International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 06, ACSCON - 2026

Ultrafine grain structure development in Aluminum alloy Processed by Cyclic Constrained Groove Pressing

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Abstract: Severe Plastic Deformation (SPD) processes are wide popularity in developing ultrafine grained (UFG) structured materials for a variety of applications. Among SPD techniques, there are a few techniques that are specially used to process metallic sheets and plates. Cyclic Constrained Groove Pressing (CGP) is one technique, which can produce fine grained structures in metallic sheets or plates in bulk. The process was introduced to develop UFG metallic sheets and plates nearly a decade ago and is now gaining great interest in the material processing field. The objective of this work was to study the influence of CGP processing on the super plastic behaviour of an Aluminium alloy. Samples in "ascast" conditions were processed by CCGP with as cast, 1, 2, 3 and 4 passes. Material obtained was characterized microhardness measurements were done for different test specimens. Grain refinement and microhardness increased with the number of CGP passes.

Keywords: Groove pressing; SPD; Dislocations; Aluminum alloy; ultrafine grain;

1. INTRODUCTION

There have been great advancements in the development of the high-strength metals and alloys and there is always a need for additional enhancements in the properties of materials. Various industries have a need for structural components that are lighter and stronger, particularly in the automotive industries. One of the methods to enhance the properties of the materials is manufacturing the components with ultrafine Grain. Many methods have been used to synthesize materials with Ultrafine Grain (UFG) sizes (10–1000 nm), including inert gas condensation [1], high-energy ball milling and sliding wear [2], etc. These techniques are attractive for producing powders with grain sizes below 100 nm, but cannot be used to make bulk samples. To consolidate the nanometer-sized powders into bulk materials, high pressure and moderate temperature are usually needed. Grains might grow during consolidation, making the bulk materials partially or completely lose the nano-characteristics [3]. It is usually impossible to completely eliminate porosity, even in materials consolidated under very high pressure and temperature. In addition, nano- powders are highly susceptible to oxidation and absorb large quantities of impurities such as O_2, H_2 and N_2, making it difficult to obtain clean bulk materials. The porosity as well as impurities significantly affects the mechanical properties of the bulk materials, often making them brittle [4]. These problems prevent the researchers from studying the intrinsic properties of bulk nano-materials. As a consequence of these difficulties, much attention has been paid to alternative procedures of introducing ultrafine grains in materials by severe plastic deformation (SPD).

UFG materials refer to a class of materials with grain sizes in the range of 100 to 1000 nm, i.e., <1 μm. These materials have grain sizes larger than nano-materials which have now come to be accepted as those with grain sizes less than 100 nm. Methods to produce UFG materials can be grouped into two categories: Bottom-up approach: Bottom-up approach involves consolidating nano- or ultra-fine grain materials from the atomic scale. Examples of such processes include Inert Gas Condensation (IGC), and Chemical Vapor Deposition (CVD).Top-down approach: Top-down approaches involve the refinement of coarse grains to ultrafine grains by SPD techniques that subject the work-piece to high-accumulated strains [5].

SPD process may be defined as metal forming processes in which a large plastic strain is introduced into a bulk metal in order to create UFG metals. The main importance of a SPD process is to produce high strength and lightweight parts with less cost, minimum time and environment harmony. Since several years, it is known that SPD - the plastic deformation of a metallic material up to highest amounts of plastic strain (up to some thousands percent) at low homologous temperatures (typically below 0.3 times of the melting temperature) leads to a subdivision of the initially coarse-grained microstructure into a hierarchical system of cell blocks and dislocation cells. The grain size of the material decreases with the increase in straining of the material. At the same time, the disorientation difference in crystallographic orientation increases. In order to obtain smallest microstructure sizes plastic strains of more than 600 to 800% are necessary.

