Simulation of ECAP process by finite element method

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Abstract

Ultrafine-grained materials represent a new generation of advanced materials exhibiting unique and technologically attractive properties. Today there are more than 30 different processes for manufacture of nanostructured materials, some of them include methods, which are based on severe plastic deformation (SPD). The ECAP, which is one of them, is nowadays one of most used and promising technologies for processing ultrafine-grained metals. The paper deals with influence of channels angle ECAP die on the state of stress, the state of strain and evolution of temperature, realized by mathematical simulation.

Simulations were realized for IF steel in software product DEFORM based on FEM. It results from mathematical simulation, that the highest values of deformation forces and temperature have been achieved when the angle of channels was 90°. When the value of the angle of channel is increased, the value of effective strain and temperature is decreased. Based on the mathematical simulation, the concentration of the stress to transitional area of punch has been defined. This fact was later supported by the experiment, when during ECAP processing a superficial damage at the tension strain $\sigma_{3,\mathrm{real}} = 2750$ MPa has occurred.

K e y w o r d s: SPD, ECAP, FEM, ultrafine, nanostructured materials, stress, strain

1. Introduction

At present time material research is intensively concentrated on development of ultrafined and nanosized grains of metallic and nonmetallic materials by severe plastic deformations (SPD). To achieve such grain parameters, it is essential to resolve not only opened research problems from the fields like physical metallurgy, construction of equipment for SPD, tribology etc., but also synthesis of knowledge leading to industrial realization of materials with high physical and mechanical properties. Development of nanosized structures by SPD has started 25 years ago when the author [1] for the first time published possibilities of ultrafined structures formation by plastic deformations. The experimental works realized on materials Ni, Al, Cu, Ti, Fe-ARMCO or their alloys were described for example in [2–5]. Questions related to formation of mechanisms of ultrafined material are still opened. Evolution of structure in the SPD process is connected with transformation of dislocation substructure onto ultrafined structures with high angle boundaries [6]. Dislocation and diffusion reactions within and in the grain boundaries take part in the plastic deformation process in nanostructured materials at relatively low temperatures [7, 8].

The finite element method (FEM) is suitable for analysis of deformation processes including the equal channel angular pressing (ECAP) [9–13]. By means of FEM simulations, an analysis of the effects like geometry, shape, radius, angle of channels [13, 14–19] on homogeneity and effective strains, effective stresses, strain rates [6, 14–16] and temperature of specimen during the ECAP [10, 13, 16, 20–24] can be realized. Homogeneous plastic deformation in SPD processes is cumulated in the area of an outer matrix radius [6]. In [1, 7] the deformation and velocity gradients associated with a central fan plastic deformation zone

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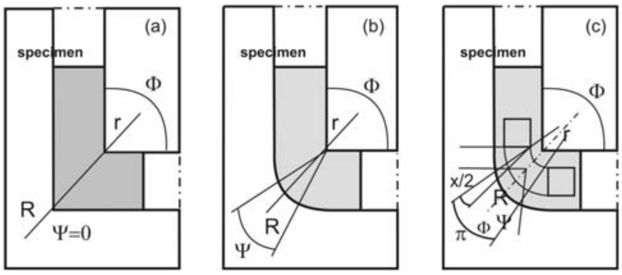

Fig. 1. Various combinations of the die channels used in ECAP process: a) $\Psi(R) = 0$ and $r = 0$, b) $0 \leq \Psi(R) \geq \pi - \Phi$ and $r = 0$, c) $0 \leq \Psi(R) \geq \pi - \Phi$ and $r \geq 0$.

(PDZ) and a bottom region of the low shear deformation were determined.

Kim et al. [15] showed that shearing strain depends on geometry of instrument, which is defined by the angle between two channels Φ, angle on outer corner of die ψ (or radius R) and angle within internal corner (or radius r) of die. Various combinations can occur in the ECAP process between transformed parameter of die L_0, Φ, R, r for single angles Φ, as shown on Fig. 1.

The heterogeneous plastic deformation along the ECAP-ed specimen was determined by FEM analysis [25, 26]. Three main zones can occur: head, body and tail. Plastic deformation in the head and tail of the sample is affected by:

a) Material characteristic – in the case of the same angle ψ, head and tail lengths are larger for a material with strain hardening (SH) than for perfect plastic (PP) material. With bigger angle ψ, head and tail length increases for PP material, but remains about constant for SH material [25].

b) Length of heterogeneously deformed head zone increases with angle Φ, simultaneously the length of tail zone decreases [26].

