Effect of Die Design parameters on materials processed by Equal Channel Angular Pressing

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Abstract- Equal Channel Angular Pressing technique is used for grain refinement in bulk materials, where the material is passed through the die in which the two channels intersect at some angle, that result in finer grains. There are number of die design parameters which affects the production of ultra-fine grains. This paper presents the effect of die design parameters such as channel angle, corner angle, several passes and route followed for processing of the material for grain refinement. The results of different parameters are compared, and it was observed that the optimum values for producing maximum shear strain is for channel angle 90° and it reduces with the increase in channel angle. About 20° corner angles is found to suitable for filling the corner gap, around 4 to 6 passes, and route Bc leads to the ultrafine grained structure of homogeneous equiaxed grains separated by high angle grain boundaries in the materials. The sample of Al-TiO2 was prepared and its microstructure and mechanical properties were tested after equal channel angular pressing.

Keywords- SPD, ECAP, Grain refinement, Microstructure.

1 Introduction
In recent years, it has been felt by different industries that material should have high strength and at the same time the material must have low weight. To fulfill the combination of required properties, number of techniques have been utilized in recent years. The mechanical and physical properties of any material can be described by several factors, and one of them is average grain size. The average grain size of the material plays an important role and often the dominant role in defining the strength of the material. Hall – Petch equation given in (1) states that strength or grain boundary strengthening of the material can be increased by decreasing the average grain size of the material [1-5].

$$\sigma_y = \sigma_0 + k d^{-1/2}$$  (1)

In this equation,  is known as friction stress,  is a constant of yielding and  is the mean grain size diameter. For changing a coarse-grained material into an ultra-fined grain material, it is important to produce a high shear strain to introduce a high level of dislocation, which causes re-arrangement of the grain boundaries. Ultra-fined grained material can be produced by using the techniques of SPD, where a very high strain is imposed on bulk solid without any change in the overall dimension of the work piece and which ultimately causes the grain refinement. The major SPD techniques which are already used to make UFG materials are accumulative roll-bonding (ARB), Multi-directional forging (MDF), High-Pressure Torsion (HPT), Twist Extrusion (TE), ECAP, etc. [6-12].
ECAP is one of the techniques of SPD in which a rod-shaped billet is passed through a die in which two channels intersect at some angle known as channel angle. The billet is pushed through the top channel of the die & taken out from the side channel and at intersection it must pass through the main deformation zone where high strain is imposed, which ultimately causes a grain refinement without any change in overall dimension. Since the dimensions of the billet remain unchanged, and that is the reason, the billet can be processed repeatedly for attaining exceptionally high strain [13, 15]. ECAP is known to be a homogenous process which simply means that workpiece has a uniform distribution of stress. There are factors which may affect its homogeneity. Broadly there are two factors that are internal and external factors. Internal factors are those which are dependent on type of material and its mechanical properties. External factors are those which are dependent on die design parameters like temperature, ram speed, friction, back pressure, rate of loading, geometry of die and passing routes. Internal factors majorly depend on material of workpiece and its properties.

Segal and his team introduced ECAP, also known as Equal Channel Angular Extrusion (ECAE), for the first time, in the early 1980s. Fig. 1 shows the processing of the materials through the ECAP die where the corner angle (a) $\Psi = 0$, (b) $\Psi > 0$.

![Fig.1. showing the processing of the material through the ECAP die](image)

Composites are new advancement in getting light weight and high strength material in present days. They have the ability to fulfill the requirements of industry of getting the desired properties. Al-TiO2 is a composite which can be prepared by adding titanium in to the Aluminum by metallurgical process. The properties of these composites can be further enhanced with the help of ECAP. This paper studies the microstructure and mechanical properties of this sample after 0, 1, 2, 3 and 4 passes of ECAP.

2 Method of shear strain produced

This paper is mainly focused on the observation of the effect of different die design parameters such as channel angle, corner angle, number of passes & routes through which the material passes from the die [16,18,20]. The governing equation relating channel angle, corner angles and number of passes has been mentioned in Eq. 2 modified by Iwahashi, which was earlier given by Segal [17]. The equivalent strain after the N cycle is given by:
Where $\varepsilon = \frac{N}{\sqrt{3}} \left[ 2 \cot \left( \frac{\phi}{2} + \frac{\psi}{2} \right) + \psi \csc \left( \frac{\phi}{2} + \frac{\psi}{2} \right) \right]$  \hspace{1cm} (2)

From the above equation, the conclusion can be made that friction also plays an important role apart from channel angle and corner angle in pressure requirement.

### Results and discussions

The effect of different die design parameters such as channel angle, corner angle, number of passes and routes followed has been done by using computational techniques [19, 21-26]. Different channel angles varying from $90^\circ$ to $135^\circ$ were used to analyse the effect of channel angle on strain produced. Corner angle were varied from $0^\circ$ to $40^\circ$ and number of passes were 1 to 2. All routes were considered during the process.

