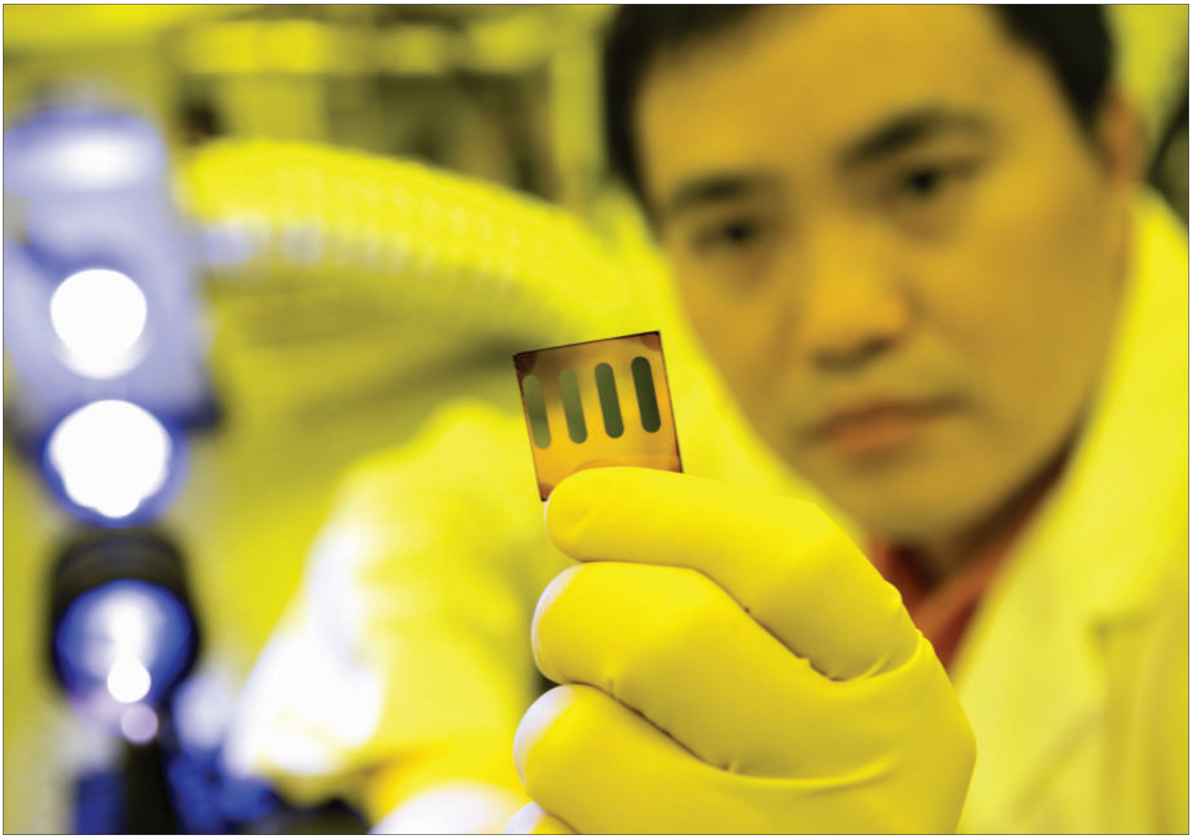

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Research Article

Finite Element Simulation of Deformation Behaviour of Aluminium Alloy Processed by Cyclic Constrained Groove Pressing

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Abstract

Background and Objective: Cyclic constrained groove pressing (CCGP) is a SPD technique which is applicable for metallic sheets or plates and can produce fine grained structures for various applications. The aim of the present study was to understand the impact of CCGP processing on the behaviour of 6061 aluminium alloy. **Materials and Methods:** A hydraulic press with suitable dies was used in the process to corrugate and straighten the specimens. Samples in "as cast" conditions were processed by CCGP with 0, 1, 2, 3 and 4 passes. The samples obtained were characterized for their hardness and tensile strength. Advanced tools such as finite element method (FEM) and scanning electron microscopy (SEM) have been used in order to better explain the process and the results obtained. **Results:** It was observed that the grain refinement, hardness and tensile strength of the samples increased with the number of CCGP passes. The hardness of the specimen was found to increase with the number of passes of corrugation and straitening from 29-50 HV 10. Tensile strength of the specimen was found to increase with the number of passes of corrugation and straitening from 60-145 MPa. The SEM analysis of the fractured specimens due to tensile testing of the UFG samples showed that they have a dimple structure characteristic. **Conclusion:** The study revealed that the hardness of the specimen increased with the number of passes of corrugation and straitening from 29-50 HV 10. Tensile strength of the specimen was found to increase with the number of passes of corrugation and straitening from 60-145 MPa. The SEM analysis of the fractured specimens due to tensile testing of the UFG samples showed that they have a dimple structure characteristic.

Key words: Severe plastic deformation, constrained groove pressing, dislocations, aluminium alloy, ultrafine grain

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

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 (UFG). Many methods have been used to synthesize materials with UFG sizes (10-1000 nm), including inert gas condensation[1] and high-energy ball milling[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 required. 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 100-1000 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 <100 nm. Methods to produce UFG materials can be grouped into two categories, the bottom-up approach and the top-down approach. The 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 vapour deposition (CVD). The top-down approach approaches involve the refinement of coarse grains to ultrafine grains by SPD techniques that subject the work-piece to high-accumulated strains[5].

An importance purpose of the 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, which involves 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 micro structure 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. Literature says that huge plastic strains of the order of about 600-800% are necessary to obtain very small micro structure sizes[6,7].

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 very huge amount of plastic deformations are achievable since the same sample can be subjected to the SPD process several times with an objective of accruing the total amount of plastic strain required. 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[8,9].

An attempt is made in the present investigation to find the influence of the test parameters on the deformation behavior of aluminium alloys and also to simulate the process for better understanding. The material properties that were considered for evaluation during the present study were tensile strength and hardness.

MATERIALS AND METHODS

The present study was conducted during 2018-2019 at Bangalore.