Conventional methods such as rolling and forging of material processing do not provide such a high straining of the material without failure. The special feature of all variants of SPD is that the cross section of the material remains constant during or after SPD processing. Thus highest degrees of plastic deformation are possible because one sample can be subjected several times to SPD in order to accumulate

the total amount of plastic strain. Even though many different variants are known, only a few of them have industrial potential. SPD processes are typically achieving grain refinement in the metal or alloys through the introduction of large strain. The energy accumulated due to deformation helps in the formation of ultrafine grains in a continuous recrystallization process, rather than a nucleation and growth process that is observed in traditional thermo-mechanical processing operations. Another feature of SPD processes is that the external dimensions of the work piece remain unchanged. This allows for the repeated application of the process to accumulate larger strains. Grain refinement by SPD implies the creation of new high angle grain boundaries. This can be achieved by three mechanisms: the first is the elongation of initial grains during plastic deformation, causing an increase in high angle boundary area, the second is the creation of high angle boundaries by grain subdivision mechanisms, and finally, an elongated grain can be split up by a localization phenomenon such as a shear band. Among the three of the mechanisms mentioned, second mechanism is the most important one. The grain subdivision starts at low to medium strains when grains break up in cells and cell blocks. With increasing strain, this substructure evolves towards a lamellar structure. During this process, new high angle boundaries are generated, it happens by the simultaneous action of a microstructural and a texture mechanism. The former starts at low deformations and consist in the accumulation of dislocations in the cell and cell block boundaries in which the misorientions gradually increase with increasing strain. Some boundaries remain low angle boundaries but a significant fraction evolves into medium-high angle boundaries mostly in the range 15° - 30°. The texture mechanism involves the rotation of different parts of a subdivided grain towards different end orientations. This can generate very high misorientations in the range 20° - 60° [21].

2. CGP DEVELOPMENT

Many of the SPD processes developed to achieve UFG materials have their own limitations. CGP is a new technique which has the potential to overcome many of the limitations of the other SPD methods. design with the groove angle (θ) of 45°, a single pressing yields a shear strain of 1 at deformed region. This is equivalent to an effective strain, ε_{eff} , of 0.58. The second pressing is performed with a set of flat dies (Fig.1.6 (c)). By flat

pressing under the constrained condition, the previous deformed region is subjected to the reverse shear deformation while the previous undeformed region remains undeformed. The cumulative strain, ε_{eff} , in the

deformed region following the second pressing becomes 1.16 (double hatched area in Fig.1.6 (c)). After the second pressing, the sample is rotated by 180° (Fig.1.6 (d)). This allows the undeformed region to be deformed by further pressings due to the asymmetry of the grooved die. Then, the successive pressings with a grooved die (Fig.1.6 (e)) and a flat die (Fig.1.6 (f)) result in a homogeneous effective strain of 1.16 throughout the sample. By repeating a CGP process, very large amount of plastic strain can be accumulated in the sample without changing its initial dimensions and, resultantly, an ultrafine grained structure can be obtained.

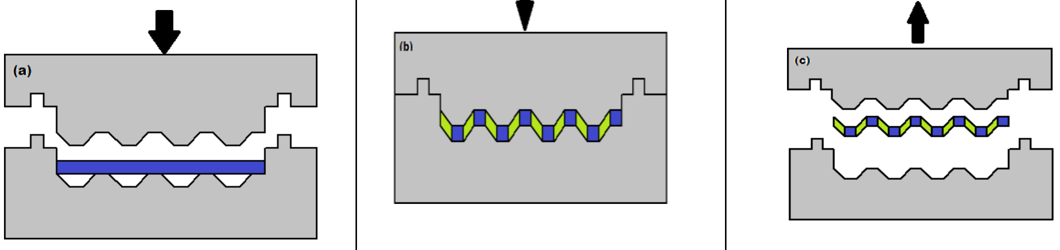
Many of the SPD processes developed to achieve UFG materials have their own limitations. CGP is a new technique which has the potential to overcome many of the limitations of the other SPD methods. CGP is a practical process to impose nearly uniform strain to specimen by asymmetrical grooved and flat dies. The CGP dies and one pass which contain four stages are exhibited. In each groove pressing, a specimen is placed in the die with slight gap which is equal to the sheet thickness. In each groove stage, the inclined region of the sample is subjected to pure shear, under plane strain condition [11]. In the first pressing, the equivalent strain of 0.58 is imposed to the work piece. Then the second stage, by flat pressing, the previous deformed region is subjected to another 0.58 strain in reverse direction. So after first pressing, the cumulative strain of 1.16 is applied to the deformed sheet. After second stage, the specimen is rotated 180^0 around the pressing direction. By repeating the groove pressing stage, strain of 0.58 is imposed to the previous undeformed region. At the end, the specimen flattened again and one pass of CGP with total strain of 1.16 in whole specimen is completed. The repetition of this process leads to a large amount of plastic strain in sample with no dimension change and ultrafine microstructure is achieved [12]. By repeating the CGP process, a large amount of plastic strain can be accumulated in the work piece without changing its initial dimensions [13]. Fig.1 (a-i) shows a schematic diagram of one pass of CGP specimen with total strain of 1.16. Also Fig.2 (a-g) shows a three dimensional illustration of a Constrained Groove Pressing Technique.

