Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 23
ISSUE 2
August
2007

Increasing SPD effectiveness by changing deformation process in the first pass through the ECAP die

S. Rusz [a,*], K. Malanik [b], M. Klos [a]
[a] VSB – Technical University of Ostrava, Faculty of Mechanical Engineering, 17 listopadu 15, 708 33 Ostrava – Poruba, Czech Republic
[b] VUHZ Dobra a. s., 738 01 Dobra, Czech Republic
* Corresponding author: E-mail address: groot@amme.com

Received 04.04.2007; published in revised form 01.08.2007

Analysis and modelling

ABSTRACT

Purpose: Purpose of this paper Technology ECAP belongs to the most efficient technologies for production of materials with ultra-fine grained structure. Its disadvantage consists in necessity to make 4 to 5 passes through the channel of forming tool in order to obtain high degree of deformation needed for grain disintegration.
Design/methodology/approach: Newly proposed geometry of the channel makes it possible to achieve up to double amount of deformation during the first pass through deformation tool.
Findings: In this manner it is possible to obtain much higher efficiency of the whole process. It is a completely new approach to development of this technology.
Research limitations/implications: New geometry of tool has been designed which represents the first step toward application of the given equipment in semi-industrial conditions.
Practical implications: Obtained results form good pre-requisite for further development of technology for production of ultra-fine grained materials.
Originality/value: Achievement of high amount of deformation already at the first pass through the modified ECAP tool. This will create an ultra-fine grained structure, which makes it possible to obtain required mechanical properties of formability with much lower number of passes. New findings will be applied in the field of forming.
Keywords: Computational material science; Severe plastic deformation; Amount of deformation; ECAP geometry; Curvature radius; Mathematical simulation; Stress and strain dissolution; Formability

1. Introduction

1.1. Description of theoretical models of formation of nano-structural materials

Models of nano-crystalline materials are defined as two-phase composites determining mechanical properties according to the so called "mixture rule". Yield point of nano-crystalline materials is ratio of yield point of the phase of grain interior and the phase of its edges, which depends strictly on voluminal crack of the grain boundary. It is presumed that yield point of the phase of grain boundary is lower than that of the phase of grain interior [1]. Evaluated theoretical models are characterised by process of deformation mechanisms, description of these mechanisms and movements of lattice dislocations (shifting of grain boundaries, diffusion massive shifting) [1, 2]. Theoretical models are based on structural characteristics of nano-crystalline materials (nano-dimensional structures), on big volume of dislocations at grain boundaries and on deformation behaviour of nano-crystalline

materials. One of specific features of deformation process in nano-crystalline materials is manifested by deviations from the known relation of grain size scale. Classical Hall-Petch relationship (1) describes relation between yield point and grain size of poly-crystalline material. This equation is determined for grain size bigger than 1 micron.

$$\tau = \tau_0 + k \cdot d^{-1/2} \tag{1}$$

Some types of theoretic models are based on the principle of movement of dislocations in grains as basis of deformation mechanism in nano-crystalline materials (see Figure 1). By this modification it is possible to obtain nano-dimensions in comparison with primary poly-crystals.

1.2. Masumura's theoretical model

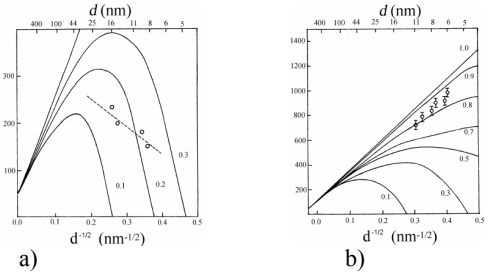
Masumura started from data in Hall-Petch diagram - yield point and grain size exponent – expressed by relationship 1 till the time, when very fine grain is obtained. Arrival of nano-crystalline materials, where grain size is measure in nano-meters, required revision of results with simultaneous verification of usability and validity of Hall-Petch relationship (1) with use of experiments [1].

a) b)

Fig. 1. Grain size (a) act as obstacles for lattice dislocation in primary poly-crystals, (b) as softening of building elements, which carry plastic flow in nano-crystalline materials [1, 2]

$$d_{c1} = q \cdot \delta \cdot \frac{1-q^2}{2 \cdot q} \left(1 - 2 \cdot \frac{\tau'_m}{K_m} \sqrt{\frac{\delta(1-q^2)}{2q}} \right) \tag{2}$$

The principle consisted in description of yield point or micro-hardness of inter-granular phase by selection of data fro amorphous materials of similar chemical composition and according to dislocations, which can exist in nano-crystals or in nodes of grain boundaries [1, 3].



a) b)

Fig.2. Dependence of micro-hardness on grain size at different atomic densities of grain boundaries: (a) Cu and (b) Fe. This quantity is characterised by the parameter q. Numbers on curves give value of this parameter. Straight broken line was plotted on the basis of obtained experimental values

1.3. Carsley's theoretical model

Very similar model, the principle of which consists in movement of dislocations was later proposed by Carsley for description of micro-hardness of nano-crystalline materials [1, 3].

