Constrained Groove Pressing (CGP): Die Design, Material Processing and Mechanical Characterization

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Abstract: Constrained groove pressing (CGP) is a severe plastic deformation (SPD) technique used as a strengthening method for sheet metal. In the current work, an optimal/cost-saving design for CGP dies was attained using the stress analysis tool in SolidWorks Simulation Xpress wizard. This study examined low-cost and widely industrially applied aluminium materials, i.e., pure 1050 Al and 5052 Al alloy. Each material was subjected to three passes of the CGP process using a 150 tons capacity press. For both materials, inter-pass annealing treatment was undertaken before the third pass. The effect of the number of CGP passes on the microstructure and tensile properties was studied after each pass. For CGPed pure 1050 Al with respect to the as-received material, the ultimate tensile strength (UTS), yield strength (YS) and YS/UTS ratio increased with an increasing number of CGP passes until the second pass, while elongation decreased with the number of passes. For CGPed 5052 Al alloy, the UTS and YS increased after the first pass and then decreased after the second pass. Variations in the elongation and YS/UTS ratio of 5052 Al alloy after the CGP process were insignificant. After inter-pass annealing and applying the third CGP pass, the strength of pure 1050 Al decreased, and that of 5052 Al alloy increased, which was attributed to the influence of composition on their structures. The strength-ductility balance decreased with an increasing number of CGP passes in both materials.

Keywords: CGP, die design, 1050 Al, 5052 Al, processing, microstructure, tensile properties.

1 Introduction

Upgrading the mechanical properties of metals and their alloys has drawn increasing interest from materials scientists over many decades to response to the growing demand from industry to broaden the applications of already-known and available materials in strategically important industries, such as the automotive, aerospace and military industries.

Producing metals and their alloys with ultra-fine grain (UFG) structures is one of the methods used to enhance mechanical properties and increase the strength-to-weight ratio, which in turn enables the material weight required for a certain strength value in an application to be reduced. This property is highly significant, especially in the transportation system industry, where reducing fuel consumption and the resultant pollution are of great interest.

Two methods are used to produce UFG materials, bottom-up and top-down approaches. The bottom-up approach is unsuitable for industrial manufacturing because this process

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produces a porous structure, while the top-down approach produces a bulk structure material that can be widely utilized in many applications. Severe plastic deformation (SPD) is a very effective technique to manufacture UFG materials via a top-down approach [Thangapandian and Balasivanandha (2015)].

Several methods of SPD have been introduced in recent decades for bulk and sheet metal deformation to enhance the mechanical properties of metallic materials by producing UFG structures. Accumulative roll bonding (ARB), repetitive corrugation and straightening (RCS), constrained groove rolling (CGR) and constrained groove pressing (CGP) are utilized to manufacture sheet-shaped materials [Gupta, Tejveer and Singh (2016)].

Among these techniques, CGP is the most appropriate methods for manufacturing sheet metals with a UFG structure and hence has outstanding, unique and desirable properties. Shin et al. [Shin, Park, Kim et al. (2002)] developed a CGP technique in 2002 for the fabrication of plate-shaped UFG metallic materials without changing their initial dimensions. In CGP, the sheet work-piece is set between the lower and upper halves of a tightly constrained die; hence, when the dies compress the work-piece, the work-piece cannot move in the longitudinal or transverse directions. The sheet metal work-piece is undergone to repetitive corrugating and straightening through plane strain deformation by alternate compressing using grooved and flat dies. This creates a considerable amount of plastic shear strain in the work-piece without altering the original dimensions. Shin et al. [Shin, Park, Kim et al. (2002)] demonstrated that the mechanical properties of sub-micrometre-grained pure aluminium fabricated by the CGP technique are enhanced. The microstructure and mechanical properties of aluminium [Thangapandian and Balasivanandha (2015); Shin, Park, Kim et al. (2002); Niranjana and Chakkingal (2010); Satheesh Kumar and Raghu (2014); Wang, Liang, Guan et al. (2014); Krishnaiah, Chakkingal and Venugopal (2005)], copper [Rafizadeh, Mani and Kazeminezhad (2009)], low carbon steel [Khodabakhshi and Kazeminezhad (2011)] after CGP processing have previously been investigated.