Authors [10, 14, 24, 25, 27] analysed the effect of friction on filling the bottom matrix corner and homogeneity of plastic deformation in specimens. By means of FEM they stated that high friction helps to stuff better outer corner of ECAP matrix. Authors [25, 27] mentioned that high friction results in better filling of channel, but on the other hand higher heterogeneity of plastic deformation in a body of specimen was observed.

FEM enables to verify the influence of the ECAP die geometry (Φ, ψ) and processing variables (material characteristics, friction conditions) on plunger load – with bigger angle Φ the load on plunger is lower. Authors in the report [25, 28] studied effects of the angle ψ, material characteristics and friction on changes in load on plunger and resulted in following conclusions:

a) With increasing angle Φ the external loading of

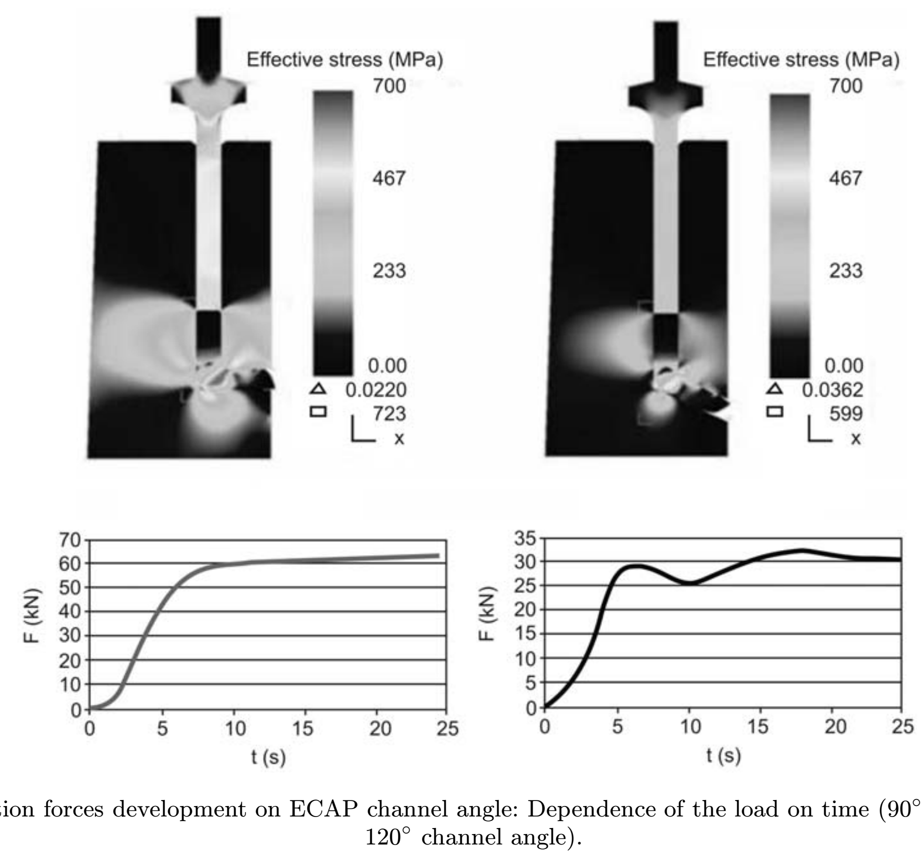

Fig. 2. Deformation forces development on ECAP channel angle: Dependence of the load on time (90° channel angle and 120° channel angle).

Table 1. Chemical analysis (wt.%) and mechanical properties of IF steel before ECAP

C	Mn	Si	Al	S	P	Ti	Cu	N_2	$R_p0.2$ (MPa)	R_m (MPa)	A (%)
0.005	0.128	0.005	0.027	0.009	0.007	0.074	0.032	0.003	182	275	70