Properties of inter-granular phase were considered as properties suitable for metallic glasses, micro-hardness H_{gb} of which was considered as constant and equal approximately to 1/6 of shear modulus of metallic glass μ_{gl}, while in case of crystalline metal it was rounded to the half of μ_{cr} [1, 3]. Thickness of grain boundaries was chosen to be 1 nm. In comparison with experimental data for nickel, iron and copper the Carsley's model determines precisely main shape of the curve H - $d^{-1/2}$ for all three metals (see Figure 2).

1.4. Kim's theoretical model

Theoretical model is based on existence of critical grain size of nano-crystal dc, and on validity of Hall-Petch relationship (1). It is valid only for the variant, when d≥ dc, in smaller grains relation (d≤ dc) is valid. No strengthening effect is included. Mode of ideal plasticity, which is realised if micro-hardness is constant and does not depend on grain size, is expressed by the relation 3 [1, 4].

$$d_{pedk} = \left[\frac{3\delta}{\beta}(H_o - H_{ic}) + \sqrt{\left[\frac{3\delta}{\beta}(H_o - H_{ic}) \right] + 7\delta^2} \right] \tag{3}$$

Calculations were made for the same metals (Ni, Fe a Cu) as in previous case, with the same values of parameters. Practically identical curves H($d^{-1/2}$) were obtained, which had characteristic values of maximum $d = d_{pedk} \approx 3 \div 4$ nm [1,4,6].

Significant deviations of micro-hardness according to the Hall-Petch relationship (1) and reduction in the areas of small grain sizes are explained by peculiarities of interactions of dislocation slippage along grain boundaries with obstacles. Model of diffusion flow was considered to be the mechanism of grain boundaries plasticity [1, 4, 7]. Diffusion of grain boundaries is at small grain sizes the dominant deformation mechanism. In case of coarse-grained materials strain rate is the main mechanism of dislocation slippage [1, 4, 8].

1.5. Ovidk's theoretical model

This theoretical model describes slippage of grain boundaries as prevailing deformation mechanism of plastic flow in nano-crystalline materials at elementary, nano-dimensional levels. Plastic deformation behaves as general defects of crystals. Dislocation of crystal lattice and dislocations at grain boundaries expressed by Burgers vectors have usually order of the lattice parameter. Plastic deformation at nano-dimensional level of nano-dislocations is described with variable Burgers vectors. Each nano-dislocation is defined as super-position of shifting of grain boundary dislocations, belonging to one grain boundary. Nano-dislocation is kind of super-dislocation, which consists of all mobile dislocations of grain boundaries at one nano-dimensional grain boundary [1, 3, 9].

1.6. Obtained findings form individual theoretical models of formation of nano-structural materials

Theoretical models concentrate on microscopic (physical) mechanisms of plastic deformation in nano-crystalline materials. This approach attributes to Hall-Petch effect basic adaptation of usual movement of lattice dislocation or transition into another deformation mechanism in plastically deformed nano-crystalline materials with high density of grain boundaries [4]. Various theoretical models give various explanations of unusual Hall-Petch relationship (1), majority of them corresponds to the appropriate experimental data. Complexity of experimental determination of deformation mechanisms in nano-crystalline materials consists in their very complicated nano-dimensional structure and in their ability to transform at various lengths during plastic deformation [2, 4, 10].

It is necessary to further analyse in greater detail theoretical description of new deformation mechanisms (especially rotation of nano-grains) in nano-crystalline materials.

It is also necessary to specify more accurately theoretical description of the task of triangular nodes and quadratic nodes of grain boundaries (which are considered as thermodynamically distinct phases, independent, separated from grain boundaries and grain interiors), at deformation processes of nano-crystalline materials [1, 11].

Very important is development of general model, which will described combined role of various deformation mechanisms (such as movement of lattice dislocation in grains, slippage of grain boundaries, mechanism of plastic diffusion combined with dispersion of grain boundaries and diffusion of ternary nodes) influence of which on plastic flow in nano-crystalline materials depends on properties of material, distribution of grains and conditions of loads [1, 12].