Niranjana et al. [Niranjana and Chakkingal (2010)] applied a groove pressing process to commercial-purity aluminium sheets under three different orientations relative to the rolling direction (RD). The anisotropic plasticity (r), normal anisotropy (r_m) and earing tendency (Δr) values, as well as the limiting drawing ratio (LDR), of the groove-pressed specimens were experimentally determined. The authors found that these values were improved for aluminium sheet specimens groove-pressed at 0° and 45° to the RD.

Satheesh Kumar et al. [Satheesh Kumar and Raghu (2014)] studied the effect of five passes of CGP on the structure and tensile properties of high-purity aluminium sheets. The authors found significant grain refinement, and the average grain size after five passes was estimated to be 0.9 μm. In addition, a substantial improvement in YS by 5.3 times from 17 MPa to 90 MPa during the first pass corroborated the grain refinement observed. The authors observed a marginal increase in strength during the second pass, followed by a minor drop in strength attributed to the predominance of dislocation recovery in subsequent passes. The quantitative assessment of the degree of deformation homogeneity using microhardness profiles reveals relatively better strain homogeneity at a higher number of passes.

Wang et al. [Wang, Liang, Guan et al. (2014)] studied the effect of multi-pass CGP of 1060 pure aluminium on the microstructure, tensile properties and residual stresses of the

material. The authors found that the microstructure is greatly refined after CGP and that the ultimate tensile strength (UTS) and yield strength (YS) increase up to the third pass and then decrease with further deformation. In addition, the authors observed residual tensile stresses on the surfaces of all pressed work-pieces and found that the use of lubricant reduces these residual stresses and enhances the homogenous distribution of stress along the longitudinal direction.

Krishnaiah et al. [Krishnaiah, Chakkingal and Venugopal (2005)] studied the effect of groove pressing on commercial pure aluminium at both room temperature and cryogenic temperatures. The authors found, in both cases, that sub-micron-sized grain structures are obtained after deformation and that there is no significant difference in the microstructures obtained under room-temperature and cryogenic-temperature deformation conditions.
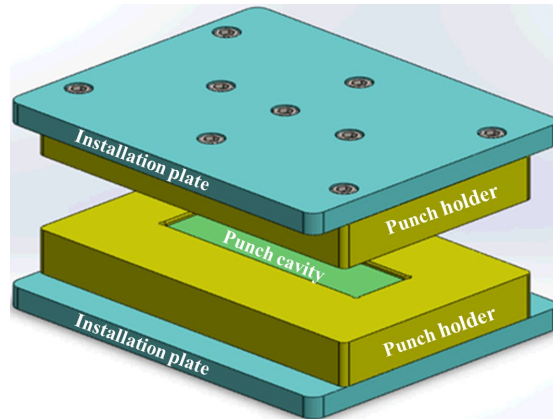
Most of the previous works have focused on studying the effect of a process on a material's structure and properties with no information about the design of the die. Therefore, the current work implemented the CGP technique. Designing and manufacturing a CGP die with the lowest possible cost was attempted using the program SolidWorks to ensure safe design. Then, the designed CGP die was used in the processing of pure 1050 Al and 5052 Al alloy. Both materials are non-heat-treatable and have a wide range of applications in industry. The microstructure and tensile properties of both materials were evaluated after each CGP pass.
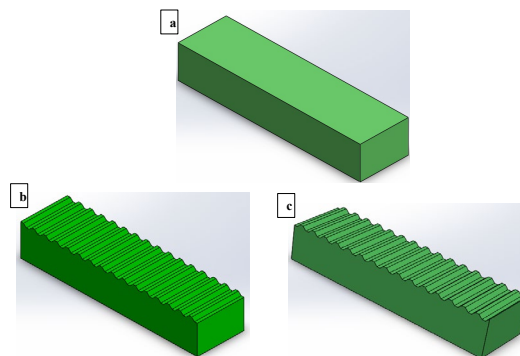
2 Procedure

2.1 Die design and manufacturing

2.1.1 Design and materials

The CGP technique requires two dies: one to act as the corrugating press and the other to act as the flattening press. The optimum die design can perform the necessary function while saving material and machining costs. To save the manufacturing cost of two dies (flat and corrugated), the idea of utilizing one cored die body with alternately inserted flat and corrugated punches has been suggested. CGP die design involves two steps: (i) proposing a die design with dimensions; many freehand sketches with a range of dimensions are drawn as suggestions to reach the optimum design; and (ii) selecting the most suitable material for the die. Fig. 1 shows the proposed CGP die assembly. The upper and lower setups of the proposed CGP die consist of an installation plate and a punch holder. Installation plates are used to fix the die on the press, and punch holders are used to hold the flat and corrugated punches. The flat and corrugated punches are shown in Fig. 2. A pair of corrugated/flat punches (replaceable) is used to apply a shear force on the specimen through the corrugating/flattening presses. The upper and lower corrugated/flat punches are hung inside the upper and lower punch holders, respectively.

