Processing ultrafine-grained Aluminum alloy using Multi-ECAP-Conform technique

Elvira Fakhretdinova 1, Georgy Raab 1, Oleg Ryzhikov 2, Ruslan Valievy 1
1Ufa State Aviation Technical University, Ufa, Russia
E-mail: yelka89@mail.ru
2Bashkir State University, Ufa, Russia

Abstract. The stress-strained state (SSS), contact and force parameters of a new SPD technique – Multi-ECAP-Conform – have been studied. The new technique ensures a high level of accumulated strain €=4…5 per one processing cycle. Physical and computer modeling by finite element method in Deform-3D software was applied to evaluate the parameters. It is shown that the results of physical and computer modeling correlate with each other. Equipment has been upgraded, and experimental samples of Al-Mg-Si system alloy have been processed.

Introduction

Currently considerable interest is paid to development of industrial technologies by severe plastic deformation techniques (SPD), which ensure nanostructuring of metals. SPD technologies can be applied to manufacture long-length semi-products (wires, bars, rods) for example from low-doped and comparatively cheap heat-hardenable alloys of the Al-Mg-Si system for electrical engineering [1-3]. Structure refinement to an ultrafine-grained (UFG) state in these alloys in combination with heat treatment results in simultaneous increase of strength and electric conductivity [4,5]. Promising SPD techniques, such as ECAP-Conform [6] and ECAP in parallel channels (ECAP-PC) [7], ensure UFG structure formation in billets in the conditions of high-cycle processing. A high metal utilization is very important for industrial production. However, these schemes have their disadvantages connected with processing duration (high-cycle processing) and, therefore, enhanced energy- and labor consumption. A new modification of ECAP-Conform – Multi-ECAP-Conform – has been developed to eliminate the mentioned drawbacks. The Multi-ECAP-Conform ensures a 3-times-enhanced level of accumulated strain per one processing cycle. Careful investigation of the new modification features of the ECAP-Conform technique is required, which would include investigation of the stress-strained state, deformation schemes, contact conditions “billet-tool” and force parameters of Al-Mg-Si system billet processing. The analysis was conducted through physical experiment and computer modeling by the finite element method in the Deform-3D software.

1. Principle scheme of Multi-ECAP-Conform processing

The main feature of the Multi-ECAP-Conform is that it combines three successive shears through one processing cycle [8].

The process is implemented as follows (Fig. 1): a rod-shaped metal billet 1 is subjected to continuous angular pressing; the billet is fed to the input of a working channel formed between the rotating roll 2 with a U-shaped groove and a fixed limiting base (shoe) 3, surrounding the turning roll and covering a part of the groove length. The billet is pressed through the working channel in the direction towards the outlet in the shoe 3 due to rotation of the roll 2 and friction forces initiated between the groove and the billet.
2. Modeling by finite element method

The analysis of the proposed scheme was performed through computer modeling with the DEFORM-3D software [9]. The material of the initial billet is aluminum (Al-6101), its size is 12x12 mm, the cross-section of the final rod-shaped product is 10x10 mm.

Conditions and assumptions used in modeling with the software DEFORM-3D are:
- The billet material in the initial state (before deformation) is isotropic and has no initial stresses and strains;
- The billet temperature is assumed constant – 150 °C, the deformation heating is neglected;
- The tool is assumed absolutely rigid; geometry of the tool (3D models) is created in KOMPAS 3D 11V and saved with the extension stl;
- The initial billet material is assumed ductile;
- The material taken for modeling is Al 6101, the hardening curves were taken from the DeForm-3D library;
- The coefficient of friction (shear) between the tool and the billet was taken equal to 0.5, as recommended by DeForm-3D;
- The number of modeling steps - 360, with a step of 0.05 s.
- The roll speed is 20 turns per minute.

3. Results of computer modeling

Investigation of the deformation scheme

Taking into account that the shear scheme increases the intensity of initial structure refinement [10], investigations were performed to evaluate a scheme formed in the deformation zones. A Lode-Nadai coefficient was used as a criterion for deformation scheme evaluation [11]. The calculations of the Lode-Nadai coefficient were conducted via the formula:

\[ L = \frac{1}{3} (\sigma_{11} + \sigma_{22} + \sigma_{33}) \]

where \( \sigma_{ij} \) are the principal stresses.

Fig. 1. Scheme of Multi-ECAP-Conform:
1 - billet, 2 - roll, 3 - limiting base
where $\sigma_1$, $\sigma_2$, $\sigma_3$ - are the main stresses (MPa) for three successive shear deformation zones obtained from the mathematical modeling database. Fig. 2 a, b displays the investigation scheme of deformed areas on the symmetry axis and the results.

