED STRUCTURE, MATHEMATICAL MODELING

1. Introduction

Currently, there is a considerable interest in extending the range of application of low-alloy and relatively cheap thermally hardenable aluminum Al-Mg-Si alloys in automotive industry, aviation, construction and electrical engineering [1-3]. In this regard, the topical problem is to enhance mechanical properties of such materials, which would reduce dimensions and, hence, the weight of produced articles. One of the ways of increasing strength and other properties of aluminum alloys is severe plastic deformation (SPD), which makes it possible to produce an ultrafine-grained structure and achieve enhanced properties via several cycles of deformation combined with heat treatment [4]. The most advanced for commercial application techniques are ECAP-Conform and ECAP in parallel channels (ECAP-PC), which ensure the UFG structure formation via high-cycle processing in elongated and discrete billets with high metal utilization factor. But these techniques have disadvantages – the process duration (multi-cycle processing) and higher energy consumption. In order to remove the above shortcomings, we developed a new modification of ECAP-Conform (Multi) providing the enhanced – ~ 3 times – level of accumulated strain in one processing cycle. In this regard, a thorough study of the features of the new ECAP-Conform modification is required, including the investigation of the stress-strain state and its relationship with mechanical and functional properties of the aluminum Al-Mg-Si alloy.

2. Principle of Multi-ECAP-Conform processing

The main feature of Multi-ECAP-Conform is that it combines the advantages of a continuous process of ECAP-PC and ECAP-Conform resulting in a significant change of the deformation scheme at a pressing stage, as compared to other SPD methods. The process is implemented as follows: the metal billet 1 in the form of a rod is subjected to continuous angular pressing; it is fed to the input of a working channel formed between the rotating roll 2 with U-shaped engraving and a fixed limiting base (shoe) 3, surrounding the turning roll and covering a part of the groove length of. Via the roll 2 rotation and frictional forces appearing between the engraving and the billet 1, the billet is moved through the working channel in the direction towards the outlet in the shoe 3.

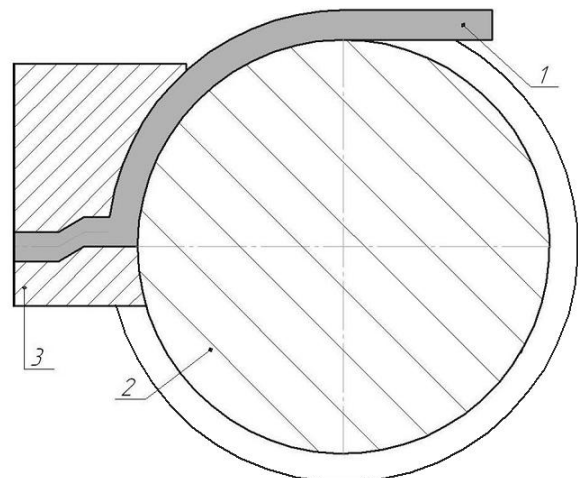


Fig. 1. Scheme of Multi-ECAP-Conform:
1 - billet, 2 - roll, 3 - limiting base

In this regard, the purpose of this work is to study the stress-strain state of the Multi-ECAP-Conform and the impact of this process on the mechanical and functional properties of aluminum Al-Mg-Si alloys.

3. The process modeling

The analysis of the proposed scheme was performed using mathematical modeling on software DEFORM-3D [6]. The material of the initial billet is aluminum (Al-6101), its size is 12x12 mm, the cross-section of the final product – wire rod – is 11x11 mm.

Conditions and assumptions used in modeling on software DEFORM-3D:

- The billet material in the initial state (before straining) is isotropic and has no initial stresses and strains;
- The billet temperature is assumed constant – 20 °C, the deformation heating is disregarded;
- The tool is assumed absolutely rigid; geometry of the tool – 3D models – were previously created in KOMPAS 3D 11V and saved with the extension stl;
- The initial billet material is assumed ductile;

- The material taken for modeling AL 6101, the hardening curves were taken from the DeForm-3D library;
- The coefficient of friction (shear) between the rolls and the billet was taken equal to 0.5, between the die and the billet – 0.5 (recommended for use);
- The number of modeling steps - 620...1030, with a step of 1 s.
- The roll speed is 40 turns per minute.

Results of computer modeling show that compressive stresses dominate in the deformation sites – this affects the fabrication of defect-free semi-products in a positive way. At the output to the horizontal channel the area with tensile stresses is observed (Fig. 2). We should note that the tensile stresses do not exceed 100 MPa and are close to the alloy yield stress value at the temperature of straining.