Figure 1: CGP die assembly

For each die component, materials and dimensions should be assigned. The BÖHLER company has recommended M238 and K110 steel alloys as the most suitable materials for die manufacturing. The chemical compositions and mechanical properties of M238 and K110 steel alloys are presented in Tab. 1 and Tab. 2, respectively. M238 steel alloy was selected for manufacturing the upper and lower installation plates and punch holders, while K110 steel alloy was selected for manufacturing the upper and lower flat and corrugated punches. The punches are the most critical components of the proposed CGP die; these components are in direct contact with the processing materials and responsible for deformation. Dimensions of 200 mm length and 50 mm width for both punches were chosen to be suitable to obtain two flat tensile specimens. A V-grooved die was used because this shape can induce a higher shear strain and hence more effectively refine the microstructure than can semi-circular dies, as reported previously by Thangapandian et al. [Thangapandian and Balasivanandha (2015)]. The groove angle of the corrugated die was selected to be 45°, as this value induces the highest shear strain ($\gamma=\tan45=1$) in the material and produces an equivalent effective strain (ε_{eff}) of 0.58 in each press, as demonstrated by [Shin, Park, Kim et al. (2002)]. The groove depth was selected to be 3 mm (sheet thickness).

Figure 2: CGP die punches: (a) upper/lower flat punch, (c) lower corrugated punch and (c) upper corrugated punch

Table 1: Chemical compositions (wt.%) of the die materials

Wt.% Designations	C	Si	Mn	Cr	Mo	Ni	V	P	S	Fe
M238	0.4	0.4	1.6	2.0	0.23	1.0	-	0.04	0.04	bal.
K110	1.55	0.3	0.3	11.3	0.75	-	0.75	-	-	bal.

Table 2: Mechanical properties of the die materials

Property Designations	Yield Strength (MPa)	UTS (MPa)	Hardness (HRC)
M238	900	1020	53
K110	1999	2204	62

To select the optimum dimensions for each die component, many trials were attempted to test the die against failure by simulating the die at maximum press capacity using a static stress analysis tool available in the SolidWorks program until the best (minimum and safe) dimensions for each proposed die component were reached. The procedure of die testing against failure is discussed below.

First, each die component was drawn using the SolidWorks program, and then, all components were assembled (Fig. 1). Simulation was carried out using SolidWorks SimulationXpress wizard. According to the manual for SolidWorks Essential [SolidWorks Essential (2012)], the following tasks should be completed to attain the optimum design:

(1) **Options:** In this step, the system of units that will be used for materials, loads and results is chosen. The metric system was selected in the current work.

(2) **Fixtures:** All the faces of die components that stay fixed during press motion are selected. The installation locations of the installation plates in the press are also determined.

(3) **Loads:** The values of the applied external loads to a specified face and their directions are assigned. A maximum press capacity of 150 tons was entered as the applied external pressure that is perpendicularly and evenly distributed on the die surface.

(4) **Material:** The materials for each die component are selected from the standard library of SolidWorks SimulationXpress wizard, where all mechanical and physical properties of standard metals and alloys are recorded. As proposed by the BÖHLER company, M238 steel alloy was assigned for the upper and lower installation plates and punch holders, and K110 steel alloy was assigned for the upper and lower flat and corrugated punches in the program.

(5) **Run:** The coarseness of the mesh is set, and the run simulation button is clicked to begin analysis.

(6) **Results:** The results of analysis, such as the safety factor, von Mises stresses and displacement, can be displayed. SimulationXpress wizard determines the value of the safety factor using the maximum von Mises stress criterion. This criterion states that a ductile material starts to yield when the equivalent (von Mises) stress reaches the YS of

the material. SimulationXpress wizard calculates the safety factor at a point by dividing the YS of the material by the equivalent stress at that point. At any location, if the safety factor is less than one, it indicates that the material at that location has yielded and that the design is not safe. If the safety factor is equal to one, it indicates that the material at that location has just started to yield. When the safety factor is greater than one, it indicates that the material at that location has not yielded and that the design is safe. The safe locations appear blue, while the unsafe locations appear red.

