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Investigation of ECAP process for enhancing process efficiency

Atul Dayal[a], K.Hans Raj[a] and Rahul Swarup Sharma[a*],

[a]*Department of Mechanical Engineering, Faculty of Engineering, DAYALBAGH EDUCATIONAL INSTITUTE, AGRA, 282005 INDIA.*

Abstract

In this work a comprehensive study of ECAP process is attempted for selection of an optimal ECAP die design for industrial implementation. An experimental analysis has been attempted on the basis of three pivotal factors that determine the industrial feasibility i.e., processing time, processing effort and mechanical properties. Mechanical testing results are presented for validating the facts. The outcome of this work certainly provides momentum in commercialization of ECAP process.

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* Corresponding author. Tel.: +91-562-2801545; fax: +91-562-2801226.

E-mail address: rahulswarup@dei.ac.in

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1. Introduction

Equal Channel Angular Pressing (ECAP) [1, 2] has attracted a lot of attention among researchers globally because of its potential to be used at an industrial level [3] for grain refinement. In ECAP, the billet is processed through an angular channel die, which is bent at an angle, having single turn or multiple turns, when the material is pressed through this bend channel /channels, severe plastic strains are developed in the microstructure of metal billet [4, 5, 6] because of induced simple shear (Fig.1).Though ECAP process has a potential to be employed at a commercial level, but still its applications are restricted to laboratory level only. Excessive processing time, labour intensiveness, larger pressing load, heavier dies and large experimental setup are the major hurdles before the successful commercialization of an ECAP process [7]. Proposed work is a step forward in selecting the ECAP die design in order to minimize processing steps thus reducing processing time and processing effort while enhancing the mechanical properties. Mechanical testing is performed for confirming the experimental results. Single turn, two

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turn, three turn and multi plunger ECAP dies design are used for FE simulations (Fig.1). In ECAP process each pass comprises following steps

P1- Billet fabrication
P2- Die setup and billet placement
P3- Extrusion process
P4- Disassembling of ECAP die and billet removal
P5- Processed billet finishing and flash removal
P6- Processed billet rotation to specific direction (route) and reinsertion

Nomenclature

Φ	Intersection angle
Ψ	Outer arc angle
µm	micrometre
nm	nanometre
R	Routes
A	Route (A)
Bc	Route (Bc)
P1-P6	Processes

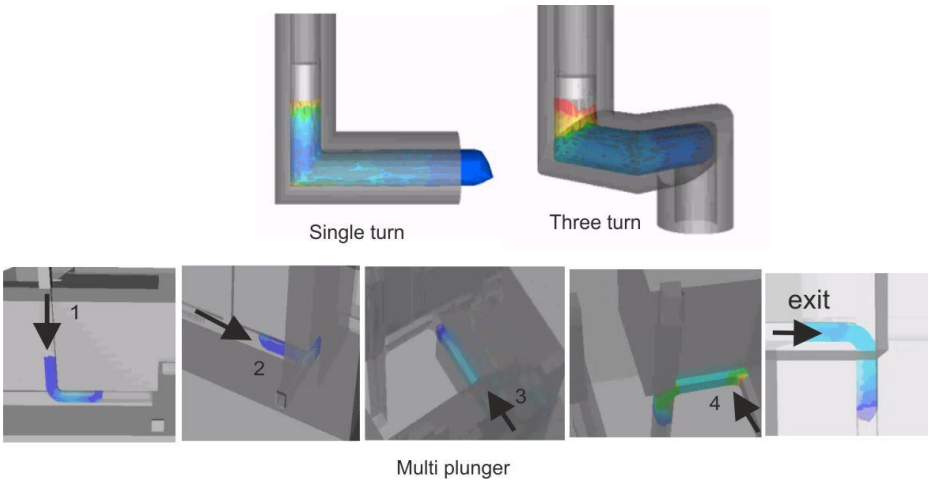

Fig 1: FE simulation of single turn, three turn and multi plunger ECAP die (i.e., 1st pass, 2nd pass, 3rd pass, 4th pass and exit stroke).

ECAP process requires minimum 4 passes for grain refinement. Therefore ECAP process involves 24 steps.

1.1. Result and Discussion

1.1.1 Processing time Study

Time based study includes processing time consumed during each pass of ECAP process involving six steps. In Table.1 an estimated processing time involved during each step for each pass is given at corresponding ECAP passes. Each process step is defined by the process code as shown in Table.1. It can be observed that process P2, P4 and P5 consumed excessive time, and processes i.e., P1 to P6 are quite labour intensive.