The present study is led by the latter approach. In order to investigate strain distribution in CGPed plates after four pressing steps FEM simulation has been accomplished [14]**.**

(a) Initial position of the corrugated dies with specimen

(b) st Pressing

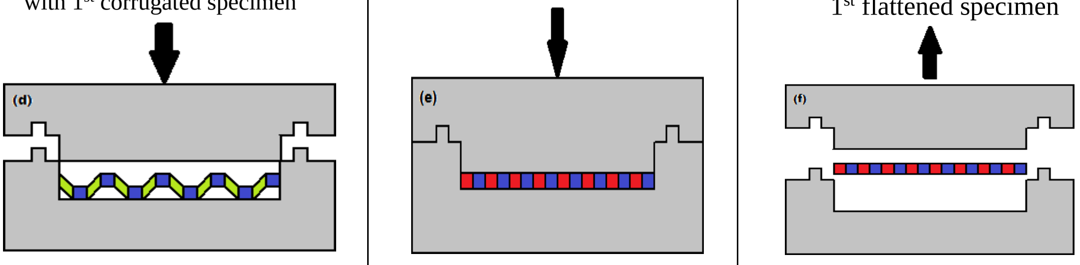
(c) Moving top die upwards to take 1st corrugated specimen



(d) Initial position of the flattened dies with 1st corrugated specimen

(e) 2nd Pressing

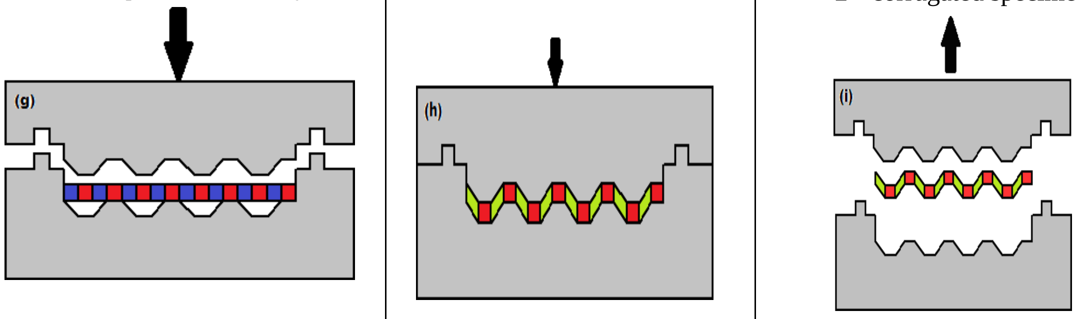
(f) Moving top die upwards to take 1st flattened specimen



(g) position of the corrugated dies with 1st flattened specimen rotated by 180^{0}

(h) rd Pressing

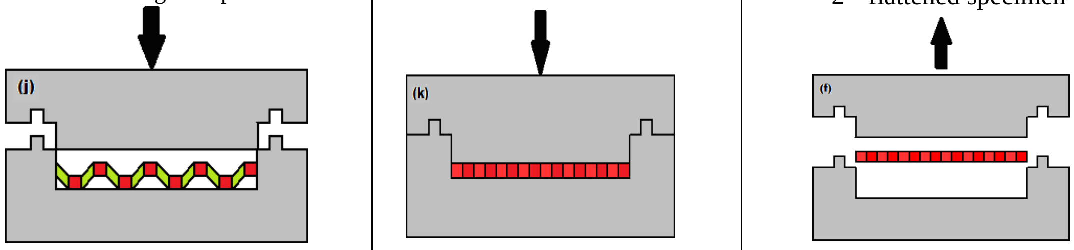
(i) oving top die upwards to take 2nd corrugated specimen