CCGP development: CCGP is a practical process to impose nearly uniform strain to specimen by using grooved and flat dies. The CCGP dies and one pass which contain four stages are exhibited in Fig. 1a-l. The process involves a die design with the groove angle (θ) of 45° and a single pressing will generate a shear strain of 1 in the deformed region. This is equivalent to an effective strain, ε_{eff}, of 0.58. The next pressing (second) is done using a set of flat dies (Fig. 1c). By employing the pressing process using the flat dies under the constrained condition, the previously deformed region experiences reverse shear deformation, while the previously un-deformed region continues to remain un-deformed. As a result, the cumulative

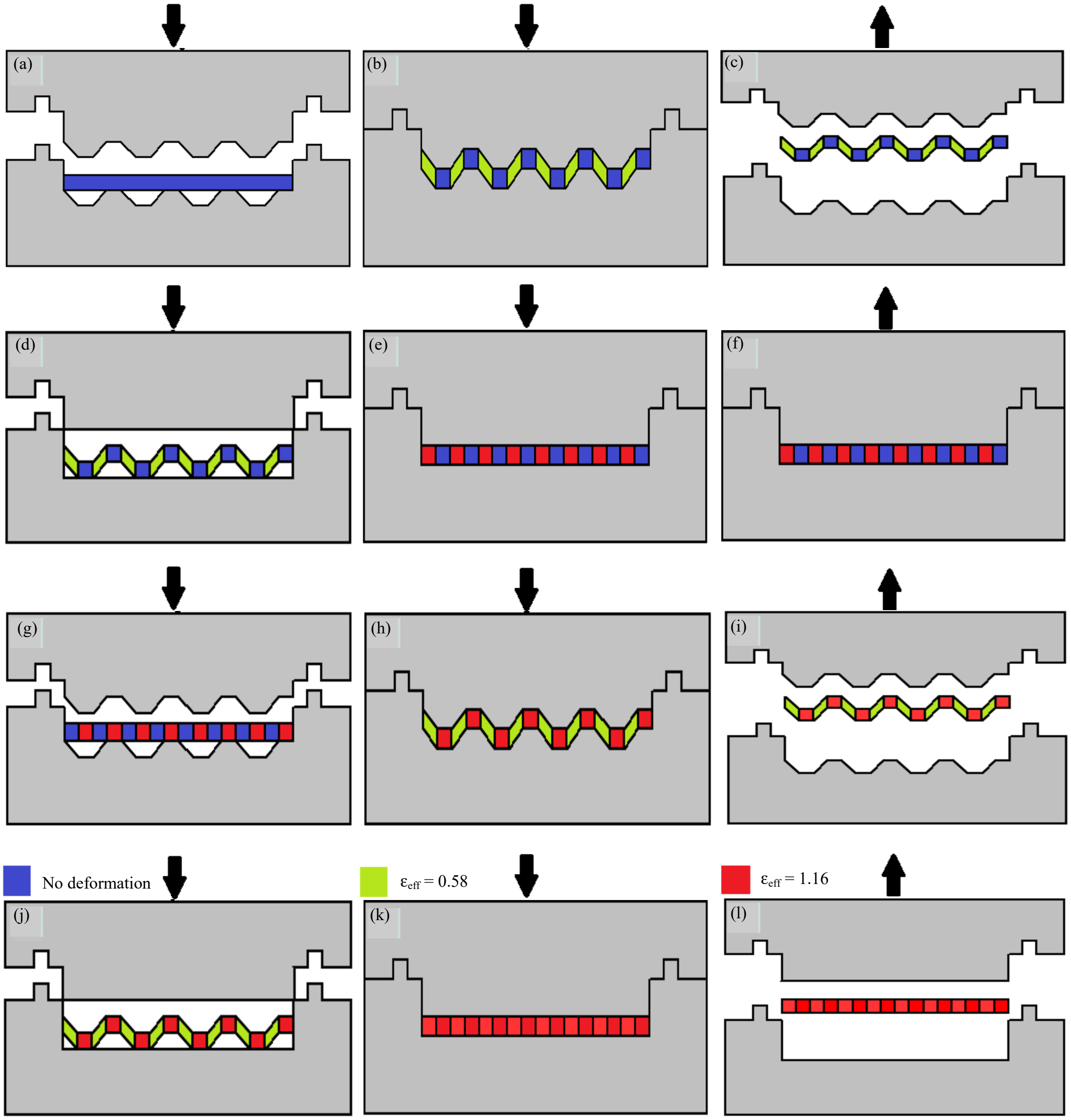

Fig. 1(a-l): A schematic illustration of a constrained groove pressing technique, (a) Initial position of the corrugated dies with specimen, (b) 1st pressing, (c) Moving top die upwards to take 1st corrugated specimen, (d) Initial position of the flattened dies with 1st corrugated specimen, (e) 2nd pressing, (f) Moving top die upwards to take 1st flattened specimen, (g) Position of the corrugated dies with 1st flattened specimen rotated by 180°, (h) 3rd pressing, (i) Moving top die upwards to take 2nd corrugated specimen, (j) Initial position of the flattened dies with 1st corrugated specimen, (k) 4th pressing and (l) Moving top die upwards to take 2nd flattened specimen

strain, ε_{eff}, in the deformed region subsequent to the second pressing will reach a value of 1.16 (double hatched area in Fig. 1c). After the second pressing, the sample is rotated by 180° (Fig.1d). The effect of this stage would be to ensure that the un-deformed region gets deformed by further pressings due to the asymmetry of the corrugated die. The consecutive pressings stages which make use of a grooved die (Fig. 1e) and a flat die (Fig. 1f) will yield a homogeneous effective strain of 1.16 throughout the sample. Thus the repetitive nature of the CCGP process, aids in amassing huge amount of plastic strain in the sample with no alteration in its initial dimensions and, as a result, an ultrafine grained structure can be achieved.

