Finite element analysis of two-turn Incremental ECAP

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ABSTRACT: Ultrafine grained (UFG) metals produced by severe plastic deformation (SPD) are characterised by improved mechanical properties, which make them suitable for advanced applications. However, the practical uses of UFG metals are rare because of the lack of industrial methods of SPD. This paper describes a new SPD process of Incremental ECAP (I-ECAP) in the two-turn, S-shape channel version. While I-ECAP opens up a possibility of continuous processing of very long billets, it still involves numerous repetitions to accumulate a large plastic strain required for advanced structural changes. The two-turn version of this process doubles the amount of plastic strain generated in one operation and, therefore, improves process productivity. In order to check the feasibility of two-turn I-ECAP, a FEA simulation is carried out and the suitable tool geometry and process kinematics are established. The mode of material flow is the same as in the well established classical ECAP (route C) process, while continuous character and improved productivity suggest that the new process might be suitable for nanostructuring of metals on industrial scale.

Key words: Ultrafine grained metals, Severe plastic deformation, Finite element analysis

1 INTRODUCTION

The known metallic materials seem to reach the limit of their performance and, therefore, are increasingly replaced by polymer composites. Attempts to improve properties of metals by changing their chemical composition and thermo-mechanical treatment usually result in small changes only. More substantial changes can be achieved by grain size reduction to micro and nano level by consolidation of nanoparticles, using special electro-deposition processes or subjecting coarse grained (CG) metals to severe plastic deformation (SPD). SPD, which can be treated as a new branch of metal forming, is envisaged as the best method for large volume and low cost nanostructuring of bulk metals. Unfortunately, the scientific success of metallurgical research on ultrafine grained (UFG) metals produced by SPD has not been matched by equally impressive engineering effort to transfer SPD processes from laboratory to industry.

The most popular SPD process is equal channel angular pressing (ECAP) [1], which was invented by V.M. Segal in the 1970s. ECAP is based on forcing a square or round billet through the L-shape channel of a constant cross-section. Simple shear, which takes place along a diagonal plane at the channel turn, results in the equivalent plastic strain of 1.15 (for the channel angle of 90°). By repeating this process, a very large (severe) plastic deformation is accumulated in the processed material and its structure refined. The billet can be rotated about its axis between consecutive passes. In order to activate more slip systems the rotation angle is usually 90°, each time in the same direction, which is known as route Bc. A 180° rotation (route C) is said to be less favourable from the structural point of view, due to the deformation reversal for even passes [2]. However, route C leads to the best material utilisation of 83.3% [3]. Route C can also be implemented using a two-turn, S-shape die channel (Figure 1) [4-10] which doubles the amount of strain in one pass and, therefore, improves productivity.

Extending this concept into a multi-turn version was also considered [11,12] but it is rather impractical because of a very high process force.

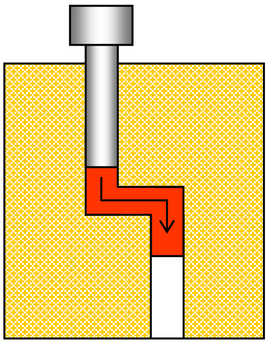


Fig. 1. A two-turn, S-shape channel ECAP.

ECAP, as well as its variations, is a batch process which can only deal with billets with a small aspect ratio of about 6. This is because of a very high force resulting from friction in the case of a long input channel and a possibility of punch buckling/fracture under this force. A small aspect ratio leads to poor material utilisation due to non-uniform strain distribution at the billet ends. These features of the batch ECAP process make it unattractive for industrial applications. More commercially viable would be a continuous ECAP process. One of such processes is known as Incremental ECAP (I-ECAP).

2 INCREMENTAL ECAP

2.1 Basic version

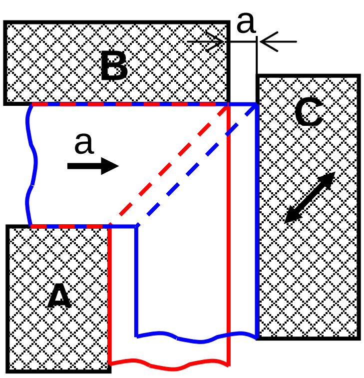


Fig. 2. Schematics of a single-turn I-ECAP.

The basic version of I-ECAP has only a single turn channel [13-15] (Figure 2). Dies A and B define the input channel while A and C the output channel. Die C is a working die, which moves in a reciprocating manner at an appropriate angle to the billet. Feeding of the billet takes place when there is no contact between the billet and the working die. When the billet stops moving and becomes fixed, the working die deforms it plastically in the "dashed" zone (Figure 2). The mode of deformation is that of simple shear and, provided the feeding stroke is not excessive, consecutive shear zones overlap resulting in a uniform strain distribution along the billet. Separation of the feeding and deformation stages reduces or eliminates friction during feeding; this enables processing of infinite billets.

