# Nanostructure Formation and Numerical Simulation of IF Steel in ECAP

Tibor Kvackaj[1,*] Michal Zemko[1], Tomas Kuskulic[1], Robert Kocisko[1], Michal Besterci[2], Sergej V. Dobatkin[3], Maria Molnarova[1]

[1]*Technical University in Košice, Letna 9, 042 00 Košice, Slovak republic*
[2]*Institute of Materials Research of SAS, Watsonova 47, 043 53Košice, Slovak Republic*
[3]*Moscow State Institute of Steel and Alloys, Leninsky prospect, Moscow, Russia*

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### ABSTRACT

In the present research work we investigated the influence of severe plastic deformation (SPD) realized by ECAP (equal-channel angular pressing) on microstructure and mechanical properties of IF (interstitial free) steel. For physical modelling the ECAP process with right angle channels (90°) was used. The ECAP process was also numerically simulated (namely its course of temperature, strain and stress fields and deformation forces) by FormFEM software.

From ECAP experiments on IF steel better mechanical properties and reduction of mean grain size from entry level 19 μm on final value 135nm were obtained after three ECAP passes.

**Key words:** nanostructure, severe plastic deformation, IF steel, mechanical properties, ECAP, numerical simulation.

### I. INTRODUCTION

At the present time a topic of intense research is the refining of various type material microstructures, which have a low value of the basic deformation resistance in volume deformation processes by severe plastic deformation (SPD) at room temperature. The aim of SPD is to obtain from the initial grain sizes at μm level, after several ECAP passes, ultrafine microstructures diameter at the nm level, usually less than 500 nm /1, 2/. There are several methods of SPD realization /2/: Equal-channel angular pressing (ECAP), and High-pressure torsion (HTP) realized by the high stress, equal-channel angular rolling (ECAR) /3/, and rolling + rolls shifting /4/. Historically, ECAP is the oldest SPD process, developed more than 20 years ago /5/. Materials with ultrafine microstructure in SPD are characterized by high value of strength, hardness, elongation, fatigue facilities and increase of superplasticity. Achievement of listed facilities is conditional on the nanocrystalline structure, its distribution in volume, internal intensity, texture and other characteristics of microstructure. Experimental works, which are realized by SPD on compact materials such as Ni, Al, Cu, Ti, ARMCO-Fe materials, and any of their alloys, are described in the literature /6-12/. Opposite possibilities are also described for ultrafine powder compacting /13-16/. From the point of view of incoming material to the SPD process, it can be divided on compacting ultrafine grained powder materials and grains fragmentation in compact materials.

This paper deals with the influence of SPD realized

* Corresponding author: tibor.kvackaj@tuke.sk

in ECAP dye on the mechanical facilities, the microstructure, stress and strain material analysis in channel passes of IF steel.

## 2. MATERIAL AND EXPERIMENTAL METHODS

Commercial quality IF steel was used for experiment. Chemical analysis investigated steel is shown in Table 1.

**Table 1**

Chemical analysis of IF steel [mass %]

| C | Mn | Si | Al | S | P | Ti | Cu | $N_2$ |
|---|---|---|---|---|---|---|---|---|
| 0,005 | 0,128 | 0,005 | 0,027 | 0,009 | 0,007 | 0,074 | 0,032 | 0,003 |

The three passes were made in ECAP dye on experimental material. Pressed materials were rotated before input to next pass by 180°. The ECAP process was realized by hydraulic equipment, which makes it possible to produce maximal force on the level 1 MN. Short examinational bars ($d_o$=5 mm, $l_o$=10 mm) were machined from dyed samples after ECAP process for static tension test. Two examinational bars were made from each dyed sample. Results were shown as the average of two examinational bars. The static tensile test was realized at room temperature by ZWICK 1387 equipment in accordance with STN 420310 (STN EN 10002 – 5). Micro-hardness was measured by Vickers method on a Hanemann device. TEM analysis was made on thin foils. Mathematical simulations were made by FormFem2D software based on FEM.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

The initial values of mechanical properties before ECAP were $R_{p0,2}$=182 MPa, Rm=275 MPa, elongation A=71% and microstructure characteristic definite by mean grain size was 19 μm. Material strength properties formation after three ECAP passes remit to their increasing as is shown in **Fig. 1** and decreasing of elongation as seen in Fig. 2.