During each corrugation pressing, the specimen is placed between the two dies ensuring that a small gap exists which are in agreement with the sheet thickness. In each of the corrugation stage, the inclined region of the specimen experiences pure shear, under the condition of plane strain[10]. In the first pressing, the equivalent strain of 0.58 is imposed to the work piece. During the second stage which is the flat pressing stage, the previously deformed region is further subjected to another 0.58 strain in the reverse direction. So after first pressing, the cumulative strain of 1.16 is applied to the deformed sheet. After second stage, the specimen is further subjected to the pressing process, but after rotating it by 180° with reference to the previous pressing direction. By reiterating the corrugation pressing stage, a strain of 0.58 is levied to the previous undeformed region. At the end, the specimen flattened again and one pass of CCGP 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 the sample with no dimension change and ultrafine microstructure is achieved[11]. By repeating the CCGP process, an excessive amount of plastic strain can be amassed in the specimen with no alteration to its initial dimensions[12]. A schematic diagram is presented for one passes of CGP specimen with total strain of 1.16, (Fig. 1a-l). Also is evident a three dimensional illustration of the CCGP (Fig. 2a-g).

Another important part of the study is to investigate the strain distribution in specimen subjected to CCGP after four pressing steps and the same has been accomplished using the FEM simulation.

The following equations are used for calculating the effective strain:

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

where, γ_{xy} is pure shear strain in xy plane, γ is shear strain and t is thickness of the specimen.

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

where, ε_{eff} is effective strain, ε_x, ε_y and ε_z, are strains in x, y and z planes respectively and ε_{xy}, ε_{yz} and ε_{zx} are strains in xy, yz and zx planes:

$$\varepsilon_{xy} = \frac{\gamma_{xy}}{2} = \frac{\gamma}{2} \tag{3}$$

where, ε_{xy} is strain in xy plane, γ_{xy} is pure shear strain in xy plane:

$$\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon_{yz} = \varepsilon_{zx} = 0 \tag{4}$$

where, ε_x, ε_y and ε_z are strains in x, y and z planes respectively and ε_{yz} and ε_{zx} are strains in yz and zx planes:

$$(2), (3), (4) \Rightarrow \varepsilon_{eff} = \sqrt{\frac{4\left(\gamma/2\right)^2}{3}} \tag{5}$$

where, ε_{eff} is effective strain and γ is shear strain:

$$\varepsilon_{eff} = \frac{\gamma}{\sqrt{3}} \Rightarrow \varepsilon_{eff} = 0.58 \tag{6}$$

where, ε_{eff} is effective strain and γ is shear strain.

The method consists of bending of a flat plate by alternatively employing a set of corrugated dies and later reinstating the original shape of the specimen by using flat dies. Such iterative action is necessary to obtain a large strain and desired structural changes. It works on the combinations of shear and bending that are imposed under constraining pressure in specially designed corrugated die surfaces. Though the CCGP has very big potential in commercial production, very little research is done on this method and hence less materials in available in the literature[13]. Figure 3a-i shows the simulation of Constrained Groove Pressing technique using ANSYS and Abacus application software was used to simulate the entire operations.

In the present study, material selected for the investigation is 6061 Aluminium alloy. The chemical composition of the material is as follows: Si-0.62, Fe-0.23, Cu-0.22, Mn-0.03, Mg-0.84, Cr-0.22, Zn-0.10, Ti-0.10 and balance was aluminium. Aluminium alloys (Al 6061) is widely used as matrix material and is suitable for mass production of light weight castings, which can either be sand cast or die-cast.

A known quantity of Al6061 alloy ingots were pickled in 10% sodium hydroxide (NaOH) solution at room temperature for 10 min. 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 alcohol. These cleaned ingots were dried in air. The cleaned and