(j) Initial position of the flattened dies with 1st corrugated specimen

(k) th Pressing

(l) oving top die upwards to take 2nd flattened specimen



🟦 no deformation

🟩 €$_{eff}$ = 0.58

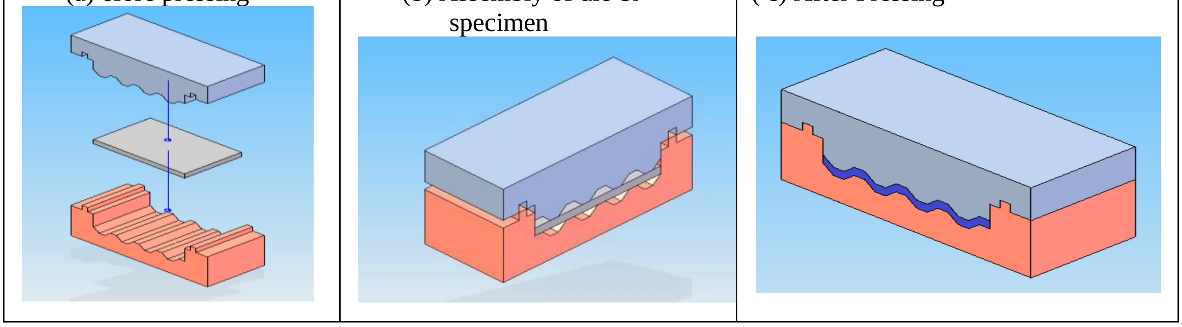
🟥 €$_{eff}$ = 1.16

Fig.1: A Schematic illustration of a Constrained Groove Pressing Technique

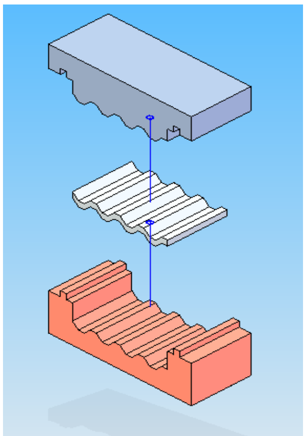
(a) efore pressing

(b) Assembly of die & specimen

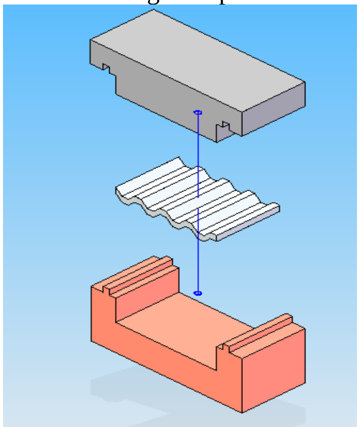
(c) After Pressing



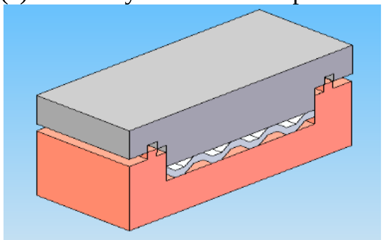
(c) After moving the Dies



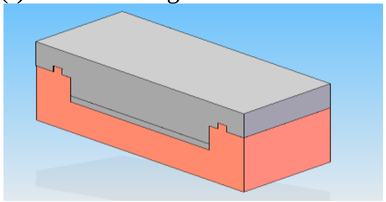
(d) Before pressing corrugated specimen



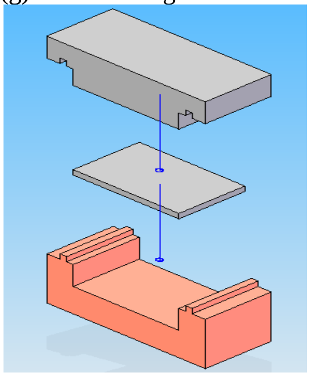
(e) Assembly of Flat die & specimen



(f) Af Pressing with flat dies



(g) Af moving Flat dies



(h) After two press the effective strain in pure shear region are 0.58 per pressing. amount of effective strain introduced is 1.16