In single turn ECAP, after each pass, ECAP die is disassembled and processed billet is pulled out. Extra metal is removed from billet and finished billet is reinserted into tightly closed ECAP die for next pass. Same process is repeated after each pass. Single turn ECAP die process took approximately 3.5 hours in each pass.

In two turn ECAP die after first pass, a fresh billet is inserted in ECAP die, fresh billet pushed first billet to second channel. Further die is disassembled and first billet is removed from the channel and reinserted into the ECAP die. Then again a fresh billet is inserted and whole process is repeated. In two trun ECAP die, process P2 and P4 can be avoided in 2^{nd} and 4^{th} passes. And process P5 can be avoided in 1^{st}, 2^{nd} and 4^{th} passes, thus processing time also reduced to approximately 2 hours for each pass.

In three turn ECAP die first billet is extruded, then a second billet is extruded and then third billet is extruded. In all extrusion operations (process P3) ECAP die remain closed. After third extrusion initial billet (first billet) reached to the last channel. After third pass ECAP die is dismantled and extruded billet is removed and reinserted into ECAP die for fourth pass. In three turn ECAP die process P2 can be avoided in 2^{nd} and 3^{rd} passes and process P4, P5 and P6 can be avoided in 1^{st}, 2^{nd} and 3^{rd} passes thus processing time further reduced to approximately 1.5 hours per pass.

In single turn, two turn and three turn ECAP process, die need to dismantle once for material removal during four corresponding ECAP passes. Dismantling of ECAP die and material removal are very labour intensive and time consuming processes. To overcome this issue a new ECAP die is proposed having multiple plungers. The die remains closed during all corresponding passes only plunger moves. First plunger pushed billet to second channel after that second plunger push billet to third channel after that third plunger push billet to fourth channel then ultimately fourth plunger push billet out of the die. With multi plunger ECAP die process P4, P5 and P6 are completely avoided and process P1 is avoided in 2^{nd}, 3^{rd} and 4^{th} pass. An estimated average processing time consumed during each pass is approximately 30 min.

Process Codes:

P1 Billet fabrication for ECAP process. (Grinding and Finishing)
P2 Die setup and billet placement
P3 Extrusion process
P4 Dismantling of ECAP die and billet removal
P5 Processed billet finishing and flash removal
P6 Processed billet rotation to a specific direction (route) and reinsertion into ECAP die for next pass.

Single Turn ECAP					
	Processing Time (Hours)				
Process Code	Ist Pass	2nd Pass	3rd Pass	4th Pass	
P1	0.5	0	0	0	
P2	1	1	1	1	
P3	0.17	0.17	0.17	0.17	Total
P4	1	1	1	1	processing
P5	1	1	1	1	time
P6	0.1	0.1	0.1	0.1	
Total Time	3.77	3.27	3.27	3.27	13.58h
Two turn ECAP					
	Processing Time (Hours)				
Process Code	Ist Pass	2nd Pass	3rd Pass	4th Pass	
P1	0.5	0.5	0.5	0.5	
P2	1	0	1	0	
P3	0.17	0.17	0.17	0.17	Total
P4	1	0	1	0	processing
P5	0	0	1	0	time
P6	0	0	0.1	0	
Total Time	2.67	0.67	3.67	0.67	7.68h
Three turn ECAP					
	Processing Time (Hours)				
Process Code	Ist Pass	2nd Pass	3rd Pass	4th Pass	
P1	0.5	0.5	0.5	0.5	
P2	1	0	0	1	
P3	0.17	0.17	0.17	0.17	Total
P4	0	0	0	1	processing
P5	0	0	0	1	time
P6	0	0	0	0.1	
Total Time	1.67	0.67	0.67	3.77	6.78h
Multi Plunger ECAP (Estimated)					
	Processing Time (Hours)				
Process Code	Ist Pass	2nd Pass	3rd Pass	4th Pass	
P1	0.5	0	0	0	
P2	0.5	0.17	0.17	0.17	
P3	0.17	0.17	0.17	0.17	Total
P4	0	0	0	0	processing
P5	0	0	0	0	time
P6	0	0	0	0	
Total Time	1.17	0.34	0.34	0.34	2.19h

Table 1. Processing time consumed during single turn, two turn, three turn and multi plunger ECAP dies.