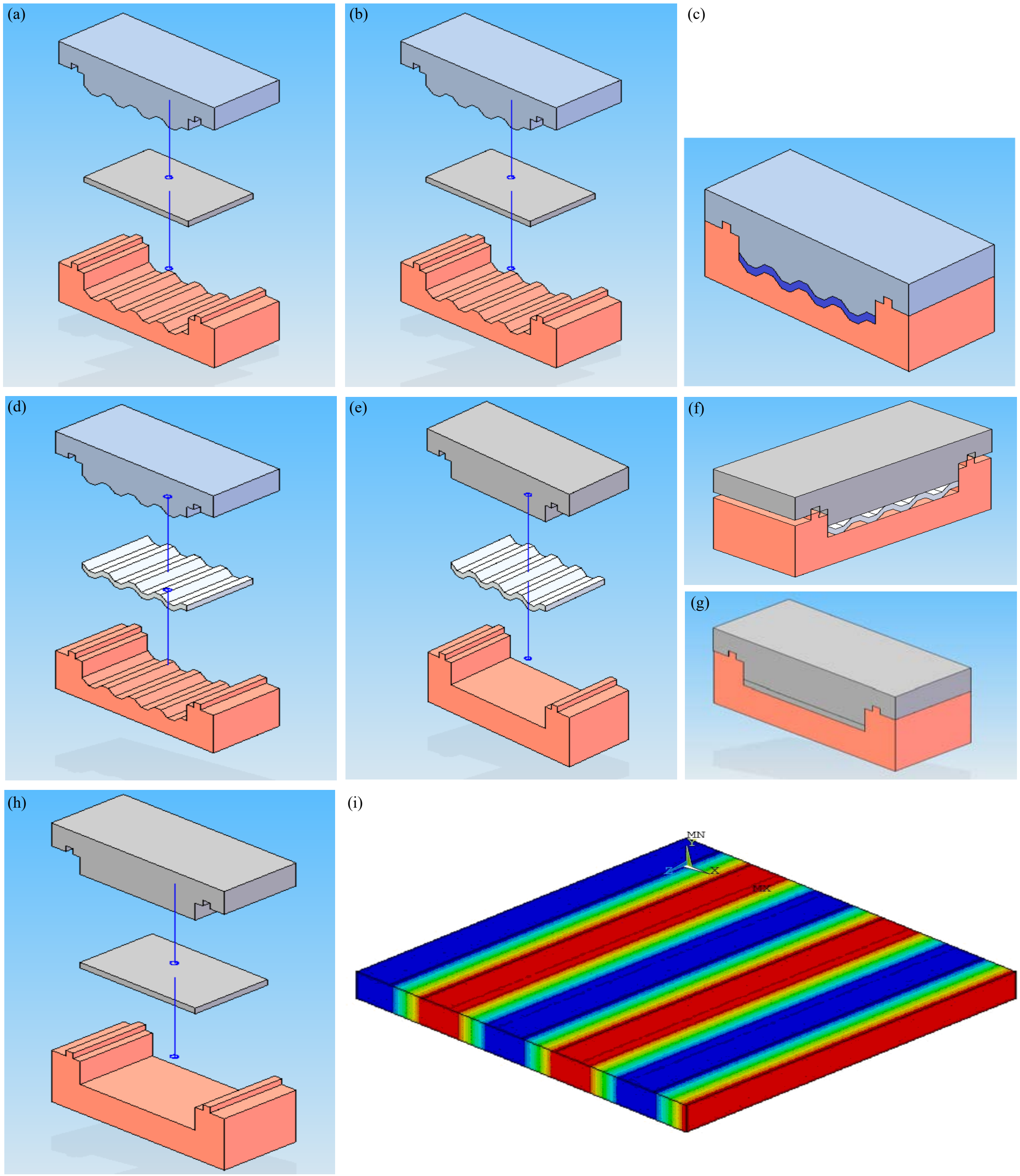

Fig. 2(a-i): Illustration of a constrained groove pressing technique, (a) Before pressing, (b) Assembly of die and specimen, (c) After pressing, (d) After moving the dies, (e) Before pressing corrugated specimen, (f) Assembly of flat die and specimen, (g) After pressing with flat dies, (h) After moving flat dies and (i) After two press the effective strain in pure shear region are 0.58 per pressing, amount of effective strain introduced is 1.16

pickled ingots of the alloy, weighing around 700 g were placed in the graphite crucible for melting. Argon gas was supplied at the rate of 5 mm^3 h^{-1} continuously into the melting chamber to avid contamination.

The molten metal was kept super heated to a temperature of 700°C and maintained at that temperature till the alloy melted completely. A preheated and assembled die was placed below the pouring point and the melt was poured

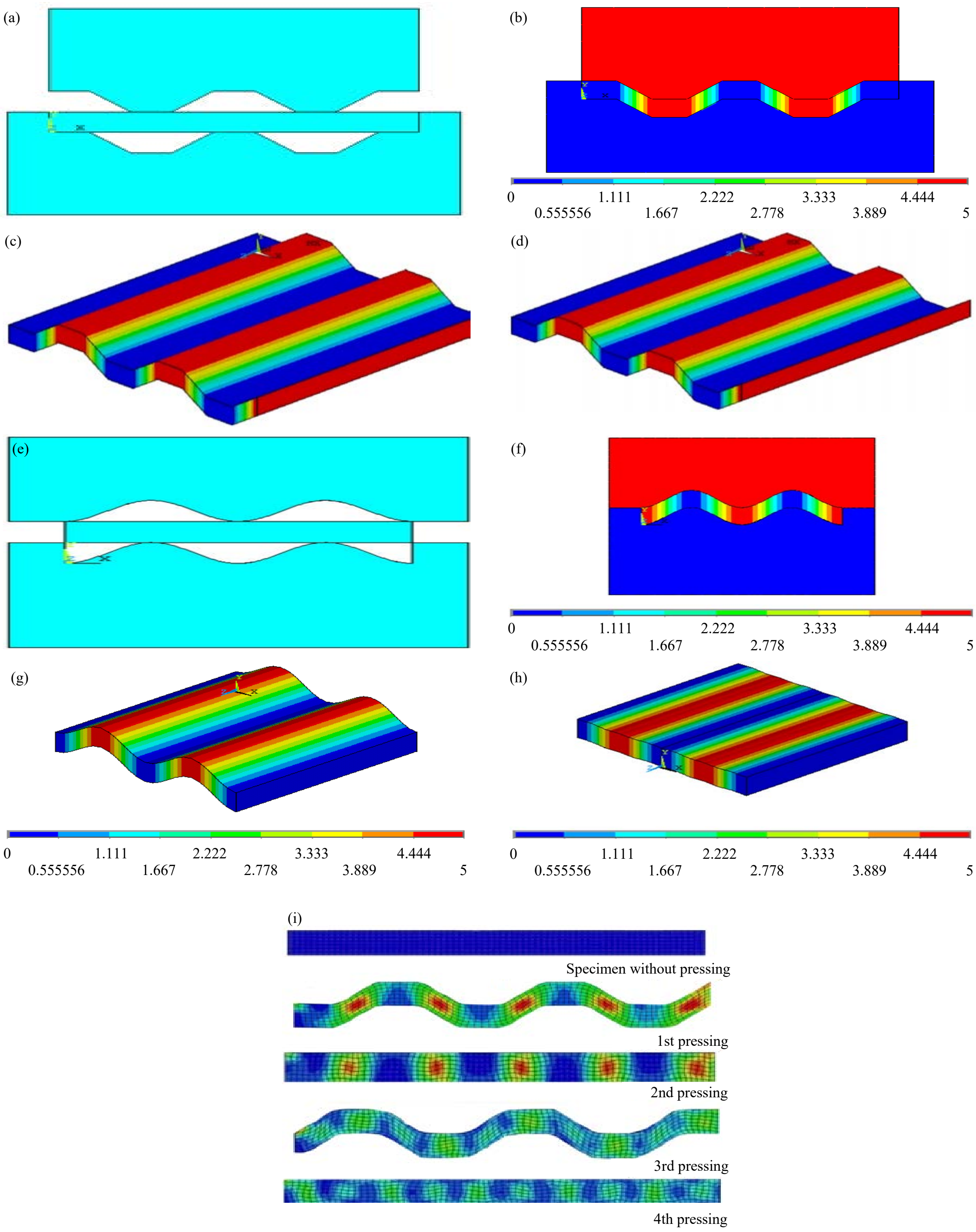

Fig. 3(a-i): (a) Corrugated die with specimen, (b) Specimen pressed in the corrugated die, (c) Corrugated specimen accumulated the effective strain of 0.58, (d) Flat specimen accumulated the effective strain of 1.16, (e) Radial die with specimen, (f) Corrugated specimen accumulated the effective strain 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 and (i) Effective strains accumulated in the CGP specimen after one pass