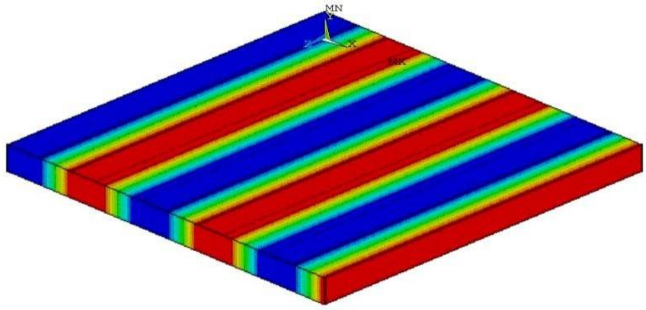


Fig.2: Illustration of a Constrained Groove Pressing Technique

The following gives the equation for the effective strain,

$$\gamma_{xy} = \gamma = \frac{x}{t} = \frac{t}{t} = 1 \tag{1.1}$$

$$\varepsilon_{eff} = \sqrt{\frac{2}{9}\left[(\varepsilon_x-\varepsilon_y)^2+(\varepsilon_y-\varepsilon_z)^2+(\varepsilon_z-\varepsilon_x)^2\right]+\frac{4}{3}\left[\varepsilon_{xy}^2+\varepsilon_{yz}^2+\varepsilon_{zx}^2\right]} \tag{1.2}$$

$$\varepsilon_{xy} = \frac{\gamma_{xy}}{2} = \frac{\gamma}{2} \tag{1.3}$$

$$\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon_{yz} = \varepsilon_{zx} = 0 \tag{1.4}$$

$$(1.2),(1.3),(1.4) \Rightarrow \varepsilon_{eff} = \sqrt{\frac{4(\gamma/2)^2}{3}} \tag{1.5}$$

$$\varepsilon_{eff} = \frac{\gamma}{\sqrt{3}} \Rightarrow \varepsilon_{eff} = 0.58 \tag{1.6}$$

This method consists of bending of a flat plate using corrugated dies and then restoring the original shape of the plate with flat dies. The repetition of the processes is required to obtain a large strain and desired structural changes. It works upon combinations of shear and bending that are imposed under constraining pressure in specially designed corrugated die surfaces. As it has the potential capability in commercial production, very little research is done about this method in the scientific literature.

Fig.3 (a-i) shows the CAE simulation of Constrained Groove Pressing Technique, here used ANSYS and Abacus application software used to simulate the entire operations.

