The innovation potential of ECAP techniques of severe plastic deformation

Georgy Raab
Ufa State Aviation Technical University, Ufa, Russia
E-mail: giraab@mail.ru

Abstract
The most considerable factors influencing flow uniformity and a strained state of billets, respectively, structure formation processes and ECAP techniques with industrial potential have been studied. It is shown that the industrial potential of ECAP techniques largely depends on the intensity of strain accumulation per a processing cycle. Enhancement of this value considerably reduces the labor intensity of manufacturing of semi-products with an ultrafine-grained (UFG) structure.

1. Introduction
Severe plastic deformation by equal-channel angular pressing implies multi-cycle pressing of workpieces through two channels of equal cross sections that intersect at an angle (Fig. 1a) [1]. The angle of channels intersection \( \phi \) is usually 90\(^{\circ} \), although other angles are also used, up to 120\(^{\circ} \) (Fig. 1b). The pressing is usually conducted on presses with a vertical frame, therefore, one of the channels is taken as vertical. The initial workpiece is placed in a vertical channel and pressed by a punch into a “horizontal” channel. A next workpiece presses the first workpiece out of the “horizontal” channel. Repeated pressing of one and the same workpiece leads to a substantial change in its initial coarse-grained structure till the formation of ultrafine and nanostructured grains [2]. This change in the initial structure occurs in the conditions of intensive straining by the simple shear scheme, which takes place in the process of ECAP [1, 2]. The intensity of UFG structure formation largely depends on the pressing route, the route Bc is most preferable [2, 4]. Typically, the grain structure with an average crystallite size of about 0.3-0.5 \( \mu \)m forms in deformed metals after the accumulation of strain \( \varepsilon =4 \) and more [2].

In the last decade the interest of researchers has been focused on the development of ECAP techniques for commercial production of UFG metals and alloys. In this regard, a number of modifications of ECAP process aimed to improve its efficiency was proposed [4,5]. This paper considers recent ECAP techniques developed in our laboratory for practical use.
2. ECAP techniques for commercial use

ECAP techniques for commercial purposes must meet the following requirements. They must:
- have a high coefficient of metal utilization, i.e. minimum metal loss after processing;
- have a high productivity rate;
- have high efficiency of UFG structure formation at minimal processing cycles.

The ECAP techniques that meet these requirements to the fullest are presented below.

2.1. ECAP in parallel channels (ECAP-PC)

A distinctive feature of the ECAP-PC scheme [6] is that during one processing cycle, two shears occur (Fig. 2), the total accumulated strain reaches values close to \( \varepsilon=2 \), which enables significantly decreasing the number of pressing cycles during UFG structure formation. The coefficient of metal utilization of the ECAP-PC scheme amounts to the value close to 0.9.

---

Fig. 1, a. Schematic diagram of ECAP in the die-set with an angle of channels intersection \( \Phi = 90^\circ \) [1] 
Fig. 1, b. Geometric illustration of the simple shear scheme at ECAP depending on the \( \Psi \) parameter, where \( R \) is the fillet radius of an internal angle of channels intersection, \( r \) – the external one
The ECAP-PC scheme - (a), where N – direction of shear, K – value of channel displacement, Φ – angle of intersection of vertical channels and the one connecting them; (b) – view of deformation zones obtained by 2D-modeling of ECAP-PC; (c) – general view of the ECAP-PC die-set - with Φ = 100°, K = 1d = 18 mm and d = 18 mm

Fig. 2. The ECAP-PC scheme - (a), where N – direction of shear, K – value of channel displacement, Φ – angle of intersection of vertical channels and the one connecting them; (b) – view of deformation zones obtained by 2D-modeling of ECAP-PC; (c) – general view of the ECAP-PC die-set - with Φ = 100°, K = 1d = 18 mm and d = 18 mm

Theoretically, the billet does not change its original shape, thus, it is important to implement this condition in practice. Indeed, the practice shows that the billet geometry before and after straining is quite similar, the opportunity to produce cylindrical UFG billets with a small L/d ratio arises (Fig. 3).

