Finite element analysis of die angle at constant offset length in two-turn ECAP

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Abstract. Severe plastic deformation (SPD) is the process used to produce smaller grain in the range of 1-μm. These materials have been classified as equiaxed ultrafine grain (UFG) metals. These metals are characterised by high defect density and improved mechanical properties which make them suitable for advanced structural applications. From all available SPD techniques, two turn incremental equal channel angular pressing (ECAP), S-shape channel discussed in this paper to double the effective strain in single press. Analysis of ECAP technique by changing die geometry and process parameter helps to produce defect free UFG metals. ECAP channel continuously pressed a very long billet in which repetitions accumulate large plastic strain. Two turn ECAP is useful to increase the productivity. However, any changes in channel angle, corner angle as well as offset length are cause for variation in mechanical properties of metals. In order to check the die suitability of two-turn ECAP with variation of die angle a finite element analysis (FEA) simulation is carried out and the suitable tool geometry with process kinematics are established. ECAP channels at two different channel angles are used to study the flow behaviour of metal through 15mm offset length. The mode of material flow is the same as in the well-established classical L-shape ECAP process following route C pass, while continuous character and improved productivity suggest that new S-shape ECAP process might be suitable for grain refinement of metals as well as minimization of deformation load on an industrial scale.

Keywords: Sever plastic deformation, Equal channel angular pressing, ultrafine grain

1. Introduction
Extrusion involves a metal forming process that gives a large number of mechanical parts their final shape [1]. Its technology has progressed with the development of high strength materials, and other component. A primary shaped of billet becomes a final product after passing through a convergence channel when compressive load applied through a punch at high pressure [2]. Extrusion performance has vastly improved since the initial works started and continually adapting to new performance standards. Businesses that fail to achieve competitiveness of market demand are thrown out and lose market share. Hence maintaining the basic standard of extrusion allows accommodate in a highly competitive industrial sector with more than average benefit margins.

Metals with grain sizes from 100nm to 1000nm have received much attention over existing extrusion process. Based on grain size such metal are classified as UFG materials and grain size is less
than 100nm is termed as nano-structure materials [3]. This refinement working towards the production of bulk UFG metals through SPD processes where the nano-structure of the large volume material is possible at low cost [4-6]. There are two different methods used to produced UFG grain [7]. (a) Consolidation of powder material where fine grained materials are processes through inert gas condensation, and chemical vapor deposition. (b) In second method coarse grain is refine into ultrafine grain by SPD which accumulate high strain.

This universal method (SPD) can be applied to elasto-plastic material (fcc aluminium, bcc iron and hexagonal magnesium). SPD work on shear deformation hence plastic deformation of material is depends on their ductility. The accumulated energy of SPD is continuous recrystallization process, rather than a nucleation and growth process that is observed in traditional thermomechanical processing operations.

A number of SPD methods for producing bulk UFG metals have been developed. High pressure torsion (HPT) [8], cyclic extrusion-compression (CEC) [9], accumulative roll bending (ARB) [10], repetitive corrugation and straightening (RCS) [11] and ECAP [12] all are the type of SPD method available to achieve ultrafine grain. The significant feature of few processes is external dimensions of the work-piece do not change during the processing. Among all SPD method ECAP is mostly used for ultra large plastic strain without changing initial dimensions of sample as a patent by Segal 1977 [13]. ECAP is a process where billet is allowed to flow through an open die channel which is bent at abrupt angle, when compressive load applied over the billet. Effective strain distribution in ECAP are depends on channel angle (φ), corner angle (ψ) and number of pass (N). Maximum effective strain distribution possible at 90° (channel angle) and 0° (corner angle). A mathematical relation used for effective plastic strain (ε̇) distribution is given in equation 1 [12,14].

\[
\varepsilon = \frac{N}{3} \{ 2 \cot\left(\frac{\phi + \psi}{2}\right) + \psi \cos ec \left(\frac{\psi + \phi}{2}\right) \} \\
\]

(1)

Maximum possible equivalent strain in the L-shape channel for one pass is 1.15 and get doubled with S-shape ECAP channel because of two turns which further increases by repeating the processes as observed from equation 1. Lack of advancement in technology and failure of prediction of material behavior limited its application to industry. In forming operation, 30% cost of the product is increased by unexpected die failure [15]. Hence selection of process parameter, material properties are major concerned for ECAP process.