2. Prediction of deformation magnitude in dependence on channel angles at ECAP technology

Figure 3 explains schematically the principle of the ECAP (Equal Channel Angular Pressing) technology, where two rectangular channels intersect mutually at an oblique angle Φ. Pressing can be lead either through square configuration trough the channel.

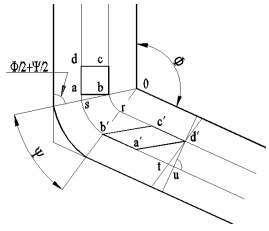


Fig.3. Principle of ECAP, where Φ is the angle of transition of two channels and Ψ curvature of transition

This situation was considered already in previous works of Segal [5]. Quantity of friction against channel wall was assigned to the angle Ψ. In practice this can be avoided by suitable lubricant. The sample is lubricated in such a way that friction effects are negligible. Figure 3 shows removal of small element of square section with dimensions given by the points a b c d, which changes after passage through the die due to effect of shear friction to the position defined by points a′ b′ c′ d′. Under presumption that identical deformation is accumulated during each pass through the channel it is possible to express deformation intensity for N-cycles by the relation 4 [13,14,].

$$\varepsilon_N = N \cdot \left[\frac{2 \cdot \cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right) + \Psi \operatorname{cosec}\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)}{\sqrt{3}} \right] \quad (4)$$

That's why it is possible to determine from the equation 4 magnitude of deformation at any conditions of pressing – subject to the condition that the angles Φ and Ψ are known. [3,15]

3. Mathematical simulation of the ECAP process for the alloy AlCu4Mg2

Objective of simulation consisted in verification of the process of material creep in the zone of plasticity, which is from the viewpoint of achievement of necessary magnitude of amount of deformation and creation of the zone of shear planes, very important for obtaining of the required disintegration of grains. At the same time magnitudes of deformation intensity and strain intensity were calculated for various geometries of tools. Geometry of channel with various outer radii of curvature of wall transition and angles ϕ, ψ were modelled. From the viewpoint of development of creep vector it was unequivocally proved that larger radius enables more perfect filling of the ECAP channel. From the viewpoint of forming process – obtaining of maximum possible refining of grain. Figure 4 shows development of magnitudes of vectors of speed of material creep. The following values of forming parameters were substituted:

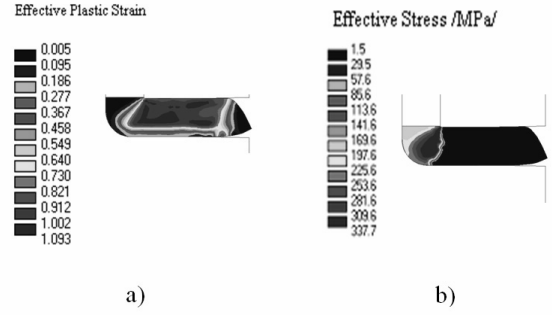


Fig.4. Developments of a) deformation intensity b) strain intensity for channel radii R1 = 5.5 mm, R2 =0.2mm

Resulting value of deformation intensity for the radius R_1 = 5.5 mm , R_2 = 0.2 mm, with tool angles ϕ = 90 °, ψ = 90°, achieves the value ε_I = 1.093. Ensuring of required disintegration of grains requires at least 4 passes through the ECAP tool (total value of deformation intensity achieves the value ε_i = 4. Effective magnitude of strain achieved max. value σ_i = 337.7 MPa. This modelling was made in 2D space. It is possible to achieve by

various magnitude of the angle of axle offset even 1.5 times higher value of deformation intensity during the first pass, which makes it possible to reduce the number of passes for obtaining of the same amount of deformation to just 2 passes. During the next stage of research works computer simulation of the first pass was made for the same alloy – AlCu4Mg2. Results of computer simulation in 3D space are illustrated in the figures below. Simulation was realised by program Superforge. Deflection of the channel in horizontal direction was 10°. It will be necessary to optimise the given angle of deflection for various types of materials. In our case we have achieved at very small deflection rather substantial increase of deformation intensity ε_I = 1.547 in comparison to ε_I = 1.093 in case of classical shape of channel with identical angles of the channel ϕ = 90 °, ψ = 90°. Obtained maximum magnitude of strain was σ_i = 168.9 MPa (see Figure 5).

a)

b)