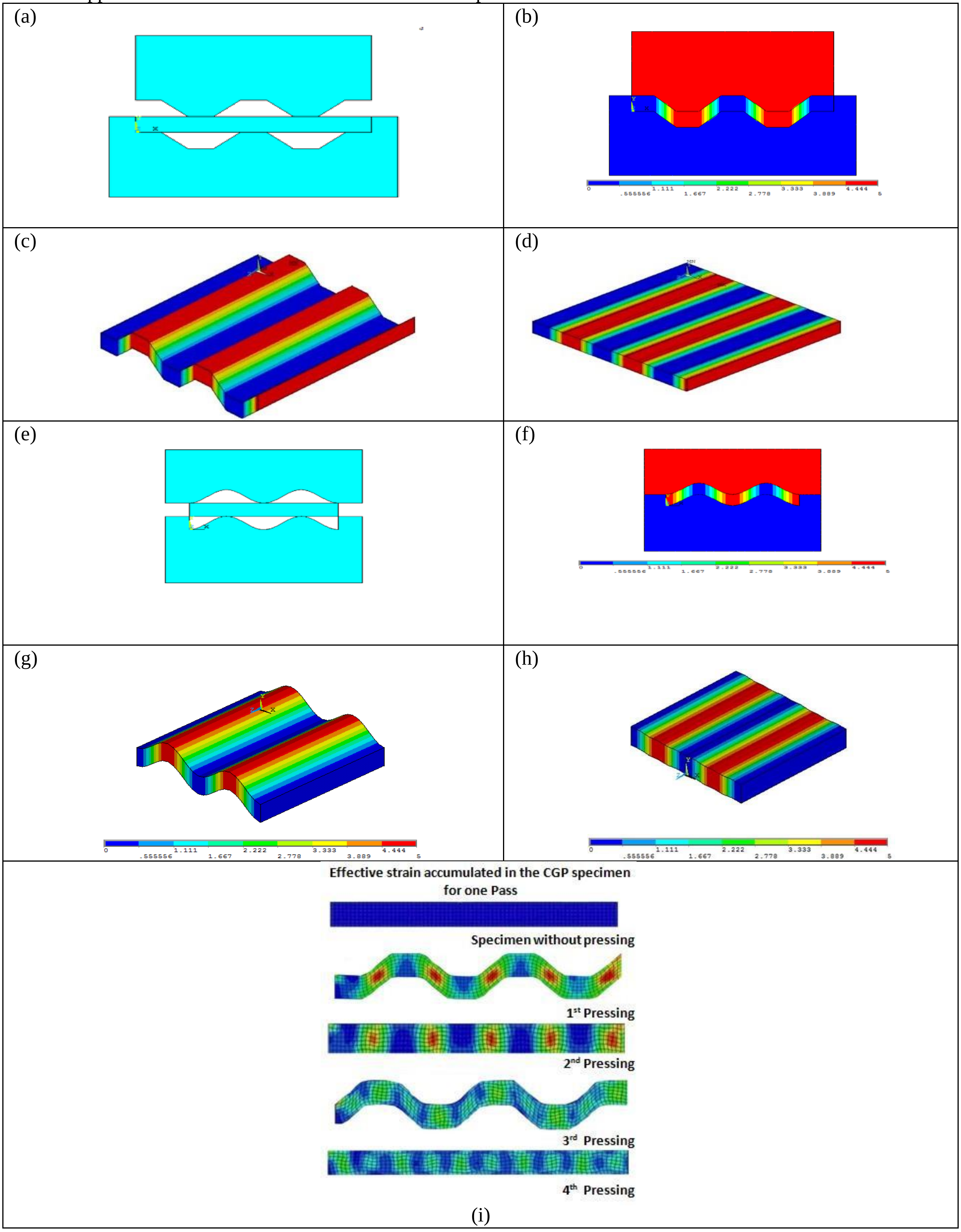


Fig.3: a) Corrugated die with specimen, b) Specimen pressed in the corrugated die, c) Corrugated specimen accumulated the effective strain of 0.58, d) Flat specimen accumulated the effective strain of 1.16, e) Radial die with specimen, f) corrugated specimen accumulated the effective strain of 0.58 with dies g) corrugated specimen accumulated the effective strain of 0.58 without dies h) Flat specimen accumulated the effective strain of 1.16,

i) Effective strains accumulated in the specimen after one pass.

3. EXPERIMENTAL PROCEDURE

In the present study, material selected for the investigation is Aluminium alloy ingots. The chemical composition of the above material is mentioned in the Table 5.1. Aluminium alloys (Al 6061). It is used as matrix material and is suitable for mass production of lightweight castings, which can either be sand cast or die- cast.

Table 1: Chemical composition of Al 6061 alloy

Contents	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
Weight %	0.62	0.23	0.22	0.03	0.84	0.22	0.10	0.10	Balance

A known quntity of Al6061 alloy ingots were pickled in 10% sodium hydroxide(NaOH) solution at room temperature for 10 minutes. Pickling was done to remove surface impurity such as grease, dust, rust, etc. The smut formed was removed by immering the ingots for one minute, in a mixture of Nitric acid (50%) and water (50%) followed by washing with alcohal. These cleaned ingots were dried in air. The powderd particulate SiC was preheated, to remove the moisture contentent using muffle furnace. It is neccessary in order to reduce the temperature gradient and to improve wetting between molten metal and reinforcement.the melting range of Al alloy is 650^{0}C to 700^{0}C, Hence pre-cleaned and preheated furnace is set to the temperature of 700^{0}C. The cleaned and pickled ingots of the alloy, weighing around 700grams were placed in the aluminium crucible for melting. Argon gas was supplied at the rate of 5mm^{3}/hr continuosly into the melting chamber to aviod any accidents and damages.