(7) **Optimize:** The optimization step is used to estimate the safety factor, maximum stress or maximum displacement values to acceptable levels by iterating the values of the dimensions. In this step, the optimization target must be determined, i.e., minimizing or maximizing a specific material property to be optimized. First, the safety factor was set to 2. Second, the goal was selected to minimize the mass to reduce the total die cost. Many trials were performed until attaining the optimum dimensions.

2.1.2 Die manufacturing

A milling machine was used to machine the upper and lower installation plates, punch holders and flat punches, while a wire-cutting machine was used to machine the V-grooves in the upper and lower corrugated punches. The upper and lower flat and corrugated punches manufactured from K110 tool steel alloy were then hardened, i.e., austenitized and tempered according to the material data sheet of the BÖHLER company, while M238 steel alloy was used in the as-received condition.

2.2 Materials processing

2.2.1 As-received materials

Cold rolled sheets of pure 1050 Al and 5052 Al alloy with dimensions of 200×50×3 mm were purchased from the Helwan Company for Non-Ferrous Industries (Factory 63), Egypt. These dimensions fit the cavity of the manufactured CGP die. The chemical compositions of pure 1050 Al and 5052 Al alloy are presented in Tab. 3. Full annealing treatment was applied to all sheets at 340°C for 1 hour before the CGP process. Inter-pass annealing at 240°C for 10 min. was carried out after a second CGP pass using a muffle furnace.

Table 3: Chemical compositions (wt.%) of the studied Al alloys

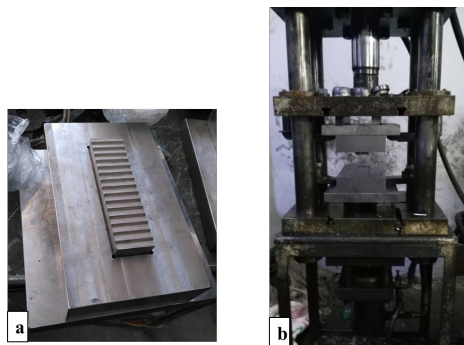| Wt.% Designations	Si	Fe	Cu	Zn	Mg	Cr	Al
1050 Al	0.104	0.301	0.046	0.028	-	-	bal.
5052 Al	0.06	0.544	0.075	0.039	2.35	0.311	bal.

2.2.2 CGP processing

The CGP process involves undergoing a sheet work-piece to orthogonal shear deformation through repetitive pressing using alternating grooved dies and flat dies [Shin, Park, Kim et al. (2002)]. A press with 150 tons capacity was used for CGP processing. First, the installation plate was fastened to the punch holder, and then, the corrugated punch was
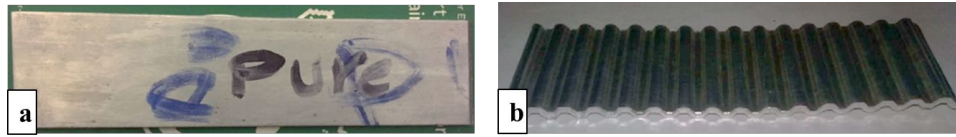
inserted into the punch holder cavity for both the upper and lower die setups, as shown in Fig. 3(a). Second, the lower and upper die setups were fastened on the bed and upper moving part of the press, respectively. Then, the Al work-piece was placed above the lower corrugated punch, as shown in Fig. 3(b). Finally, pressing was conducted so as the gap between the upper and the lower die setup was equal to the work-piece thickness. Fig. 4 shows pure 1050 Al sheets before and after applying the first pressing in the CGP process. After the first corrugation pressing, different deformation zones were created in the work-piece. To obtain uniform deformation through the work-piece, each CGP pass consists of four pressings [Gupta, Tejveer and Singh (2016); Shin, Park, Kim et al. (2002); Niranjana and Chakkingal (2010)]. Fig. 5 presents the sequence of one CGP pass.