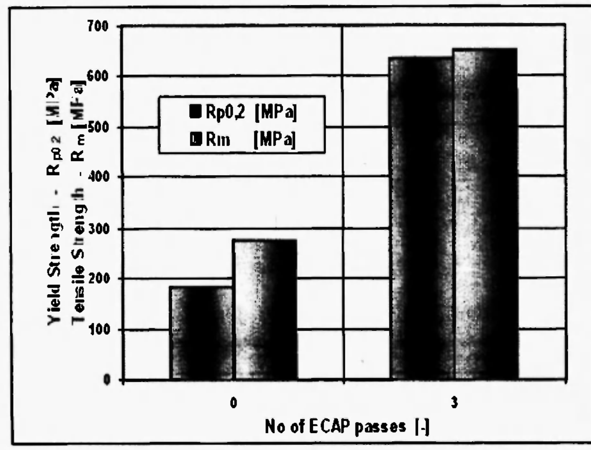


**Fig. 1:** Mechanical properties as function of ECAP passes (Steel grade: IF)

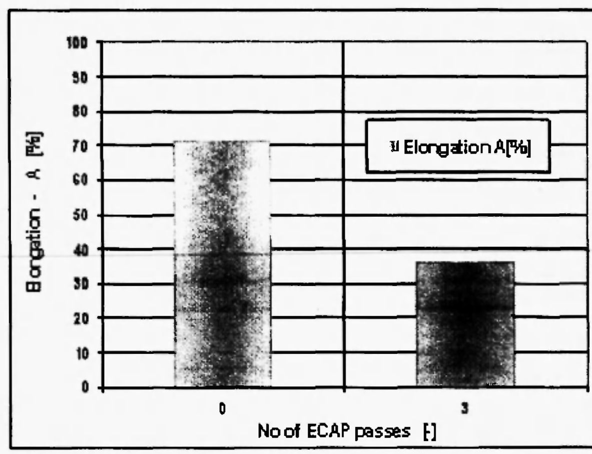


**Fig. 2:** Elongation as function of ECAP passes (Steel grade: IF)

The stress – strain curves from static tensile testing are represented in Fig. 3. The three-pass curve has a form typical of superplastic material behaviour. The initial grains were equiaxed. Steel microstructure analyzed by TEM after SPD is characterized as mixed cell – subgrain and submicrocrystalline elongated substructure with the mean grain size was from 120 to 150 nm and heterogeneities in samples cross section, as is shown in Fig. 4.

Microstructural cross section heterogeneities were occasioned by non-uniform plastic deformation in ECAP channels which are shown in Fig. 5. The influence deformation heat resulting from channel