#### 3.1 Effect of die channel angle ($\phi$)

Die channel angle is the angle where the two channels intersect, and this has great impact on the production of shear strain which ultimately leads to grain refinement. Table 1 and Table 2 shows the effect of channel angle on computational values of shear strain produced for different corner angles when $n=1$ and $n=2$ respectively. Fig. 2 and Fig. 3 illustrates the Effect of channel angle on shear strain produced when $n = 1$ and $n = 2$ respectively. The results are obtained by using equation 2 for equivalent shear strain produced for channel angle varying from $90^\circ$ to $150^\circ$ for corner angle $0^\circ$ to $30^\circ$. The maximum value of shear strain is 1.154 for $\phi = 90^\circ$ and $\Psi = 0^\circ$. The graph is showing the decreasing trend of shear strain with the increase in channel angle for single pass. For double pass, the maximum value of shear strain is 2.308 for $\phi = 90^\circ$ and $\Psi = 0^\circ$. The graph is showing the similar decreasing trend of shear strain with the increase in channel angle for double pass also [27-31].

| S. No. | Channel angle | Equivalent Shear strain for $\Psi = 0$ | Equivalent Shear strain for $\Psi = 10$ | Equivalent Shear strain for $\Psi = 20$ | Equivalent Shear strain for $\Psi = 30$ |
|-------|---------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| 1     | $\phi = 90^\circ$ | 1.154                                  | 1.123                                  | 1.092                                  | 1.063                                  |
| 2     | $\phi = 100^\circ$ | 1.105                                  | 1.076                                  | 1.046                                  | 1.017                                  |
| 3     | $\phi = 110^\circ$ | 1.058                                  | 1.028                                  | 1.000                                  | 0.971                                  |
| 4     | $\phi = 120^\circ$ | 1.016                                  | 0.985                                  | 0.956                                  | 0.926                                  |
| 5     | $\phi = 130^\circ$ | 0.974                                  | 0.944                                  | 0.915                                  | 0.885                                  |
**Fig. 2.** Effect of channel angle on shear strain produced when n = 1

**Table 2** Effect of channel angle on computational values of shear strain produced for different corner angles when n=2

| S. No. | Channel angle | Equivalent Shear strain for $\Psi = 0^\circ$ | Equivalent Shear strain for $\Psi = 10^\circ$ | Equivalent Shear strain for $\Psi = 20^\circ$ | Equivalent Shear strain for $\Psi = 30^\circ$ |
|--------|---------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| 1      | 90            | 2.308                                       | 2.201                                       | 2.109                                       | 2.032                                       |
| 2      | 105           | 1.772                                       | 1.710                                       | 1.657                                       | 1.611                                       |
| 3      | 120           | 1.332                                       | 1.299                                       | 1.270                                       | 1.245                                       |
| 4      | 135           | 0.956                                       | 0.940                                       | 0.925                                       | 0.914                                       |
| 5      | 150           | 0.618                                       | 0.612                                       | 0.607                                       | 0.605                                       |
3.2 Effect of die corner angle ($\Psi$)

Die corner angle is the angle made by the curvature of two channels on the outer side. This has great impact on the smooth passage of material through the die. Table 3 and Table 4 show the effect of corner angle on computational values of shear strain produced for different channel angles when $n=1$ and $n=2$ respectively. Fig. 4 and Fig. 5 illustrate the Effect of corner angle on shear strain produced when $n = 1$ and $n = 2$ respectively. The results are obtained by using equation 2 for equivalent shear strain produced for corner angle varying from $0^\circ$ to $40^\circ$ for channel angle $90^\circ$ to $135^\circ$. The maximum value of shear strain is 1.154 for $\phi = 90^\circ$ and $\Psi = 0^\circ$. The graph is showing the decreasing trend of shear strain with the increase in corner angle for single pass. For double pass, the maximum value of shear strain is 2.310 for $\phi = 90^\circ$ and $\Psi = 0^\circ$. The graph is showing the similar decreasing trend of shear strain with the increase in channel angle for double pass also. It can also be observed that corner angle has little effect on shear strain produced in the material.