The first corrugating pressing gives rise to pure shear deformation under plane strain conditions in the oblique zone of the work-piece. However, the flat zone remains un-deformed. This single pressing yields an effective strain (ε_{eff}) of 0.58 in the deformed inclined zone [Gupta, Tejveer and Singh (2016); Shin, Park, Kim et al. (2002)]; Niranjana and Chakkingal (2010)]. In the second pressing, the corrugated work-piece is straightened using flat punches. This step assures that formerly deformed zone undergoes to an inverted shear deformation whilst the un-deformed zone stays un-deformed. The value of ε_{eff} in the deformed zone after the second pressing is 1.16. Fig. 6 describes the values of shear stress induced after each pressing in one CGP pass. Then, the work-piece is rotated by 180° about the axis normal to the plane of the work-piece to permits the deformation of the un-deformed zone as a result of asymmetry of the grooved die. In the third pressing, the flattened work-piece is corrugated again using asymmetrically grooved punches. This creates an ε_{eff} of 0.58 in the already un-deformed zone. In the fourth pressing, the corrugated work-piece is again flattened using flat punches. These consecutive pressings with a couple of grooved and flat punches are considered one pass of the CGP process and result in a homogeneous ε_{eff} of 1.16 throughout the work-piece.
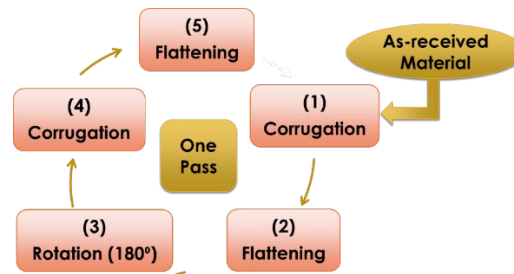
The multi-pass CGP process results in accumulating of a very huge amount of plastic strain in the work-piece without altering the original dimensions of the work-piece, and a UFG structure is usually formed. In the same way, two passes will create an ε_{eff} of 2.32, three passes will create an ε_{eff} of 3.48, and so on. For impractical analysis, the ε_{eff} is assumed to be approximately homogeneous for the sheet work-piece, although there is unavoidable heterogeneity in the real process [Gupta, Tejveer and Singh (2016)].
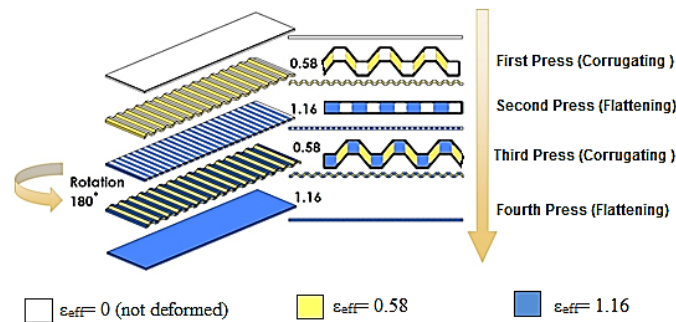

Figure 3: Photo of the die (a) and the press setup (b)

Figure 4: Pure Al sheets: (a) before and (b) after applying the first pressing of the CGP process

Figure 5: Sequence of one CGP pass

Figure 6: Shear stress developed after each pressing of one CGP pass

After each pass, the sheets were visually inspected. In both materials, micro-cracks appeared during the first pressing of the third CGP pass. Therefore, inter-pass annealing treatment was undertaken after the second pass. After inter-pass annealing, the third pass could be completed. Micro-cracks again appeared at the final pressing of the third pass.