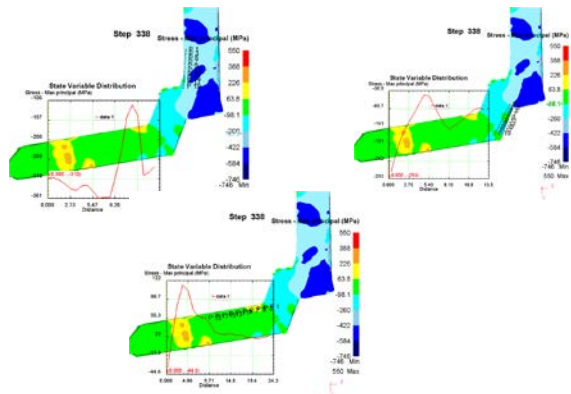


Fig. 2. Maximum stresses occurring during Multi-ECAP-Conform

Computer modeling results show that in the billet longitudinal section the strain intensity is $\epsilon = 4.5...4.7$ units, and in the cross section ~ 6 units (Fig. 3). It is known that the level of accumulated strain exceeding $\epsilon = 4-5$ typically results in the UFG structure formation during ECAP [9], therefore, accumulation $\epsilon=4-5$ per processing cycle under Multi-ECAP-Conform is a sufficient factor for the formation of an ultrafine-grained structure. This is also evidenced by the high level of obtained mechanical and functional properties of semi-finished products.

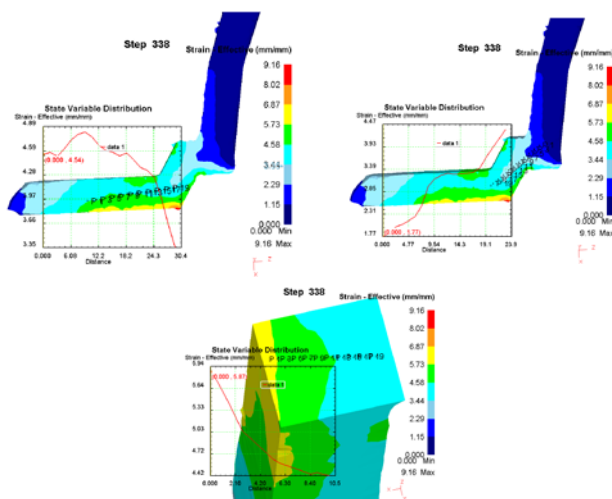


Fig. 3. Pictures of the intensity distribution in the sample deformation, with Multi-ECAP-Conform

4. Results of experimental studies

For research we used the aluminum alloy Al 6101 (Al-basis, 0.8 Mg-0.41Si-0.1Cu-0.03Mn-0.5Fe-0.1Zn wt.%) in the cast homogenized state. The billets of 12 mm in diameter and 150 mm in length were cut from the initial ingot.

Before Multi-ECAP-Conform, the billets were subjected to annealing at 540 °C and subsequent quenching in water.

In this study we used the original setup for Multi-ECAP-Conform designed and fabricated in the Institute of Physics of Advanced Materials, USATU [5].

We conducted tensile tests to evaluate the mechanical properties according to GOST 10446-80 at room temperature on Instron 1114. The traverse speed was 1 mm/min. The force measurement accuracy is 1 %. Strength characteristics were determined in accordance with GOST 1497-84, using the tensile test results of samples with the working part of $\varnothing 3$ mm x 15 mm.

Electrical resistivity (ρ) was determined according to GOST 7229-76 and GOST 12177-79 using test equipment: aspirated psychrometer MV-4M (accuracy ± 2 %), barometer – aneroid BAMB-1 (division value 0.1×10^3 Pa) and microohmmeter BSZ (accuracy class 0.1).

The measurements were performed on straightened wire samples of 1000 mm in length. The wire sizes were measured by a metal ruler with a scale of 1 mm and micrometer MK-25 with a division value of 0.01 mm. The measurement error was no more than 1%. The ambient temperature was 23.5 °C (with account of the temperature coefficient according to GOST 7229-76 - 0.9745), atmospheric pressure – 100.1 kPa, relative humidity – 55%.

Electrical resistivity (ρ) was calculated using the formula [7, 8]:

$$\rho = \frac{R \cdot l}{S}, \quad (1)$$

where R – the measured electrical resistance;

S – the cross sectional area of the sample;

l – length of the sample

After ECAP, the billet was subjected at room temperature to drawing to a diameter of 3 mm. The results of tensile tests on the wire made it possible to obtain tensile strength equal to 375 ± 10 MPa, which exceeds standard values of this alloy 60-100 MPa

Electrical resistivity is 30.94 Ohm/km for 1 mm² (55.7 %), and total elongation is over 3 %, which is a consequence of the UFG structure formation and is similar to the results of similar studies carried out according to the traditional ECAP scheme [10].

5. Conclusions

1. The stress-strain state of a new method of Multi-ECAP-Conform was investigated:

- it was revealed that at a stage of steady flow the accumulated strain reaches $\epsilon = 6$, which typically ensures the formation of an ultrafine-grained structure and, therefore, has a considerable impact on the increase in mechanical characteristics of semi-products;

- it was established that during Multi-ECAP-Conform mainly compressive stresses are formed in the deformation zones, which contributes to the fabrication of defect-free wires;

2. The obtained values of tensile strength and electrical resistivity of the samples after Multi-ECAP-Conform exceed standard values of semi-products (wires) for electrical purposes, indicating the effectiveness of the new method.

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