1.1.2 Labour Based Study

From Table.2 it can be observed that in single turn ECAP die process P2, P3, P4, P5 and P6 are repeated in each pass. In two turn ECAP die only process P1 and P3 repeated in each pass, process P2, P4 and P5 are avoided in 2nd and 4th pass. From table.1 it can be observed that process P1, P4 and P5 are consumed excessive processing time thus labour intensive too. In three turn ECAP die process P2 can be avoided in 2nd and 3rd pass and process P4 and P5 can be avoided in 1st, 2nd and 3rd pass. Only process P1 and P3 repeated in each pass. In proposed multi plunger ECAP die process P4, P5 and P6 are avoided completely for all passes.

Process code	Single turn				Two turn				Three trun				Multi plunger ECAP(Proposed)			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
P1	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
P2	Y	Y	Y	Y	Y	N	Y	N	Y	N	N	Y	Y	Y	Y	Y
P3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
P4	Y	Y	Y	Y	Y	N	Y	N	N	N	N	Y	N	N	N	N
P5	Y	Y	Y	Y	N	N	Y	N	N	N	N	Y	N	N	N	N
P6	Y	Y	Y	Y	N	N	Y	N	N	N	N	Y	N	N	N	N

Table 2. Processing steps involved during single turn, two turn and three turn ECAP die
(Y- Process occurred, N- Process not occurred)

1.1.3 Mechanical testing

The engineering stress strain curve of Al-6061 alloy before ECAP and after ECAP process is presented in Fig.2. Stress strain curve of test specimen processed through single turn, two turn and three turn ECAP die are plotted. Material process with single turn ECAP die with processing route (Bc) poses slightly better yield strength (550MPa) and ductility then compare to two turn ECAP die (yield strength 480MPa and ductility 12%) with route (A) after 4 ECAP passes. Material processed with three turn ECAP dies has yield strength 560MPa and ductility 17.5% after one complete cycle. It is observed that processing rout helps in retaining ductility; route (Bc) shows greater retention in ductility then route (A). It has been suggested that improvement in ductility occurred because of binomial distribution of grain sizes, presence of high angle grain boundaries and embedded larger grains as observed in SEM images (Fig.4).

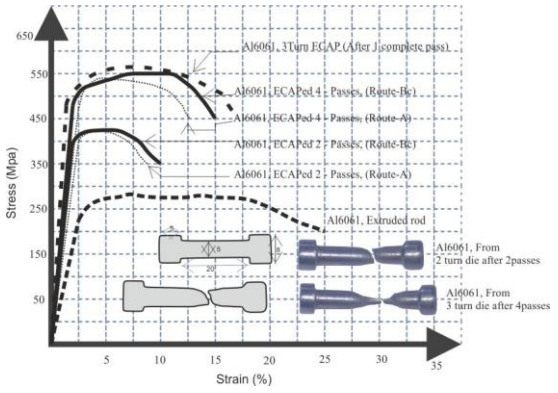

Fig 2. Engineering stress-strain curves of Al-6061 aluminium alloy processed through single turn, two turn and three turn ECAP die.

1.1.4 Microstructure analysis

In Fig.3, grain size distribution results of material (Al-6061) before ECAP and those of material ECAPed at room temperature after first, second ,third and fourth pass ($\Psi=30^0$,$\Phi= 90^0$) are shown. Billet at unprocessed stage had an average grain size 4.5µm. The microstructure of unprocessed billet were quite inhomogeneous (standard deviation =3.49). Fresh specimen is also an extruded rod of aluminium which leads to the presence of finer grain at initial unprocessed stage. Fresh billet having a binomial distribution of ultra-fine grains of 0.5 to 7 µm and fine grains of 10 to 20 µm. Microstructure was refined after first pass , degree of homogeneity in grain size distribution was also increased (standard deviation =1.05). From the figures it can be observed that after each pass average grain size reduces i.e., 1.3 µm after first pass , 0.8 µm after second pass, 0.6 µm after third pass and 0.4 µm after fourth pass (with route (B_c)). Alloy Processed with route (Bc) has standard deviation 0.52 after fourth ECAP passes , standard deviation is an indicator for uniform grains distribution, smaller the standard deviation means uniform the grains distribution. Alloy processed with route (A) has standard deviation 0.61 at fourth pass. It shows that route (Bc) gives better uniformity in grain distribution in comparison with route (A) (Fig.3).