2.2 Two-turn version

While I-ECAP opens up a possibility of continuous processing of very long billets, it still involves numerous repetitions to accumulate a large plastic strain required for advanced structural changes. Therefore, a two-turn, S-shape channel version might be considered (Figure 3).

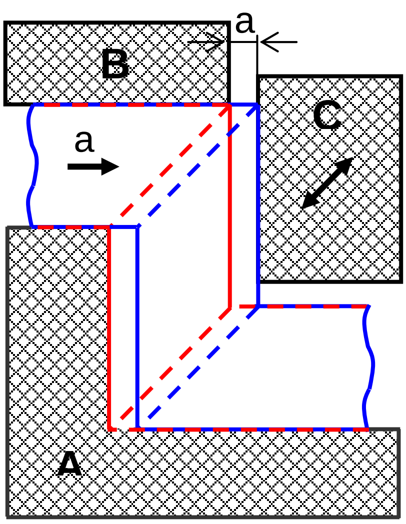


Fig. 3. Schematics of a two-turn I-ECAP.

Compared to the basic version of I-ECAP, the kinematics of the two-turn version is the same. The only change is a different geometry of dies A and C. Despite this it is advisable that the finite element analysis (FEA) is carried out to give a better insight into this new process and to avoid problems with experimental validation.

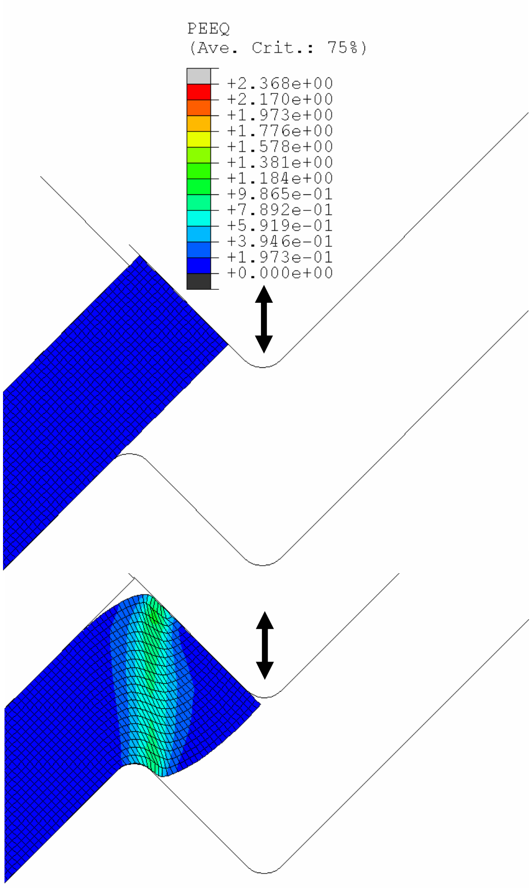
3 FINITE ELEMENT ANALYSIS

3.1 FE model

A commercial FEA program Abaqus/Explicit was used to simulate the elastic/plastic flow of the material in a two-turn, S-shape channel I-ECAP process. The tools were assumed to be rigid. The width of the channel was 10 mm. The angle of each turn was 90°. The output channel was offset with reference to the input channel by 15 mm. The channel corners were rounded with a radius of 2 mm. The feeding stroke was 1 mm and was synchronised with a reciprocating movement of the working die. The direction of this movement was 45°. The 45×10 mm billet was divided into 1800 plane-strain, bilinear, quadrilateral elements with reduced integration. Despite large strains in the process, no re-meshing was attempted so the material flow was easier to observe and interpret. The material used in the simulation was commercially pure aluminium. It was modelled as an elastic-plastic, isotropic, Huber/Mises material. Friction was assumed to follow Coulomb’s law with friction coefficient μ=0.2.

3.2 FE results

Figure 4 displays a few snapshots of two-turn, S-shape channel I-ECAP, which illustrate the incremental character of the process. The view was rotated by 45° in order to allow the working die to move vertically as if it was attached to the ram of a vertical press.