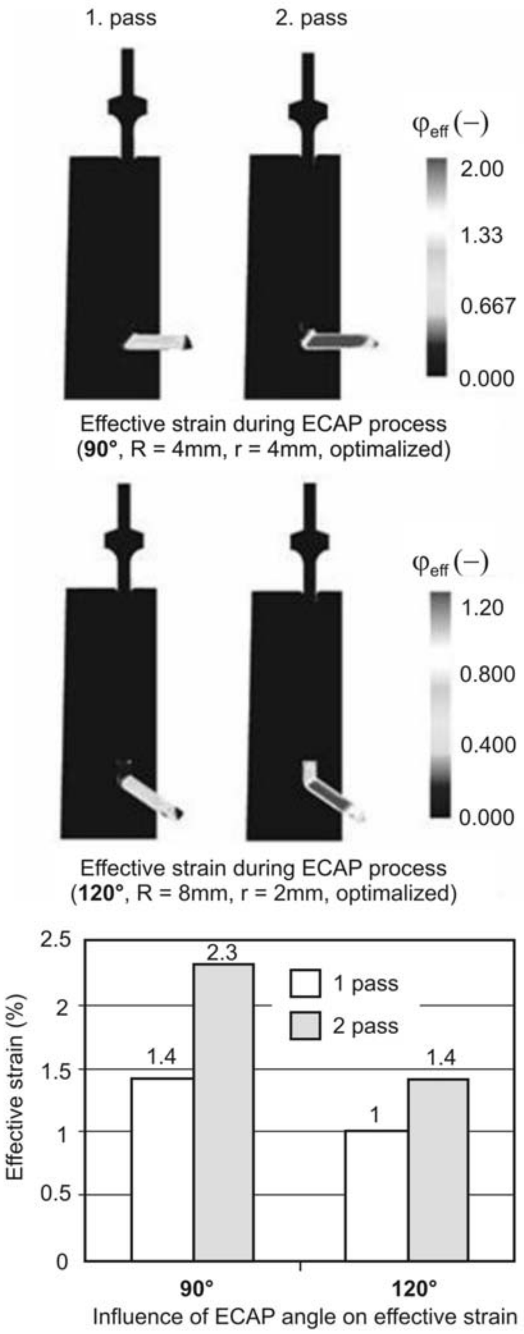

Fig. 3. Influence of ECAP angle on effective strains.

plunger decreases. It is valid for the both PP and SH materials.

b) Contact frictions have the most significant influence on plunger load – with rising friction, the load on plunger is bigger.

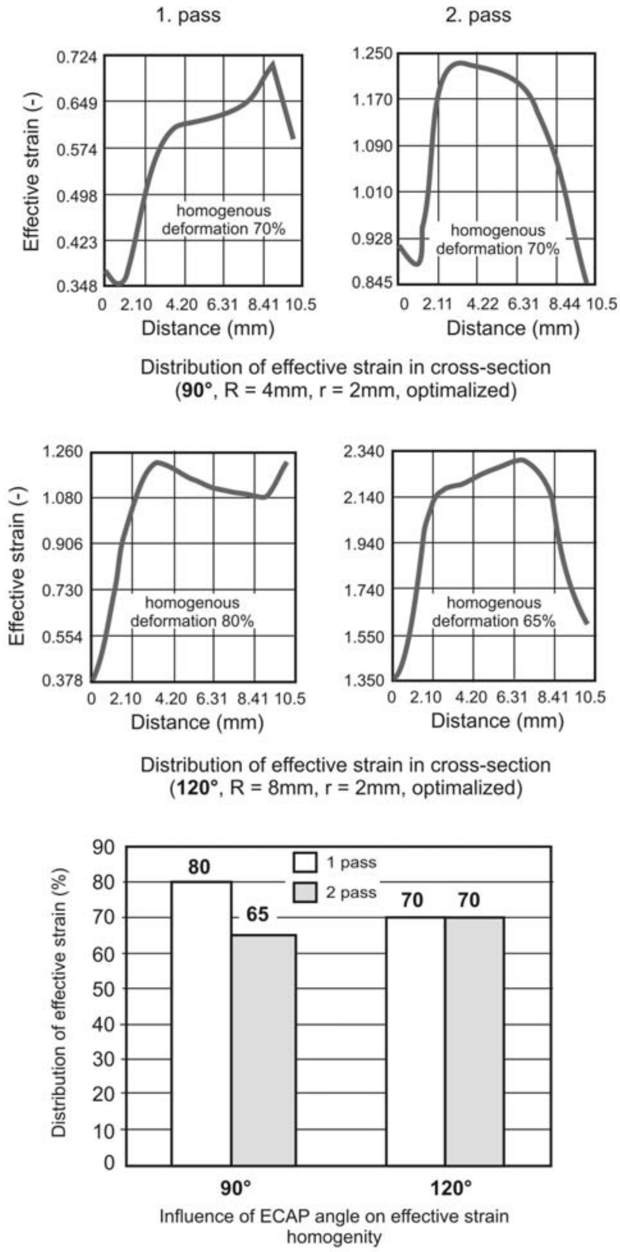

Fig. 4. Influence of ECAP angle on effective strain homogenity.