Table 3 effect of corner angle on computational values of shear strain produced for different channel angles when $n=1$

| Sr No | Corner angle | Equivalent Shear strain for $\phi = 90^\circ$ | Equivalent Shear strain for $\phi = 105^\circ$ | Equivalent Shear strain for $\phi = 120^\circ$ | Equivalent Shear strain for $\phi = 135^\circ$ |
|-------|--------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1     | 0            | 1.154                                         | 0.886                                         | 0.666                                         | 0.478                                         |
| 2     | 10           | 1.100                                         | 0.855                                         | 0.649                                         | 0.470                                         |
| 3     | 20           | 1.054                                         | 0.828                                         | 0.635                                         | 0.462                                         |
| 4     | 30           | 1.016                                         | 0.805                                         | 0.622                                         | 0.457                                         |
Fig. 4. Effect of corner angle on shear strain produced when n = 1

Table 4 effect of corner angle on computational values of shear strain produced for different channel angles when n=2

| Sr. No | Corner angle | Equivalent Shear strain for $\phi = 90$ | Equivalent Shear strain for $\phi = 105$ | Equivalent Shear strain for $\phi = 120$ | Equivalent Shear strain for $\phi = 135$ |
|--------|--------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 1      | 0            | 2.310                                    | 1.772                                    | 1.333                                    | 0.957                                    |
| 2      | 10           | 2.201                                    | 1.710                                    | 1.299                                    | 0.940                                    |
| 3      | 20           | 2.109                                    | 1.657                                    | 1.270                                    | 0.925                                    |
| 4      | 30           | 2.032                                    | 1.611                                    | 1.245                                    | 0.914                                    |
| 5      | 40           | 1.966                                    | 1.573                                    | 1.226                                    | 0.908                                    |
Fig. 5. Effect of corner angle on shear strain produced when n = 2

3.3 Effect of number of passes (n)

As per the equation 2, shear strain increases with the number of passes through the die but as per earlier study from other researchers, after 3 to 4 passes the further refinement of grains are not possible [27-30]. Sample of Al-TiO2 was prepared with TiO2 as 20% by weight and microstructure was analyzed under SEM after 0, 1, 2 and 3 passes. Figure 6(a-d) showed the optical microstructure of ECAPed experimental material up to 3 passes with magnification at 500X. The testing samples were prepared and micrographs were observed at room Temperature of 27°C. The etchant used was Keller’s Reagent which is a mixture of nitric acid, hydrochloric acid and hydrofluoric acid, used to etch aluminum alloys to reveal their grain boundaries and orientations. Figure 6(a) showed the micrograph of as received material where dark spots were visible as alloying elements and Figure 6(b) explained that the grains were significantly refined after single pass of ECAP. Further Figure 6(c) illustrated that the grains were aligned in one direction with more reduction in grain size after second pass and Figure 6(d) showed the further refinement of grains with significantly homogeneous and equiaxed grain structure.
3.4 Effect of Coefficient of Friction

Friction between sample and workpiece plays an important role in defining the homogeneity in microstructure and loading rate. F. Djavanroodi [32], states in his study that corner gap can be eliminated by high coefficient of friction which is basically formed at intersection of channels but the limitation is that it leads to increase of loading rate too. Atul Dayal [33], also reviewed the effect of friction and had made some conclusions that, there is almost no effect of friction on hard material’s homogeneity but large effect can be seen in softer materials. More the friction in soft material, high the homogenous structure.

3.5 Enhancement in hardness of material

The sample of Al-TiO2 was tested for Vickers hardness test after several number of passes. There was 30% increment in VHN from as zero pass to 4 passes of ECAP. From 189 VHN to 245.7 was noted in the experiment. Figure 9 shows the graph of increment in VHN after each pass in ECAP.
3.6 Enhancement in tensile strength of material

The sample of Al-TiO2 was tested for tensile strength on UTM machine after several number of passes and it is been concluded that from 145MPa there was increment of 36% up to 197.11MPa. There is maximum enhancement after 1 pass i.e. 12% and decreasing gradually with number of passes. It is noted that there is 5% increment in 4th pass. Figure 10 shows the graph of increment if tensile strength with number of passes.

Fig. 7. Shows the enhancement of VHN with each pass of ECAP

Fig. 8. Shows the enhancement of tensile strength with each pass of ECAP

4 Conclusion
The analysis was made to find out the effect of different die design parameters on grain refinement of materials. The following conclusion can be made regarding die design parameters: The channel angle, \( \phi \), is the most significant factor since it dictates the total strain imposed in each pass. A better strain homogeneity distribution has been obtained with less magnitude die channel angle close to 90°. The corner angle has less impact on strain distribution but it is used for smooth flow of material through the main deformation zone and filling the corner gap. The number of passes is important for producing the shear strain and results show that around 4 to 6 passes are required for optimum results for refining the grains. High coefficient of friction helps in minimizing the corner gap and better homogeneity in microstructure for softer material but high friction will increase pressing load requirement. Hardness of Al-TiO2 is increased 30% after 4th pass of ECAP upto 245.7 VHN. Tensile strength of Al-TiO2 is increased 36% after 4th pass of ECAP upto 197.11 MPa.

5 References

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Equal Channel Angular Pressing ECAP Cycling Extrusion and Compression CEC Accumulative Roll Bonding ARB Multidirectional Forging MF Twist Extrusion TE Repetitive Corrugation and Straightening RCS

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