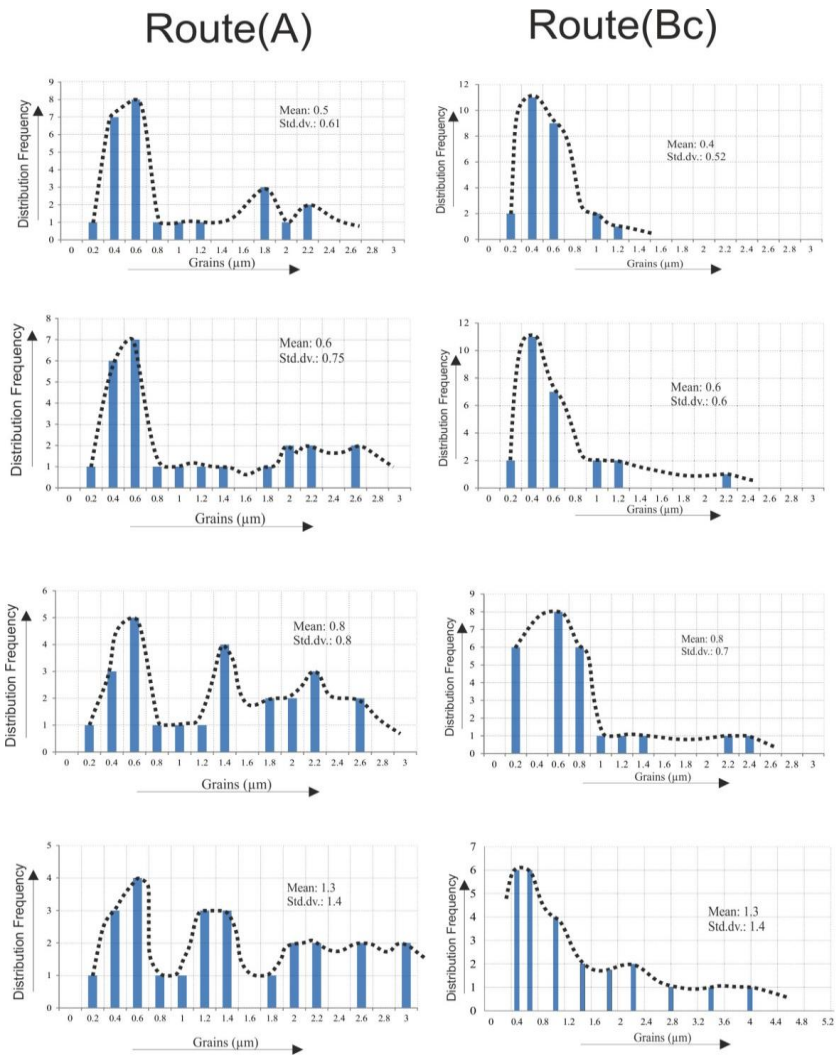

Fig 3. Grain size distribution in processed alloy (Al-6061) at two processing routes i.e., route (A) and route (B_c) and four corresponding ECAP passes.

Conclusion

Four ECAP die designs are investigated i.e., single turn, two turn, three turn and multi plunger ECAP die. First three dies are experimentally analyzed and last die is modeled using finite element technique and approximate results are presented.

- Processing time study concludes ,with single turn ECAP die average processing time consumed during each pass in 3.5 hours, in two turn ECAP die process P4 is avoided in 2^{nd} and 4^{th} pass and process P5 is avoided in 1^{st} ,2^{nd} and 4^{th} pass, average processing time consumed during two turn ECAP die is 2 hour for each pass. In three turn ECAP die process P4, P5 and P6 can be avoided during 1^{st}, 2^{nd} and 3^{rd} passes, thus the average processing time consumed during each pass reduced to 1.5 hours. In proposed Multi plunger ECAP die process P4, P5 and P6 avoided completely and approximate processing time consumed is 30 min for each pass.
- Material processed through single turn ECAP die after 4 repetitive ECAP passes with route (B_C) has yield strength 550MPa and ductility 15%. Material processed through 2 Turn ECAP die poses yield strength 480MPa and ductility 12% after 4 repetitive ECAP passes with route (A). Material processed through three turn ECAP die after one complete cycle shows yield strength 560MPa and ductility 17.5%. Results show that route (Bc) cause greater retention in ductility then route (A).
- ECAPed specimen with route (Bc) shows standard deviation in grain distribution is 0.52, And material processed with route (A) has standard deviation of 0.61 after 4^{th} ECAP pass, standard deviation is an indicator for uniform grains distribution, smaller the standard deviation means uniform the grains distribution.

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