2.3 Evaluation of CGPed sheets

The microstructures were investigated using an optical microscope. Specimens with a cross section of 10×10 mm were cut from the work-piece after each CGP pass using a wire-cutting machine. Specimens were prepared using a standard metallographic technique: grinding, polishing and etching with 20% HF aqueous solution for approximately 45 seconds. Standard flat tensile specimens according to ASTM E8 were prepared from CGPed sheets after each pass using a wire-cutting machine. The selected specimens were inspected for micro-cracks. Tensile tests were carried out using a universal testing machine (1000 KN) at room temperature with a cross head speed of 0.5 mm.min^{-1}. A tensile test
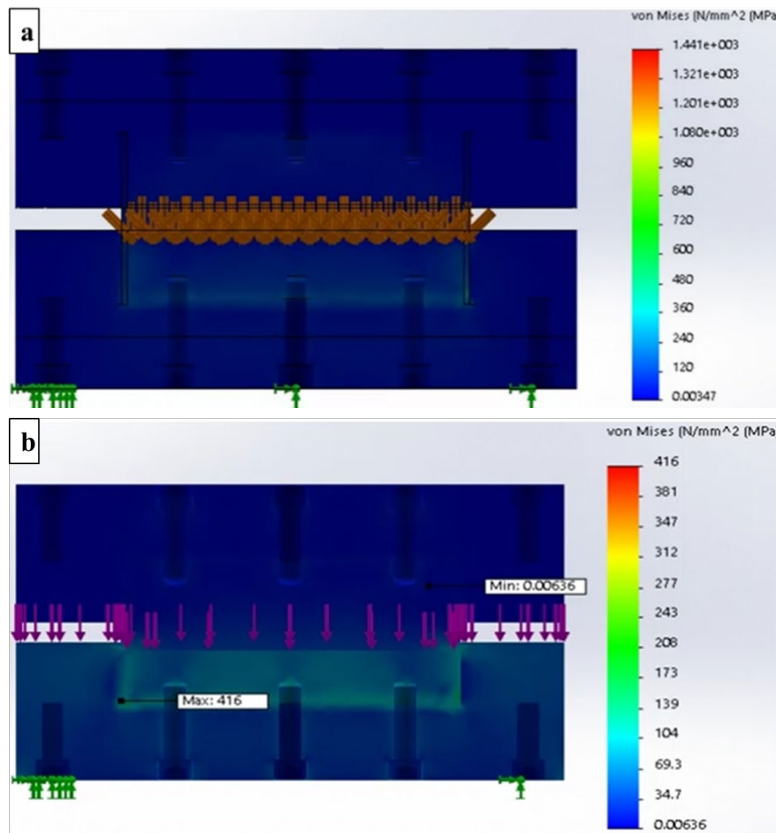
was carried out after each pass for both materials. Two tensile specimens were tested for each CGP pass, and the average results were reported.

3 Results and discussion

3.1 Stress analysis and design optimization

After the boundary conditions (fixtures and load) and design parameters (material properties and dimensions) were entered into SolidWorks simulation Xpress wizard, simulation of the CGP process during the corrugating and flattening pressings started. The simulation involved stress analysis of the die at a maximum press capacity of 150 tons to ensure safe design. Fig. 7 presents the results of stress analysis using the von Mises criterion of the die during the corrugating and flattening pressings. As shown in the figure, the maximum stress was induced on the punches (corrugated/flat). According to the von Mises criterion, the values of these maximum stresses were 1441 MPa and 416 MPa during the corrugating and flattening pressings, respectively. These values were lower than the yield strength of punch material and resulted in a safety factor greater than one, ~2; hence, a safe design was attained.
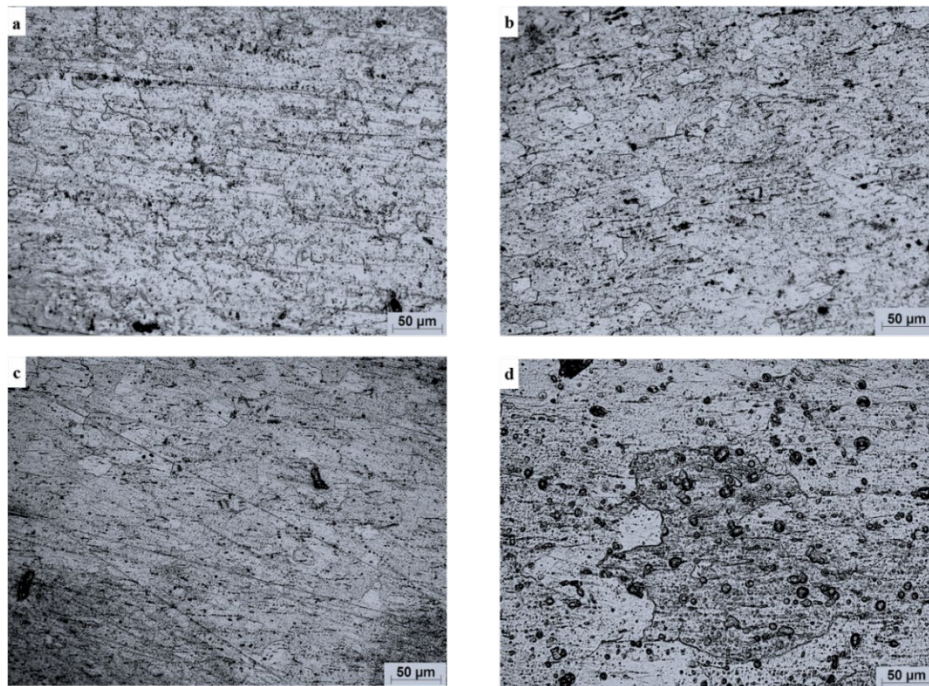