Fig.4: a) Hydraulic Press (b) specimen sandwich between the corrugated die and flat die

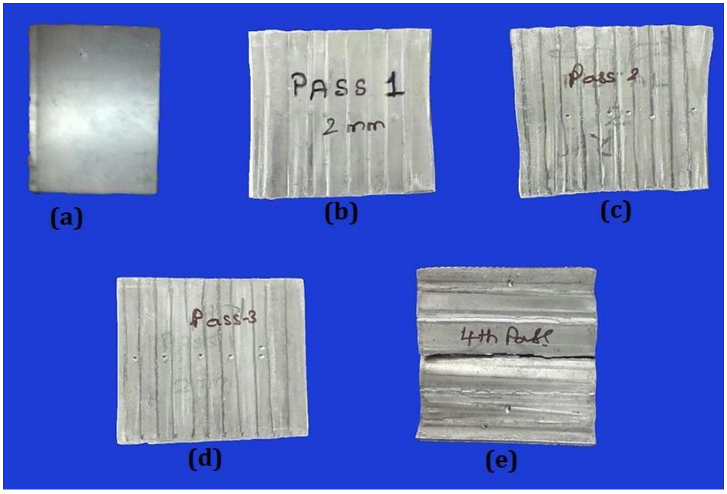


Fig.5: CGP specimens a) as cast specimen without pressing , b) After 1st pass

c) After 2nd pass d) After 3rd pass and e) After 4th pass.

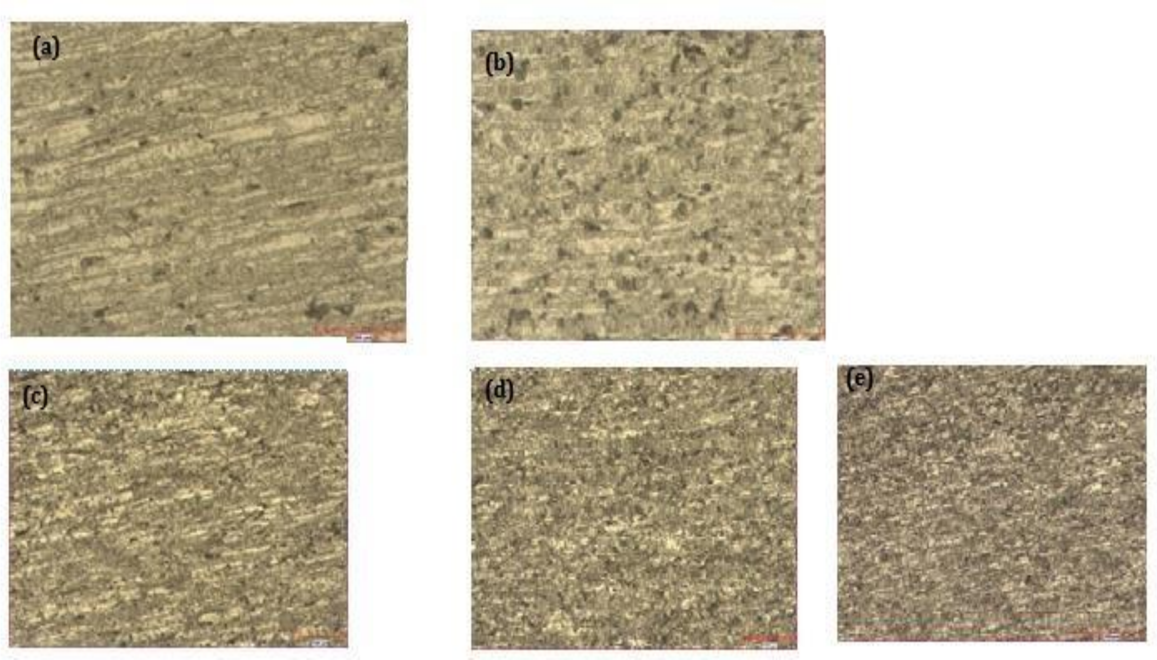


Fig.6: Optical micrographs of CGP specimens a**)** as cast specimen, b) After 1st pass c) After 2nd pass d) After 3rd pass and e) After 4th pass