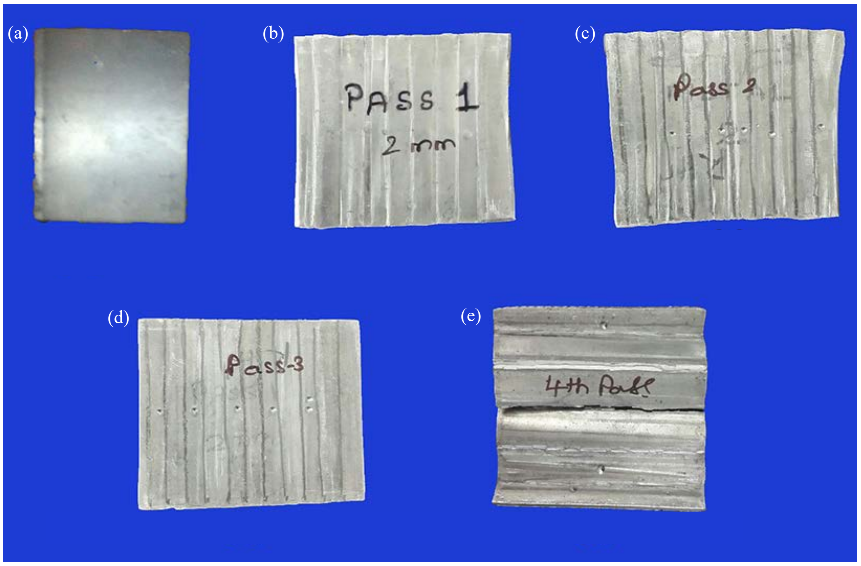

Fig. 4(a-e): CGP specimens as, (a) Cast specimen without pressing, (b) After 1st pass, (c) After 2nd pass, (d) After 3rd pass and (e) After 4th pass

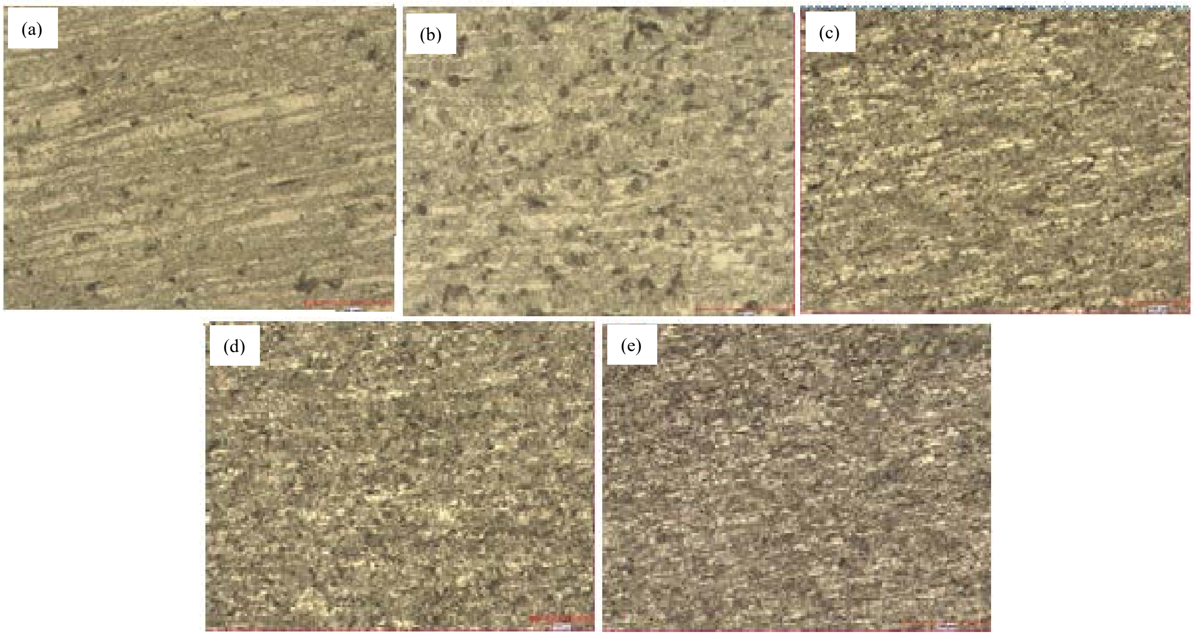

Fig. 5(a-e): Optical micrographs of CGP specimens as, (a) Cast specimen, (b) After 1st pass, (c) After 2nd pass, (d) After 3rd pass and (e) After 4th pass

into the die. After solidification, the metal was removed from the die and castings were checked for defects. The samples were cut from the castings to a width of 50 mm and length of 70 mm, while the thickness was 2 mm. The specimens with above dimensions were pressed in corrugated and flat dies alternatively and 1-4 passes of compression were considered. All the samples were processed at room temperature and each pass of the process consisted of two stages. Presented herewith are the different stages in the preparation process, Fig. 4a-e and the micrographs of the specimens subjected to different passes (Fig. 5a-e).

RESULTS

Hardness: The graph provided in Fig. 6 shows the distribution of hardness according to number of passes. The initial hardness of the non-deformed specimen has 25 HV 100 for 2 mm thickness specimen. The formation of substructure after one pass led to an increase in hardness to 36 HV 100. It is also observed that after two passes of treatment, the specimen exhibits a further increase in hardness and reached a value of 41 HV 100.

Tensile properties: The tensile properties have been evaluated for the samples from 0-4th pass. The graph presented in Fig. 7 shows the variation in strength and elongation with the number of passes. The plot shows that elongation for the initial material varies between 31-34% compared to 4-6% in the case of specimen subjected to pressing.