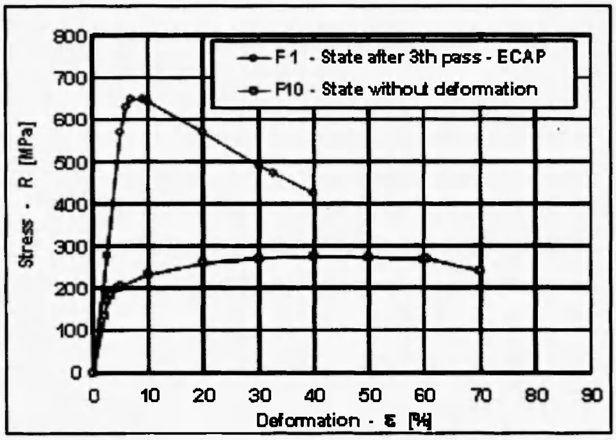


**Fig. 3:** Stress – deformation diagrams (Steel grade: IF)

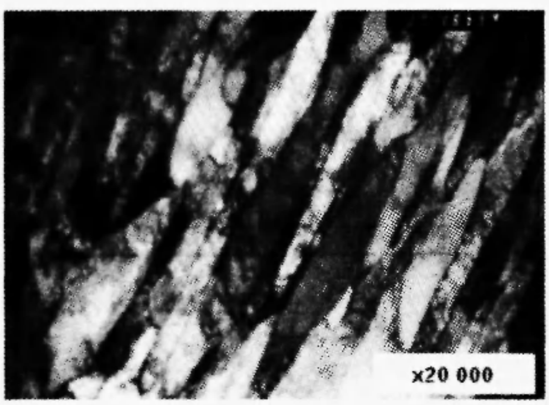


**Fig. 4:** Samples substructure after three ECAP passes

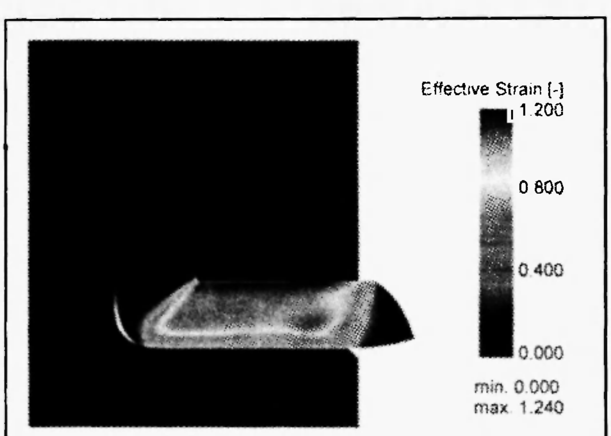


**Fig. 5:** Deformation heterogeneity in cross-section

angular deformation on strength was also tested. Mathematical simulation temperature field in ECAP dye showed that maximal samples temperature was 336 K, as seen from Fig. 6.

Microhardness measurement in dependence on temperature referred also on fact, that materials strength begins have significant changes from starting temperature 673 K, as shown in Fig. 7. The steel strength decreasing with increasing of testing temperature results in softening processes. Maximal forces loaded in dependence on pass numbers resulting from ECAP process measurement and mathematical simulations, are given in Fig. 8. Adequate conformity of measured and calculated force results were obtained.