The yield stress of metals is related to the grain diameter (d) by following Hall-Petch relation as given in equation 2 [16]. Equation 1 shows that the yield stress (σy) increases with decreasing the grain size. The decrease of grain size increases tensile strength of material without reducing the toughness. The most significant attractive properties from the structural and manufacturing point of view are that they have high strength at low temperatures [17,18].

\[
\sigma_y = \sigma_0 + Ad^{-\frac{1}{2}} \\
\]

(2)

Where σ₀ is the friction stress and A is a constant area

In this paper, the analysis of ECAP carried out for scale up to industrial sizes. At the start of the method, investigators had shown that ECAP is a viable process for producing UFG structures in a variety of metals, and these SPD metals exhibited superplastic deformation behavior at lower temperatures and higher deformation rates than metals that had been processed by conventional means [19]. However, much of the work had been done on smaller ductile samples. The objective of this paper is to show that, process can be scaled up to produce large cross section samples with minimizing the deformation load. Aluminum alloy AA-1070 was chosen to demonstrate the feasibility of the
approach used. Many of the potential benefits of using UFG material can be realized, in particular cost and energy savings through increased die life, and lowering extrusion load.

2. ECAP

A single turn channel is the basic version of the ECAP method as shown in figure 1 [12]. “A” and “B” defined as input and output length of one turn ECAP channel. Another member known as punch is reciprocated in die input channel to deform the billet. Billet feed inside the die input channel with minor clearance. Continuous applied load plastically deforms the billet material. Billet deform inside the inlet channel move forward with plane shearing where consecutive shear zones overlap resulting, uniform strain distribution along the billet [12,14,20]. Separation of the feeding stroke from deformation stages reduces friction, this enables processing of number of billets. L-shape ECAP is still an open area for continuous processing of long billet. Numerous operations involved to achieve large plastic strain. The S-shape channel might be helpful to double the plastic strain in a single pass as shown in figure 2[21]. It is noticed that the billet rotation at $180^\circ$ in a clockwise or anti clockwise directions is a method which used for route C rotation in L-shape ECAP channel, resulting more time taken with loss in material volume as observed in die turn sections. Achieving route C rotation on S-shape ECAP channel is one more point for studies of die design in improvement of materials mechanical properties.

![Fig.1. Schematic of L-shape ECAP channels](image1)

![Fig.2. Schematic of S-shape ECAP channel](image2)

3. Method of die design

In two turn ECAP, square cross-section billet is used through two intersecting channel, each turn of ECAP die is sets at $90^\circ$ channel angle and $120^\circ$ channel angle. Inner and outermost corner are arced with 1.5mm, 1mm radius as shown in figure 2. Bottom die channel had square cross-section 8 x 8 mm$^2$ dimensions. Inlet and exit channel are offset at 15mm. Length of the inlet and outlet channel is 56mm and 40mm long as shown in figure 2. Billet with applied compressive load and velocity is pressed through the die inlet channel by using rigid body punch hence deform billet come out from die exit channel. A constant feed stroke 1mm/sec is applied on the billet. The feeding stroke is operating with a reciprocating movement of the punch. Billet 1070 aluminium alloy used for simulation with modelling as elastic-plastic, isotropic, Huber/Misses material as given in equation 3. Plastic deformation is done with a friction coefficient of 0.05.

$$\sigma = 159(0.02 + \varepsilon)^{0.27} \text{ MPa}$$

Where, $\sigma$ is flow stress, $\varepsilon$ is strain

$$27.0 \times 0.02 \times 159 \times \varepsilon = \sigma$$
4. Validation and Result

4.1. Validation

Work presented from researchers Rosochowski (2002) by using commercial FEM program Abaqus/Explicit is validated with DEFORM 3D software. Mesh size and feed stroke is few change parameter of present analysis. A 0.3mm mesh size is selected for 10,000 mesh element. To reduce the computational time punch speed is changes from 1mm/sec to 1m/sec. Analysis of the billet deformation at 15 mm offset is used in ECAP. Through present simulation, using AA1070 alloy samples, gives information of internal flow behaviour of billet produced by routes C. Selection of softer material at higher die angle has been done to avoid the flow unstability and shear localization behaviour.

4.1.1 Effective Strain

Figure 3 shows that observed effective strains in ECAPed billet have 3% higher than earlier work as presented by Rosochowski (2002). Throughout the deformation zone it could be observed tip of the billet are not shear deformed. Rest part of the billet continues to deform till it exit from the channel. When billet enters into offsets zone and consequently into second turn of the channel it pass through a die arc having radius 1mm resulting higher shearing strain. Equivalent strain in offset zone of the billet shows 1.4mm/mm and in second turn it reach to 2.8mm/mm. Observation shows that flow of effective strain is homogeneous.