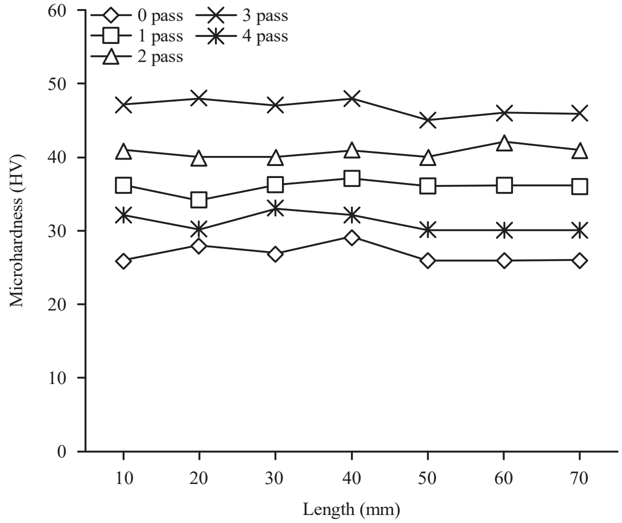

Fig. 6: Hardness distribution according to number of passes

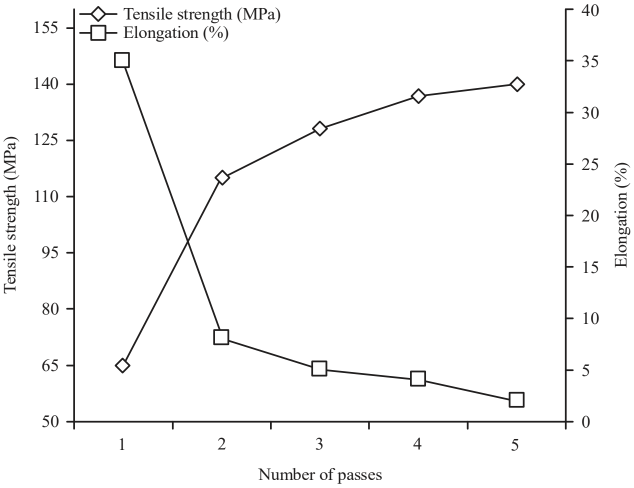

Fig. 7: Tensile strength and elongation v/s number of passes

SEM analysis of fractured tensile test specimens: The fracture surfaces of tensile specimens are provided here with Fig. 8a-c. Examination of the fractures due to tensile testing of the UFG samples showed that they have a dimple structure

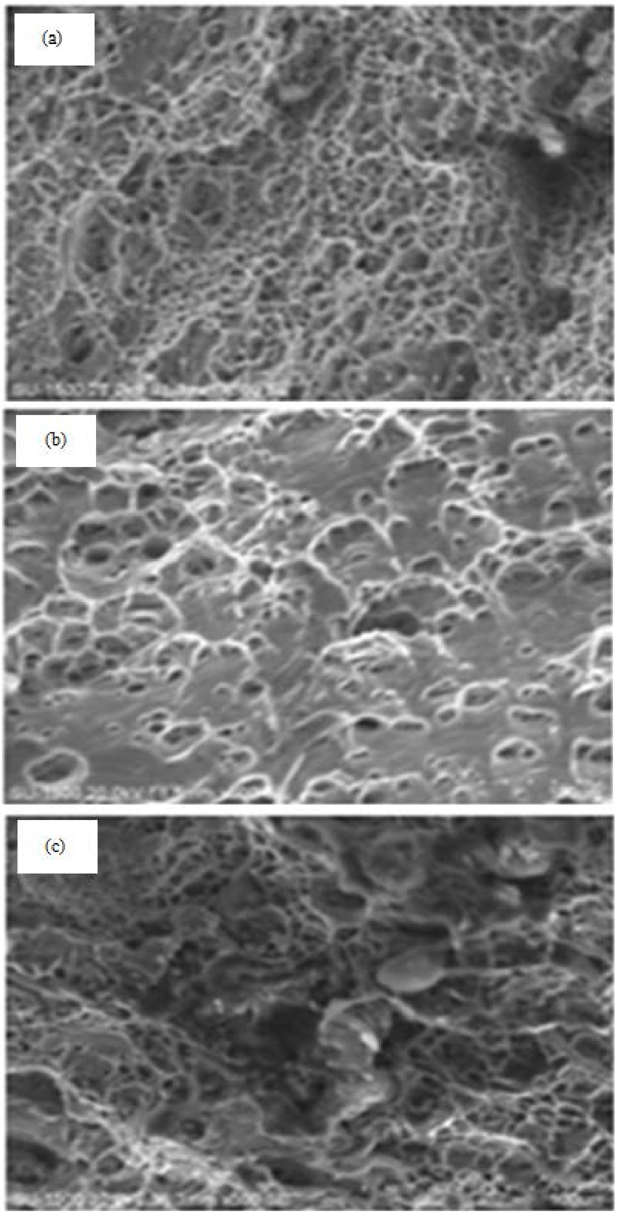

Fig. 8(a-c): Tensile strength of 2 mm thickness specimens pressed with, (a) 1 pass, (b) 2 passes and (c) 4 passes