The aim of the paper is the stress and strain states simulation and the course of temperatures in IF steel during ECAP process.

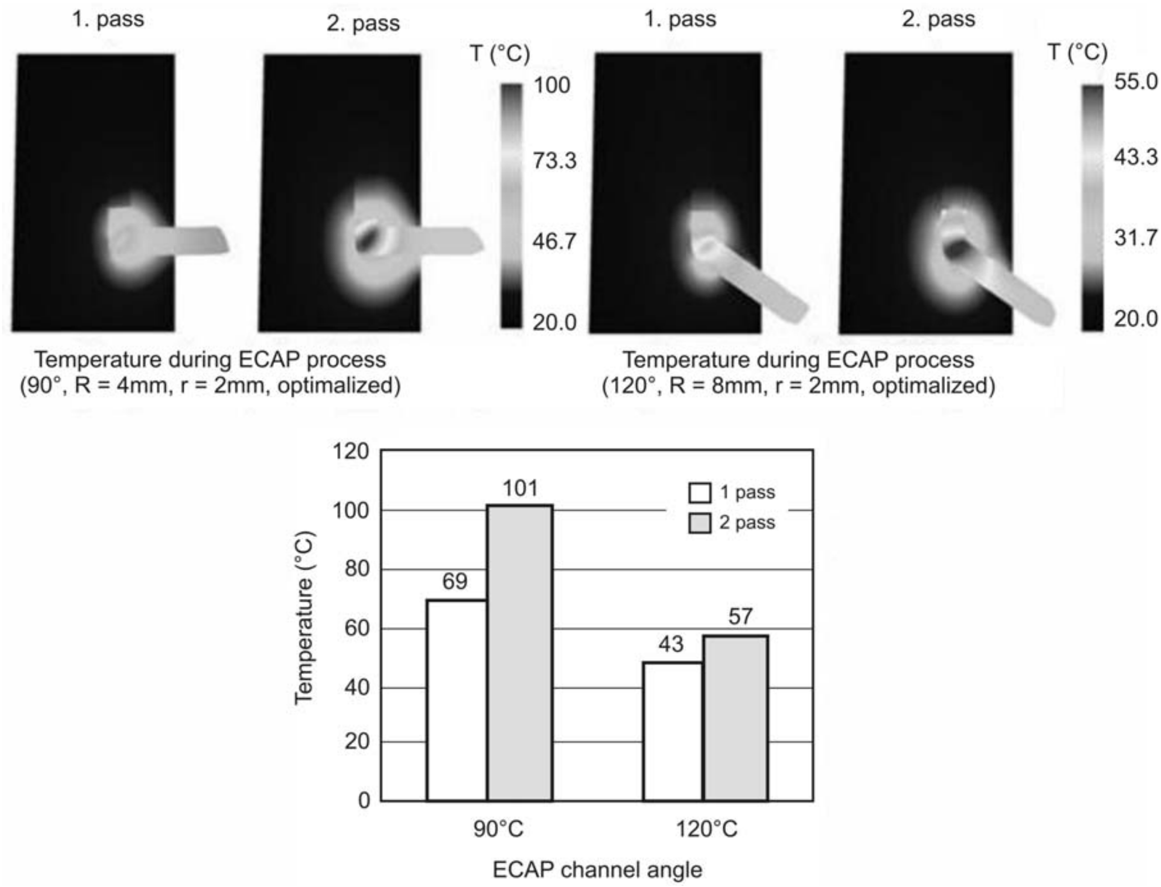

Fig. 5. Influence of ECAP angle on samples temperature.