Fig. 3. General view of UFG copper billets: (a) – after 4 ECAP cycles by the traditional scheme with an angle of channels intersection = 90°, L/d = 4; (b) – after 4 ECAP-PC cycles with an angle Φ = 100°, K = 1 and L/d = 4, (c) – after 4 ECAP-PC cycles with Φ = 100°, K = 1 and L/d = 2

However, the die-set parameters, such as the value of channels displacement K and the angle of channels intersection Φ, can affect the flow nature, the stress-strain state and force characteristics of the ECAP process. Therefore, it is essential to investigate the effect of these most important factors on the parameters of UFG structure formation for each process developed with ECAP-PC application.

Practical use of this method is most effective when the rotor lines are designed that allow for several parallel processing cycles, from 2 to 3 ECAP cycles and up to 5 cycles of post-processing (extrusion). This technique reduces the processing time per a workpiece and automatizes the processes of structuring by ECAP-PC and extrusion to fabricate final properties and shapes. In these conditions the ECAP-PC is economically sound in batch and mass production of discrete workpieces with the initial length-to-diameter ratio not over 5.

2.2. ECAP-Conform (ECAP-C)

Pressing by the Conform scheme has been is known since 1970s [5]. A distinctive feature of this process is that the deforming force is generated by active friction forces arising
on the rotor groove. The pressing channel is formed by the rotor groove 1 and work surfaces of the block 2 (shoe) and the support 3 (Fig. 4) [5]. The important characteristics of ECAP-C process are: the workpiece contact arc – \( L \) (mm) created due to eccentricity of the work surfaces of the wheel and the shoe; the torque on the rotor – \( M \) (Nm); angular velocity of the rotor rotation – \( \omega \) (s\(^{-1}\)); speed of the billet pressing – \( V \) (m s\(^{-1}\)) and an angle of channels intersection \( \Phi \) (Fig. 4.1, b).

Fig. 4. Schematic diagram of ECAP-C: 1 - rotor with a groove; 2 - block (shoe); 3 – support; 4 – workpiece; a – scheme of the active \( F_a \) and passive \( F_p \) friction forces; b - the most important process parameters, where \( L \) – the workpiece contact arc; \( M \) - torque; \( \omega \) - angular velocity of the rotor rotation; \( V \) – pressing speed; \( \Phi \) - angle of channels intersection

This scheme is advanced for the production of most demanded in industry elongated billets. The coefficient of metal utilization in ECAP-C is close to 0.95. The drawbacks of this technique include a square shape of cross section and a limited strengthening value in conditions the of multi-cycle treatment, which is commonly present in all ECAP schemes under fixed processing conditions.

Fig. 5 displays a general view of the UFG billet of commercially pure titanium after 4 ECAP-C cycles. The CP titanium strength in the UFG state is about 1000 MPa, the ductility is 12-14%.

Fig. 5. General view of a long-length billet of the UFG CP titanium with a square cross section after four processing cycles

A positive example of the implementation of a continuous technology using SPD is the manufacture of nanostructured titanium rods with an annual capacity of up to 2 tons in NanoMeT Ltd. (Russia) [www.nano-titanium.com], where the technological line including ECAP-C, drawing and final precision grinding results in production of high-strength (up to 1300 MPa) semi-products demanded in dentistry [9].

The barrier to intensive development of SPD techniques for commercial use is multiple processing cycles, which are certainly expensive. In this regard, the techniques resulting in a more intensive UFG structure formation per one processing cycle are in demand. One of such techniques is Multi-ECAP-Conform that allows accumulating shear strain up to \( e=3.5-4 \) in a long-length billet per one processing cycle (Fig. 6) [10]. The scheme was tested during the production of ultrafine-grained Al-Mg-Si billets (Fig. 6).
The implementation of this technique is the result of research focused on the tool modification, control over the material steady flow and creation of special friction conditions providing the grip of the billet and its straining. The role of flow nature in the implementation of such complex processes is presented below. Taking into account that Multi-ECAP-Conform is a combination of a conventional scheme and ECAP-PC, let us analyze these two processes.