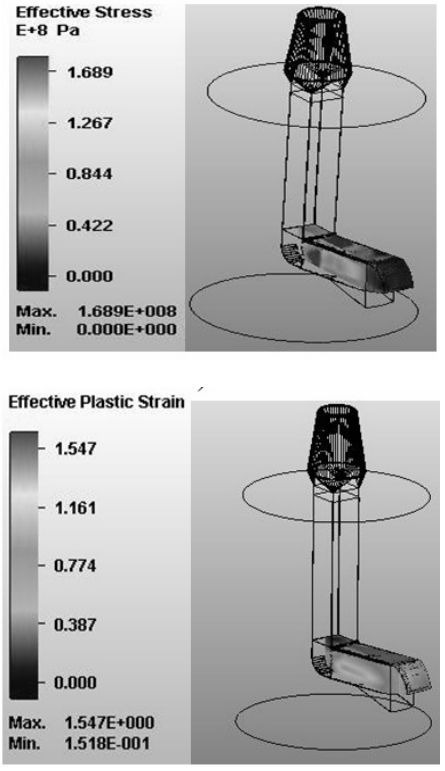


Fig. 5. ECAP channel with axle offset of 10° - obtained magnitudes of a) deformation intensity b) strain intensity

4. Conclusions

Very interesting finding follows from the obtained results, that is that at smaller magnitude of strain intensity it is possible to achieve up to 1.5 times higher amount of deformation. It was unequivocally proved that axle offset of the channel makes it possible to achieve much higher amounts of deformation during the first pass through the channel of the ECAP tool , which leads to quicker refining of structure. In the next stage of research works we will focus on multi-pass modelling of the forming process ECAP from the viewpoint of simulation of maintenance of material strengthening after individual passes and verification of experimentally obtained results. At the same time we will check influence of the angle of deflection on achievement of maximum possible amount of deformation without rupture.

Acknowledgements

The authors would like to acknowledge gratefully that the Ministry of Trade and Commerce project MPO No. 2A–1TP/124, sponsored this work.

References

[1] M. Yu Gutkin,. I..A. Ovidko, C.S. Pande, Theoretical models of plastic deformation processes in nanocrystalline materials, Reviews on Advanced Materials Science 2 (2001) 80-102.
[2] M.A.M. Bourke, S. Li, I.J. Beyerlein, D.J. Alexander, B. Clausen, Finite element analysis of the plastic deformation zone and working load in equal channel angular extrusion, Materials Science and Engineering 49 (2003) 185-204.
[3] L.I. Saiyi, I.J. Beyerlein, C.T. Necker, D.J Alexander, Heterogeneity of deformation texture in equal channel angular extrusion of copper, Acta Materialia 52 (2004) 1459-1475.
[4] X. Cheng, T.G. Langdon, Influence of a round Conner die on flow homogeneity in ECA pressing, Scripta Materialia 48 (2002) 1-4.
[5] Y. Inwahashi, J. Wang, M. Horita, Z. Nemoto, T.G. Langdon, Principle of equal–channel angular pressing for processing of ultra–fine grained materials, Scripta Materialia 35 (1995) 143-147.
[6] I. Agnew, O. Duygulu, Material Science Forum 177 (2003) 419-422.
[7] K.N. Braszczynska-Malik, L. Froven, Equal channel angular pressing of magnesium AZ91 alloy, World Wide Congress on Materials and Manufacturing Engineering and Technology,
[8] M.M. Avedesian, H. Baker (Eds.), ASM Specialty Handbook Magnesium and Magnesium Alloys, The Materials Information Society, Materials Park, OH, 1999.
[9] I.J. Beyerlein, R.A. Lebensohn, C.N. Tome, Ultrafine Grained Materials II, TMS, Seattle, 2002.
[10] K. Kuzman, Problems of accuracy control in cold forming, Journal of Materials Processing Technology 113 (2001)10-15.
[11] S.M. Byon, S.M. Hwang, Die shape optimal design in cold and hot extrusion, Journal of Materials Processing Technology 138 (2003) 316-324
[12] P.B. Prangnell, C. Harris and S.M. Roberts, Finite element modeling of equal channel angular extrusion, Scripta Materialia 37 (1997) 983-989.
[13] D.P. Delo, S.L. Semiatin, Finite-element modeling of non-isothermal equal-channel angular extrusion, Metallurgical and Materials Transactions A30 (1999) 1391-1402.
[14] M. Furukawa, Z. Horita, H.G. Langdon, Factors influencing the shearing patterns in equal-channel angular pressing, Materials Science and Engineering A332 (2002) 97-109.
[15] J.H. Lee, I.H. Son, Y.T. Im, Finite element investigation of equal channel angular extrusion process, Materials Transactions, The Japan Institute of Metals 45 (2004) 2165-2171.