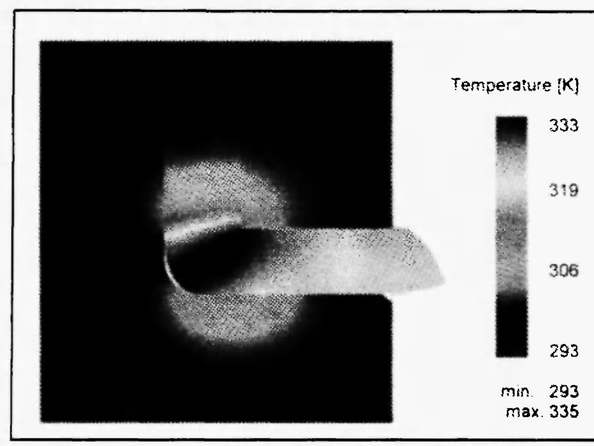


**Fig. 6:** Sample temperature field in cross-section

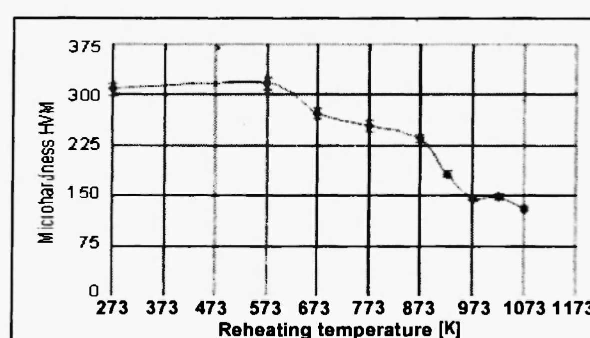


**Fig. 7:** Microhardness after three ECAP passes in dependence on reheating temperature

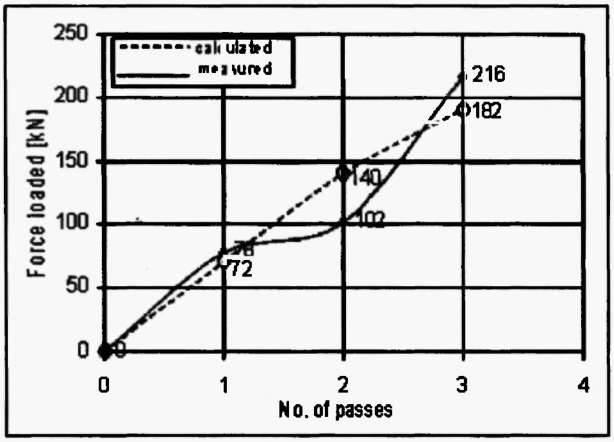


**Fig. 8:** Diagram force loaded after ECAP and mathematical simulation

## 4. CONCLUSION

The following conclusions based on our own experimental results and also on literature, were made:

1. For IF steel material we obtained the following mechanical properties compared to initial annealing state by application of SPD by ECAP: yield strength increased by 3,5 times, tensile strength increased by 2,4 times, elongation decreased by 2 times
2. Mean grain size was reduced from initial value of 19 µm to a level of 135 nm
3. During ECAP process intensive deformations occurred without a radical change of shape, sizes of sample and inner or surface defects
4. Temperature development in ECAP process has no influence on strength and microstructure

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## REFERENCES:

1. R.Z. Valiev, *Proceedings of Ultrafine Grained Materials*, Tennessee, March 12– 16, (2002), p. 339.
2. T.C. Lowe, R. Z. Valiev, *JOM*, **52**, 27 (2000).
3. J.W. Park, J.W. Kim, Y.H. Chung, *Scripta Materialia*, **51**, 181 (2004).
4. F. Grosman, J. Pawlicki, *Acta Metallurgica Slovaca – SI*, **8**, 178 (2002).
5. 5. V.M. Segal, V.I. Reznikov, A.E. Drobyševskij, V.I. Kopylov, *Izvestia AN – ZSSR, Metally*, **1**, 115 (1981).
6. M. Furukawa, Z. Horita, M Nemoto, T.G. Langdon, *Journal of Materials Science*, **36**, 2835 (2001).
7. V.V. Rybin: *Bolsie plasticeskie deformacii i razrusenie metallov*, Metallurgija, Moskva, USSR, (1986).
8. T. Kvackaj, J. Cech, V. Vrchovinsky, M. Vlado, I. Pokorny, Z. Novy, *Proceedings of Forming 2003*, Podlešice, Poland September 10-13, (2003), p.91.
9. M. Bestreci, T. Kvackaj, L. Kovac, K. Sulleiová, *Metallic Materials*, **44**, 101 (2006).
10. T. Donic, M. Martikan, *Acta Metallurgica Slovaca – SI*, **.11**, 322 (2005).
11. J. Kusnierz, J. Bogucka, *Archives of Metallurgy* and Materials, **50**, 219 (2005).
12. J. Kusnierz, M-H. Mathon, J. Dutkiewicz, T. Baudin, Z. Jasienski, R. Penelle, *Archives of Metallurgy and Materials*, **50**, 367 (2005).
13. E. Oda, T. Ohtaki, A. Kuroda, H. Fujiwara, K. Ameyama, K. Yoshida, *Proceedings of Powder Metallurgy*, Busan, Korea, September 24-28, (2006), p.126.
14. J. Yuuki, A. Kawasaki, H. Kwon, A. Magario, T. Noguchi, J. Beppu, M. Seki, *Proceedings of Powder Metallurgy*, Busan, Korea, September 24-28, (2006), p.1056.
15. M. Balog, K. Izdinsky, J. Nagy, F. Semacik, *Proceedings of Nenamat*, Stara Lesna, Slovakia, February 13-16, (2005), p.18.
16. Q. Wei, T. Jiao, K.T. Ramesh, E. Ma, L.J. Kecskes, L Magness, R. Dowding, V.U. Kazykhanov, R.Z. Valiev, *Acta Materialia*, **54**, 77(2006).