The molten metal was kept superheated to a temperature of 700^0C and maintained at the same temperature till Al alloy melts. The speed of the stirrer was set to 500 rpm to create vertex in the molten metal. Preheated and known quantity of SiC particulate of 5% by weight was added into the molten metal and continuously stirred in the presence of Argon gas. A preheated and assembled die was placed below the pouring point and the melt was poured into the die. After solidification, the metal was removed from the die and castings were checked for defects physically. From the castings, the samples were cut to a width of 50mm and length of 70mm, for 2mm thickness of several specimens. The Al alloy plates with above dimensions were pressed in a corrugated and flat dies, 1 to 4 passes of compression were considered. All the samples were processed at room temperature. Each pass of this process was consists of two stages and the process was carried out using a pairs of corrugated and flat dies. Fig.4 shows the a) Hydraulic Press b) specimen sand witch between the corrugated die and flat die, Fig.5 shows CGP specimens a) as cast specimen without pressing, b) After 1st pass, c) After 2nd pass, d) After 3rd pass and e) After 4th pass. Fig.6 shows the optical micrographs of CGP specimens a) as cast specimen without pressing, b) After 1st pass, c) After 2nd pass, d) After 3rd pass and e) After 4th pass.

4. RESULT AND DISCUSSION

Fig.7 shows the microhardness distribution according to number of passes. The initial hardness of the undeformed specimens has 29HV for 2mm thickness specimen. The formation of substructure after one pass led to an increase in microharness to an average of 7 to 8HV. It is also observed that after two passes of treatment exhibit a further increase in hardness, i.e., average of 7HV. After every pass of CGP, the hardness of the specimen shows increasing trend with an average increase in hardness of 1 to 2HV in all the specimens. Hall- petch equation gives strength of any materials which is inversely proportional to grain size.

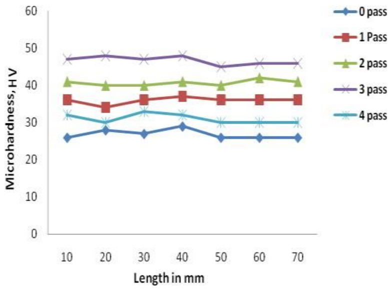


Fig.7: Microhardness distribution according to number of passes

In SPD method the yield strength of any materials can be increased by decreased the grain size. As discussed earlier, higher refinement in the grain size leads to an increase in the hardness of the specimens. But the grain refinement is strongly influenced by the increase in strain. The results shows that, increase in microhardness value of the specimens pressed, as the number of passes is increased the hardness increases. After 4th pass maximum fall of hardness that material loses it hardness. We can see that as dislocations formed in the coarse grains, the grain size decreased more and more refined grain size giving rise to the better hardness. The grain size is refined, thereby increasing the hardness during corrugation and straightening process.

5. CONCLUSION

The effect of SPD by Cyclic Constrained Groove Pressing process on the mechanical properties of Aluminium alloy at room temperature was studied. In the present work the following conclusions are summarized.

- Complete process of CGP process simulated using CAE tools.
- Deformation behaviour is characterized by the compression and elongation of material near the flat surface, bending/stretching of the plate in the other region during pressing. Shear regions revealed two distinct deformation zones within the regions; one is simple shear drformation zone, in which the material flow in central regions is characterized by simple deformation, and the other is rotational deformation zone in which the material flow is characterized by rotational deformation observed away from the central regions.
- Two dimensional finite element simulations were carried out to study the stresses induced in CCGP processing with a corrugated and flat dies.
- Aluminium alloy was processed by CCGP from as cast condition with 1 to 4 passes. It was developed procedure to CCGP processing with a corrugated and flat dies.
- The hardness of the specimen has been increased with the number of passes of corrugation and straitening from 29HV to 50HV.
- It was concluded that the ductility will inevitably be detenorated with increase in density on dislocations of dislocations of grain grain boundaries, which directs the great enhance

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