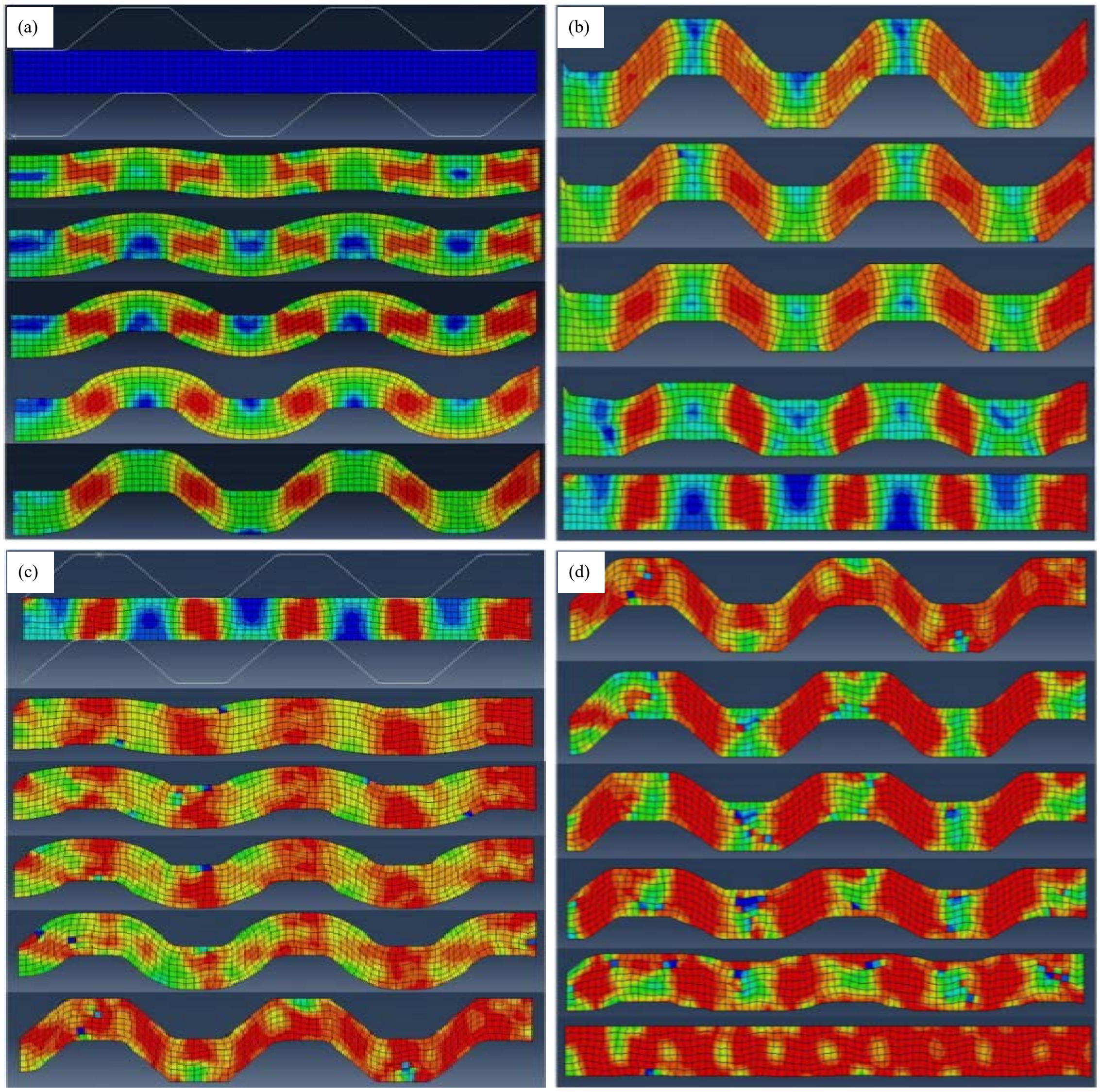

Fig. 9(a-d):Strain distribution for, (a) First pressing stage using corrugated dies and the effective strain is accumulated in corrugated specimen, (b) Second pressing stage using flat dies and the effective strain is accumulated in straightened specimen, (c) Third pressing stage using corrugated dies and the effective strain is accumulated in corrugated specimen and (d) Fourth pressing stage using flattened dies and the effective strain is accumulated in straightened specimen

characteristic. This reveals the pits occurrence in the process of tensile deformation as a result of the formation of macroscopic cracks and brittle failure of these specimens. It is apparent that with increasing number of passes, the number of well-developed dimples increases and the features of the fracture change to that of a typical brittle failure.

The non-uniformity of strain distribution shown in Fig. 9 may not indicate the non-uniformity of the strength and microstructure developed. It follows from the results obtained that the stress distribution is relatively uniform, compared to the strain distribution. It is to be noted at this stage that the experimental stress values deduced from the hardness results are in considerably good agreement with the simulated results.

The equivalent strain distribution at the central line of the deformed material after first and second straightening are also presented in Fig. 10a-b, respectively. Plastic strains vary harmonically along the transverse direction and are symmetrically distributed after each groove.

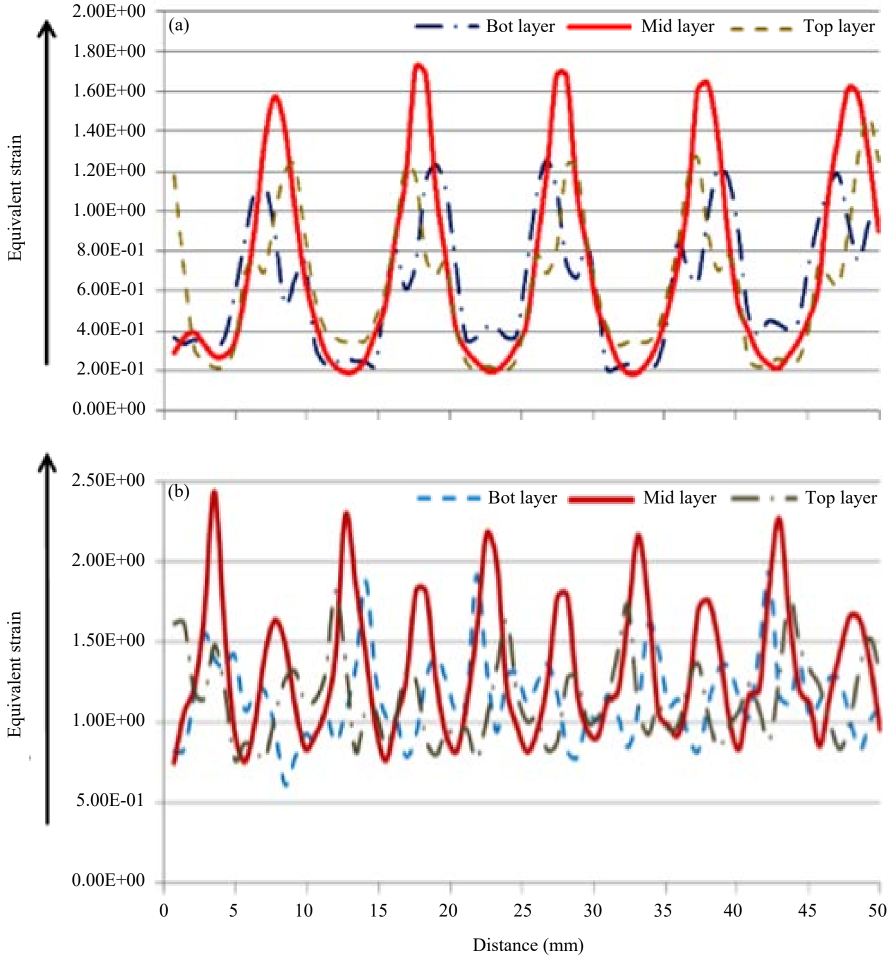

Fig. 10(a-b): Equivalent strain after, (a) First straightening and (b) Second straightening

DISCUSSION

The results show an increase in hardness value of the pressed specimens proportionally with the number of passes the specimen is subjected to. But it is to be observed that after 4th pass, there is a decrease in hardness. Hence the safe limit for the SPD process for the material considered in the present study is 3 passes.