Figure 7: Stress analysis of the die using the von Mises criterion during the (a) corrugating pressing and (b) flattening pressing

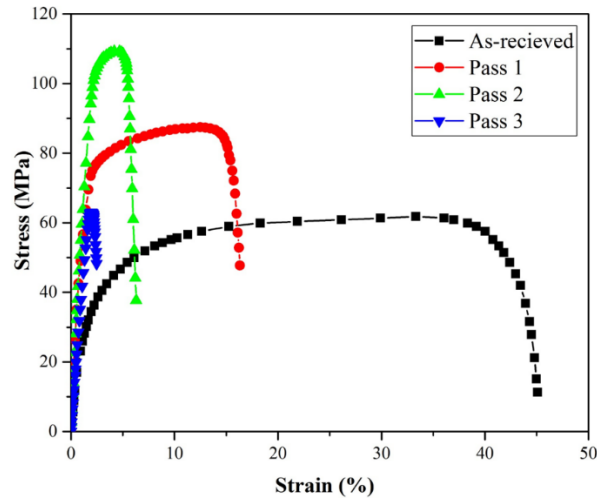### 3.2 Effect of CGP on microstructure and tensile properties

3.2.1 Pure 1050 Al

The microstructure of pure 1050 Al before and after each CGP pass is shown in Fig. 8. Grain refining was observed after the first and second CGP pass, while after inter-pass annealing and the third pass, grain coarsening was observed. Fig. 9 presents the stress-strain curves after each CGP pass for pure 1050 Al. Fig. 10 shows the variation in tensile properties with the number of CGP passes for pure 1050 Al. Strength increased with an increasing number of CGP passes until the second pass. UTS and YS increased by 41.58% and 165%, respectively, after the first CGP pass and by 76.84% and 275% after the second pass compared to the as-received material. This increase is attributed to the grain refinement that happens as a result of the SPD and strain hardening because of the growing in the dislocation density after imposing a high shear strain, which in turn demands a higher applied stress to move the dislocation by slip, as illustrated by Hosseini et al. [Hosseini and Kazeminezhad (2011)], who developed a new microstructural model based on dislocation generation and consumption mechanisms through CGP on aluminium.
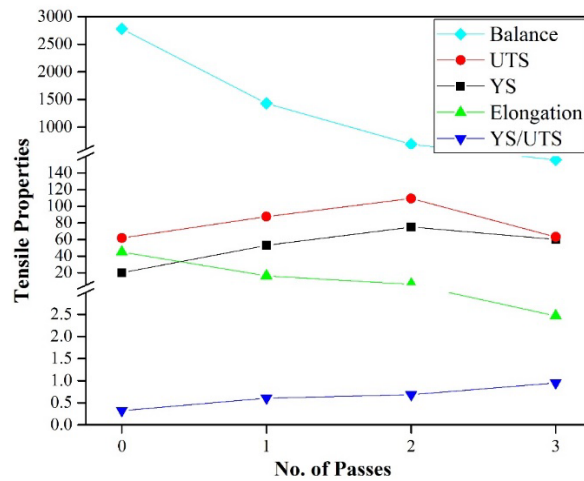

Figure 8: Microstructure of pure 1050 Al: (a) as-received, (b) after first pass, (c) after second pass and (d) after inter-pass annealing and third pass

After inter-pass annealing and the third pass of CGP, UTS and YS decreased compared to the values after the first and second pass but were still higher than the values in as-received material, by 2% and 20%, respectively. This difference in strength may be due to the high annealing temperature, which results in recrystallization, grain growth and dislocation annihilation, as reported previously by Khodabakhshi et al. [Khodabakhshi and Kazeminezhad (2011)] for low carbon steel.