2. Experimental material and methods

Commercially available IF steel was used for the experiment. Local chemical analysis of the investigated steel is listed in Table 1. Experimental material was deformed by three passes in the ECAP die with channels angle $\Phi = 90°$. Pressed materials were rotated before input to the next pass by 180°. The ECAP was realized by hydraulic equipment, which makes possible to produce the maximal force of the value of 1 MN. Short testing bars ($d_0 = 5$ mm, $l_0 = 10$ mm) were machined from ECAP-ed material for the static tensile test. Two testing bars were made from each sample. The static tensile test was realized by ZWICK 1387 equipment at room temperature in accordance with STN 420310 (STN EN 10002-5). Microhardness was measured by Vickers method on Hanemann device. TEM analysis was made on thin foils. Mathematical simulations were realized by DEFORM 2D software for reducing of computational time.

3. Results and discussion

Results of simulations for the first ECAP pass are shown in Fig. 2. It is evident that the highest value of strain forces $F_{\mathrm{D1,sim}} = 60$ kN was achieved in the case, when the angle of channels was $\Phi = 90°$. $F_{\mathrm{D1,real}} = 78$ kN is the measured value of the true strain force. The highest calculated effective stress in the die was concentrated into the head part of the transition plunger. Its value for the simulated first pass is $\sigma_{1,\mathrm{sim}} = 700$ MPa. IF steel true experiment confirmed the above mentioned stress concentration into the transition part of plunger, which was brittle damaged during the third ECAP pass in the plane of maximal shear stresses (Fig. 1a). The true strain force achieved the value of $F_{\mathrm{D31,real}} = 216$ kN, which is in relation to the compression stress $\sigma_{3,\mathrm{real}} = 2750$ MPa. On the other hand, in the case of the 90° angle of channels, the highest concentration of the effective stress in the deformation zone of the specimen is achieved.

Realized mathematical simulations determining the influence of channel angles of ECAP equipment on the development of effective strain showed, that the highest effective strain is achieved if the angle between channels is 90°. Simultaneously the effective strain with the bigger angle of channels is reduced as given in Fig. 3.

Influence of channel angles of ECAP equipment on homogeneity of effective deformation in the cross section of deformed specimen is represented in Fig. 4. It

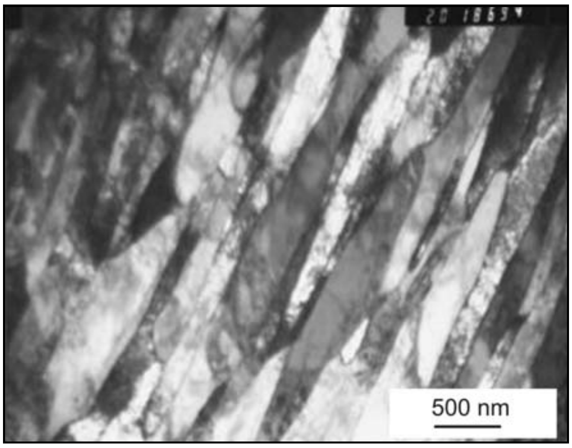

Fig. 6. Substructure of the material after three ECAP passes.

can be seen that the most homogeneous deformation in the specimen is reached at the angle of 120°.

Realized mathematical simulations showed that the highest samples warm up from plastic deformation is reached at the 90° angle of channels and with increased channel angles the samples warm up from plastic deformation is decreased, as described in Fig. 5.

Simulations showed that maximum sample warm up from plastic deformation developed specimens temperature at the level 100 ℃. Microhardness measurements were realized in dependence on the development of temperature in deformed specimens. It results from measurement that the significant recovery process can be recognized for temperatures over 300 ℃ [29]. Simulations confirmed that the die temperature is influenced by the deformation heat only negligibly, as is shown in Fig. 5. Maximal die temperature was 60 ℃.

Steel structure analysis by TEM after SPD is characterized as mixed cell-subgrain and submicrocrystalline structure with the mean grain size from 120 to 150 nm and heterogeneity in cross section of specimens, as shown in Fig. 6.

4. Conclusions

Mathematical simulations in software product DEFORM 2D showed:

1. The highest effective stress in the ECAP die was achieved for the angle of channels $\Phi = 90°$. Maximum stress concentration is in the transition part of plunger head. Destruction in the localized part of plunger was confirmed experimentally.

2. The highest effective strain is reached at the 90° angle of channels. With the bigger angle the effective strain is decreasing.

3. The highest warm up of the specimen is reached at the 90° angle of channels; bigger angle involves temperature decreasing.

4. SPD processes resulted in the decreasing grain size in the studied material and simultaneously conduced to the better strength characteristics of suitable plastic properties of the materials.

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