![Fig.3. Equivalent effective strain at 90° channel angle](image)

4.1.2 Deformation load

Required punch load to deform the billet through two different offset lengths is shown in figure 4. At inlet channel and first turns load required to compress the billet sharply increases with increasing stroke length, but when billet enters into offset channel and exit channel, load gradually increases due to planes shearing of billet. From figure 4 it clear that first turn of billet required 16KN of maximum force while in the second turn it reaches 37 KN.
4.2. Result
With following previous work, a new die with \(120^0\) channel angle is used to know its effect on effective strain distribution and punch load required to deform the billet.

4.2.1 Effective Strain
Throughout the deformation, tip of the billet remain un-deformed. Rest part of the billet continues to deform till it exit from the channel. There is no more effect of die arc on effective strain distribution. Maximum effective strains observed in offset channel are \(0.8\text{mm/mm}\) and in exit channel it is \(1.5\text{mm/mm}\) as shown in figure 5. Observation shows that flow of effective strain much more homogeneous than lower channel angle.

4.2.2 Deformation load
With increase in channel angle, load required to deform the billet is shown in figure 6. Following observation have been made during simulation through ECAP channel. Almost 50% load reduced with increasing channel angle from \(90^0\) to \(120^0\) with keeping constant offset length. From figure 6 it clear that first turn of billet required 6KN of maximum force while after the second turn it reaches 16 KN.
5. Conclusion
ECAP metal forming processes in which ultra-large plastic strain imposed on a bulk material was tested by FEA. It has been observed that, selected tool geometry and process parameter enables to obtain a uniform strain distribution as well as to reduce the overall load. In order to make plane orientation, larger channel angle is preferable with 50% reduction in deformation load. Raise of effective strain is partially higher from one turn of 90° ECAP channel.

References
[1] P. kumar and S. S. Panda, Proceedings of the 5th international and 26th AIMTDR-2014 conference
[2] P. C. Edmund and R. N. Parkins, The extrusion of metals. Chapman & Hall, 1960
[3] R. Z. Valiev, et al., JOM, pp 33-39 (2006)
[4] R. Z. Valiev, R. K. Islamgaliev, and I. V. Alexandrov: Prog. Mater. Sci., 45(2000)103-89
[5] B. Srinivas, Ch. Srinivasu, Banda Mahesh, Md Aqheel, Advanced Materials Manufacturing & Characterization, 3(1) (2013) 291-296
[6] M. Govindaraju, K. Balasubramanian, Uday Chackingal, K. Prasad Rao, 3rd International Conference on Materials Processing and Characterisation (ICMPC 2014), Procedia Materials Science 6 (2014) 37-42
[7] M. Morehead, Y. Huang, American Society of Mechanical Engineers,-Manufacturing Engineering Division, v 16-2 (2005) 1167-1176
[8] Y. Harai,, Yuki Ito and Zenji Horita, Scripta Materialia, 58(6) (2008) 469-472
[9] A. Korbel and M. Richert, Acta Metall, 33(11) (1985) 1971-1978
[10] Y. Saito, H. Utsunomiya and H. Suzuki, M. Geiger (ed.), Advanced Technology of Plasticity, III(1999) 2459-2464
[11] J. Y. Huang, Y. T. Zhu, H. Jiang and T. C. Lowe, Acta Materialia, 49(9) (2001) 1497-1505
[12] V. M. Segal, Materials processing by simple shear, Materials Science and Engineering A, 197(2) (1995) 157-164
[13] V. M. Segal, The method of material preparation for subsequent working." Patent of the USSR 575892 (1977)
[14] M. Furukawa, Y. Iwahashi, Z. Horita, M. Nemoto, T. G. Langdon, Materials Science and Engineering A, 257 (1998) 328-332
[15] L. Lavtar, T. Muhic, G. Kugler, M. Tercelj, Eng. Fail. Anal. 18 (2011) 1143-1152
[16] G. E. Dieter, Mechanical Metallurgy, McGraw-Hill, 1988
[17] E. O. Hall, Proc. Phys. Soc. London, Vol. 643 (1951) 747
[18] N. J. Petch, J. Iron Steel Inst. London, Vol. 183 (1953) 25
[19] S. Komura, Z. Horita, M. Furukawa, M. Nemoto, T.G. Langdon, Metall. Mater. Trans. A 32 (2001) 707-716
[20] P. kumar and S. S. Panda, 5th International Conference on Materials Processing and Characterzation (ICMPC 2016), Materials Today: Proceedings
[21] A. Rosochowski, L. Olejnik, Journal of Materials Processing Technology, 125-126 (2002) 309-316