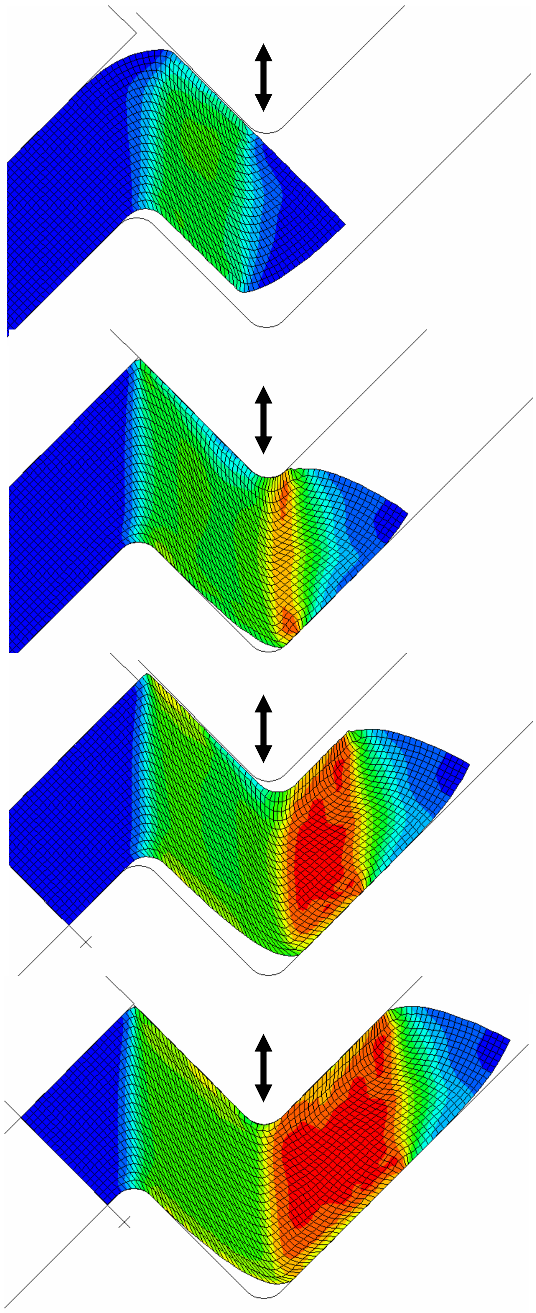


Fig. 4. Equivalent strain distribution in two-turn I-ECAP.

The uniform material flow, with well defined zones of shear deformation, proves feasibility of the process. However, it has to be emphasized that these good results have been obtained for an optimised tool geometry and process parameters. Choosing other than tested conditions may lead to poor results. As an example, let the offset of the output channel be 10 mm rather than 15 mm used above. As shown in Figure 5, this will lead to a non-uniform strain distribution. Another entirely defective material flow and shape defects can be observed for the excessive feeding stroke of 5 mm (Figure 6).

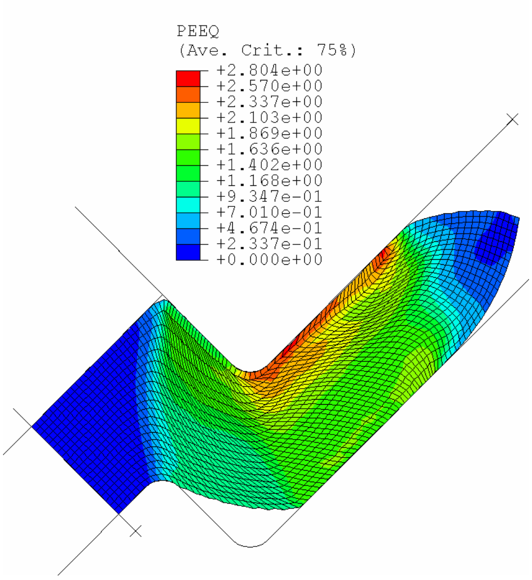


Fig. 5. Non-uniform strain distribution resulting from small channel offset.

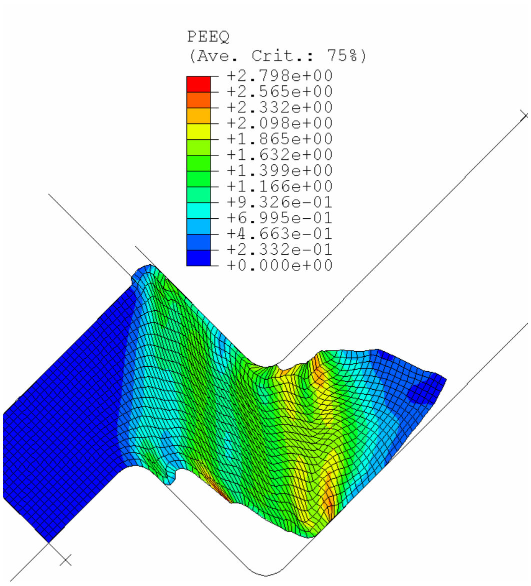


Fig. 6. Non-uniform strain distribution and shape defects resulting from a large feeding stroke.

4 CONCLUSIONS

The feasibility of the two-turn, S-shape channel version of I-ECAP was tested by FEA. It has been shown that, for the appropriate tool geometry and process parameters, the new version of I-ECAP enables obtaining a well defined and uniform strain distribution. This, together with the improved productivity and the continuous character of the process, should make it an interesting option for industrial applications.

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