3. Role of the material flow nature during ECAP

The die-set geometry and the friction conditions have a decisive impact on the flow nature during straining. Thus, using the example of pressing of copper with backpressure, one can trace the flow features during conventional ECAP. For the die-set geometry with an angle of channels intersection 90° and absence of fillet radii, i.e. $R = r = 0$, the formation of a stagnant zone is observed in the interior angle area. Even separation of the billet part located in the stagnant zone can occur during straining (Fig. 7). This phenomenon does not depend on the kind of ECAP technique, but results from the used geometry and a certain backpressure value in the horizontal channel. Therefore, when the shear straining processes are combined, as in Multi-ECAP-Conform, this factor should be taken into account. The measures should be planned to eliminate these negative factors.

Fig. 6. Scheme of Multi-ECAP-C (a) and aluminum semi-products obtained through this technique (b)

Fig. 7. Flow nature of copper M1 billets with a section of 16×16 mm during ECAP by backpressure = 500 GPa: a – experiment, the mesh method ($R = r = 0$), b – flow pattern of copper M1 billet with a section of 16×16mm with backpressure (finite element method) ($R = r = 0$), c – general view of the billet and the separated part of the material in a stagnant zone.
Fig. 8 shows the flow patterns during the ECAP-PC depending on the used geometry. It can be stated that the parameter of parallel channels displacement K has a decisive impact on the flow nature, at K=0.5d the output channel is not filled at all, the material flow is extremely non-uniform. As K parameter increases to K=1d, the channels are filled completely, the uniformity of the flow increases. The most uniform flow in this case is formed when the fixed fillet radii of channels are used. Fig. 7 represents the channels fillet radii equal to 0.2d, where d is the diameter of the billet. Such channel geometry provides a high level of the flow uniformity and, accordingly, ensures the uniformity of the structural state after treatment.

Conclusions
1. For the development of processes employing ECAP techniques, there were investigated the most significant factors affecting the uniformity of flow and strained state in the billets, and, accordingly, of metal nanostructuring, especially when the ECAP techniques combining successive shears are used.
2. It is shown that the commercial potential of ECAP techniques strongly depends on the intensity of strain accumulation per processing cycle. The increase in this value greatly reduces the labor intensity of the manufacturing of semi-products with a UFG structure.

References
[1] Segal V.M., Reznikov V.I., Drobyshevskiy A.S., Kopylov V.I. Plastic working of metals by simple shear // Metals. 1981. – V.1. p.115 -123 (in Russian).
[2] Valiev R.Z., Islamgaliev R.K. and Alexandrov I.V., Bulk Nanostructured Materials From Severe Plastic Deformation, Prog. Mat. Sci. 45 (2000), pp.103-189.
[3] Valiev R.Z. and Langdon T.G., Principles of equal-channel angular pressing as a processing tool for grain refinement, Prog. Mater. Sci. 51 (2006), pp. 881-981.
[4] Cheng Xua, Steven Schroederb, Patrick B. Berbonc, Terence G. Langdon Principles of ECAP–Conform as a continuous process for achieving grain refinement: Application to an aluminum alloy // Acta Materialia Volume 58, Issue 4, February 2010, Pages 1379–1386.
[5] Georgy J. Raab, Ruslan Z. Valiev, Terry C. Lowe, Yuntian T. Zhu Continuous processing of ultrafine grained Al by ECAP–Conform // Materials Science and Engineering: A 382 (2004) pp. 30–34.
[6] Raab G.I. Plastic flow at equal channel angular processing in parallel channels // Mat. Sci. Eng. 2005. V. A 410–411. P. 230–233.
[7] Green D. // J. of Inst. Of Metals. 1972. Vol. 99. 76-84
[8] Horita Z., Ohashi K., Fujita T., Kaneko K. and Langdon T.G.. Achieving High Strength and High Ductility in Precipitation-Hardened Alloys. //Advanced Materials. 17. 2005. P.1599-1603.
[9] Patent No 2490356 “Ultrafine-grained two-phase alpha-beta titanium alloy with increased mechanical properties and the method of its fabrication”. Authors: Semenova I.P., Raab G.I., Polyakova V.V., Valiev R.Z. published on August 20, 2013.
[10] Application for an invention No 2013156136 of December 17, 2013 “Continuous equal channel angular pressing of metallic workpieces shaped as rods”. Authors: Raab G.I., Fakhretdinova E.I., Kapitonov V.M., Valiev R.Z.