The performed analysis of the obtained results showed that a shear scheme dominates in the central area of deformation zones (I,II,III), to which the obtained Lode-Nadai
Coefficient values close to zero testify. A compression scheme prevails in the areas between the zones (P1-P2) and (P6-P8), and in the (P11-P13) zone a tension scheme is predominating. **Investigation of main stresses and strains.** The analysis of the results of computer modeling showed that compressive stresses prevailed in the axisymmetric area of a deformed billet. The compression schemes, as a rule, ensure manufacturing of defect-free semi-products. An area with low tensile stresses up to ~10 MPa (Fig. 2b) forms in the horizontal channel, which is considerably lower than the flow stress (~150 MPa) of the alloy at the deformation temperature.

![Diagram](image)

**Fig. 3** – Scheme of sample investigation (a), maximum compressing and tensile stresses (b), strain degree (c) in the deformed zone of the sample obtained from the mathematical modeling database

As it follows from the analysis of the strain distribution picture (Fig. 3a), the accumulated strain in the longitudinal section is $e=4.5...4.7$ (Fig. 3c). As it is known, the level of accumulated strain during ECAP exceeding $e=3$ results in formation of a UFG structure, as a rule [12]. One may assume that the shear character in the deformation zones and high level of accumulated strain $e=4-5$ per one processing cycle are sufficient for the UFG structure to form. **Investigation of contact stresses.** Investigation of contact stresses at the stage of stable flow indicates that the maximum contact stresses are up to ~750 MPa and are not critical for the process to take place. The allowed values of stresses for cold deformation of modern steels can amount to 2500 MPa (Fig. 4) [13].
4. Results of experimental studies

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 was used for research. Billets of 12 mm in diameter and 150 mm in length were cut from an initial ingot.

Before Multi-ECAP-Conform processing, the billets were subjected to annealing at 540 °C (2 hours) and subsequent quenching in water.

In this study an original setup for Multi-ECAP-Conform (Fig. 6a) designed and manufactured in the Institute of Physics of Advanced Materials of Ufa State Aviation Technical University was used [8].

Figure 5 – Practical implementation of Multi-ECAP-Conform:
(a) the die-set for Multi-ECAP-Conform; billets before (b) and after (c) pressing
One of the purposes of the study is to assess the force parameters of Multi-ECAP-Conform processing, therefore, a comparative analysis (physical experiment and computer modeling) of torque during processing of billets was conducted. The frequency control system was used in the physical experiment to register the torque with registration of data in LabVIEW software. All data are entered into the program virtually using freeware NI MODBUS Library 1.2.1 [14]. It uses RS485 ports built-in the frequency controller that work under the MODBUS RTU protocol. The fragment of a block diagram of data received from a frequency controller and a temperature controller is shown in Figure 6.

![Fig. 6. Block diagram of data reception](image)

The data of the computer modeling and physical experiment are presented in Figure 7. The analysis shows that the plotted torque-versus-time curves are of similar nature, and the physical experiment shows a higher maximum torque that exceeds the results of computer modeling by 0.4 N • mm.
b) Fig. 7 - Graph of torque versus time as of the modeling results (a) and experiment (b)

It can be seen that the estimated error of the maximum torque value deviation during the computer modeling and physical experiment is ~ 12% according to

\[ \varepsilon = \frac{3.3 - 2.9}{2.9} \cdot 100\% = 12\% . \]

Conclusions
1. A modified technique of ECAP-Conform (Multi-ECAP-Conform) was proposed and investigated the physical and computer modeling. The technique allows producing billets with ultrahigh strains \( \varepsilon = 4...5 \) per one processing cycle.
2. It was established that in the axisymmetric area of deformation zone the estimated Lode-Nadai coefficient had a value close to zero. This indicates of the shear scheme taking place in the deformation zones of the Multi-ECAP-Conform technique.
3. The analysis of the computer modeling results showed that in the axisymmetric area of the deformed billet mainly compressive stresses were formed, which contributed to production of defect-free semi-products.
4. It was established that the maximum contact stresses at the stage of stable flow amounted up to ~750 MPa, which was three times less than the allowed values, and were not critical for the process.
5. The use of computer modeling to study the process, in particular, the torque on the wheel providing force characteristics, shows a good agreement with the real physical experiment. The error of computer and experimental measurements of the torque was ~ 12%.

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