It can be observed that as the dislocations get formed in the coarse grains, the grain size decreased more and more and the effect of the refined grain size is improved hardness. The grain size gets refined, thereby increasing the hardness during corrugation and straightening process. The hardness of the specimen shows increasing trend with a consistent increase in hardness in all the specimens after every pass of CGP. The observation is in accordance with the Hall-Petch equation which states that the strength of a metal is inversely proportional to grain size and has been observed by other researchers' too[14-16]. It can be concluded from the tensile test results, that the tensile strength increases with the loss in ductility during CCGP process. The decrease in elongation is very large after 1st pass. However, there is not much difference in elongation with further CCGP passes. This indicates a pronounced loss of formability during CCGP.

The specimens prepared using the above said methods were tested for their mechanical properties alone and not tested for their wear and corrosion behaviour. The same can be carried out as an independent study by interested researchers.

Material deformation behaviour: As stated, the objective of the present work is to numerically analyse the CGP process for this material and estimate the strain in homogeneity. Homogenous strain distribution will lead to uniform grain refinement. The outcome of the present study will be used to understand the effectiveness of CGP processing route to produce UFG in different base metals.

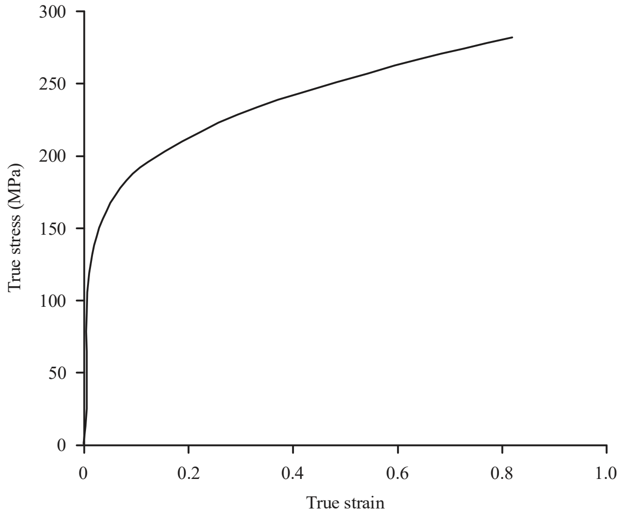

Fig. 11: Stress-strain curve of the aluminium alloy used in the simulation study

The stress-strain curve of the specimen which is available in the literature[15] was used in the simulation study and it illustrates the variation of equivalent plastic strain and material behaviour of aluminium at different stages (Fig. 11). Theoretically a uniform distribution of value of 1.16 was expected at the end of one pass. It can be seen however that the strain distribution is non-uniform. This will result in non-uniform grain refinement as the refinement is dependent upon dislocation accumulation through plastic strain.

Finite element simulation: The finite element simulation technique was applied in the present study with an objective of examining the strain distribution in the CGP process after four pressing stages. The results thus obtained are presented herewith (Fig. 10a). In order to investigate the plastic deformation and strain localization behaviour of the CGP process, the elasto-plastic FEM technique was adopted. The simulations were investigated after one full pass using the commercial finite element code ABAQUS/Explicit. The simulation was considered under 2D plane strain condition. The stress–strain curve of the aluminium alloy which was used in the simulations is presented (Fig. 9). The kind of mesh used in the simulation is CPE4 elements for the 2D plane strain conditions (CPE4R: A 4-node bilinear plane strain quadrilateral, reduced integration, hourglass control). The coefficient of friction at the interface of workpiece and die was selected as 0.1, which is within a typical (0.05-0.1) range in the cold forming of metals. It is essential to note that in spite of the increase in average strain levels and the intensification of strain localisation as a result of increase in the CGP cycles; the same need not be trend for stress levels, since the stress gradient decreases with strain.

Strain distribution shows peaks of maximum strain at the middle of groove region and valleys of minimum strain at the corner region. According to die geometry, sheets at 4 mm distance from both the ends are not subjected to any shear deformation, but they show some deformations in these regions too. This is due to the corner effect mentioned in the previous section. Analysing the strain distribution, it is found that strain peaks observed in the 4th stage of flattening is slightly more compare to peaks of second stage flattening due to work hardening of materials in previous stages. The same trend of effective strain distribution in finite element simulation of CGP process is also by other researchers' too[16].

CONCLUSION

The effect of SPD using the cyclic constrained groove pressing process on the mechanical properties of aluminium alloy at room temperature was studied. The entire process of CGP process was simulated using CAE tools. The 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 deformation 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. The hardness of the specimen was found to increase with the number of passes of corrugation and straitening from 29-50 HV 10.Tensile strength of the specimen was found to increase with the number of passes of corrugation and straitening from 60-145 Mpa. The SEM analysis of the fractured specimens due to tensile testing of the UFG samples showed that they have a dimple structure characteristic.

SIGNIFICANCE STATEMENT

This study discovers that the effect of severe plastic deformation on the structure and the mechanical properties of aluminium alloys. The methodology adopted for severe plastic deformation was constrained groove pressing using suitable dies and a hydraulic press. The observations made are quite significant. It was observed that the grain refinement, hardness and tensile strength of the samples increased with the number of CCGP passes. This study will help the researchers to understand the importance of grain size on the mechanical properties of materials and the possible ways to achieve the same.

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