Figure 9: Stress-strain curves before and after CGP of pure 1050 Al

Figure 10: Tensile properties before and after CGP of pure 1050 Al

In previous works, the drop in strength of pure 1050 Al usually occurred after more than four or five CGP passes, but here, the strength dropped after the third pass, possibly because of the impurity of 1050 Al and/or the incorrect conditions of the annealing treatment of the as-received material.
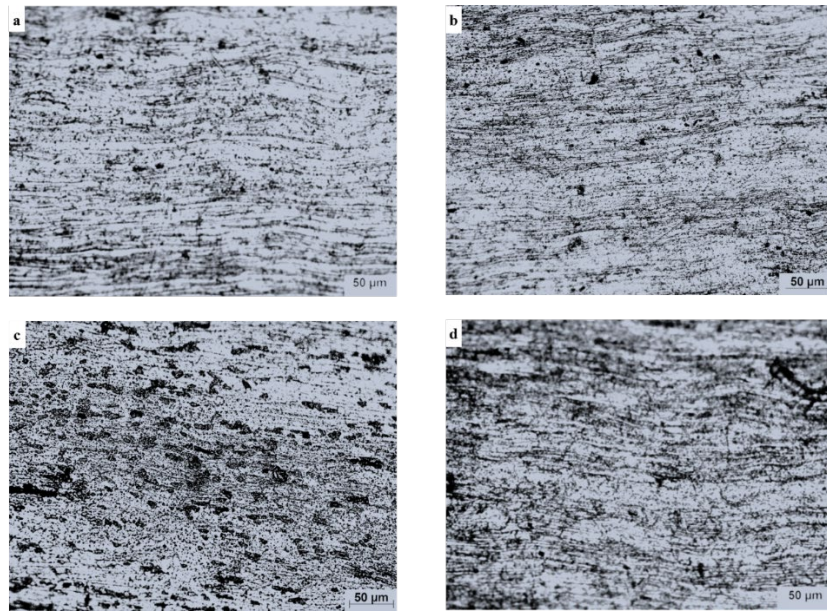
However, elongation decreased and the YS/UTS ratio increased with an increasing number of CGP passes, as shown in Fig. 10. A high YS/UTS ratio indicates a narrow uniform plastic zone, which reduces ductility. This is due to the high work hardening and accumulated strain induced during the CGP process. This means that as the number of CGP passes increases, the ductility (elongation to failure) of the pure 1050 Al decreases as the plastic zone diminishes. Although the work hardening stages decrease with the increase in the number of CGP passes, ductility decreases. Similar behaviour in tensile properties were

stated previously [Gupta, Tejveer and Singh (2016); Shin, Park, Kim et al. (2002); Niranjana and Chakkingal (2010); Satheesh Kumar and Raghu (2014)].

The balance between strength and ductility can be obtained by multiplying UTS and total elongation. As shown in Fig. 10, the balance of strength and ductility decreased with an increasing number of CGP passes, which means that the best combination for CGPed pure 1050 Al is obtained after the first pass.

3.2.2 5052 Al alloy

Fig. 11 shows the microstructure of 5052 Al alloy before and after each CGP pass. Slight grain refining was observed after the CGP process. Stress-strain curves after each pass of CGP for 5052 Al alloy are presented in Fig. 12. Fig. 13 illustrates the effect of the number of CGP passes on the tensile properties.

Figure 11: Microstructure of 5052 Al alloy: (a) As-received, (b) after first pass, (c) after second pass and (d) after inter-pass annealing and third pass
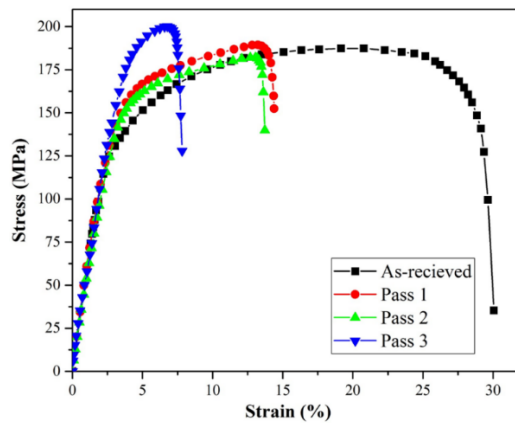
UTS and YS show the same behaviour with an increasing number of CGP passes. UTS increased after the first pass by 1.1% and then decreased after the second pass by 2.8% compared to the as-received alloy. The increase in strength after the first pass is due to the grain refinement that occurs as a result of severe CGP deformation and work hardening. The reduction in YS and UTS after the second pass may be attributed to the annihilation of dislocations as the accumulated strain increases along with the formation of micro-cracks. Similar strength behaviour has been observed in previous works [Wang, Liang, Guan et al. (2014); Krishnaiah, Chakkingal and Venugopal (2005); Rafizadeh, Mani and Kazeminezhad (2009)].

After the second pass, inter-pass annealing was applied, followed by a third CGP pass. Both UTS and YS increased again to values higher than those in the as-received alloy by
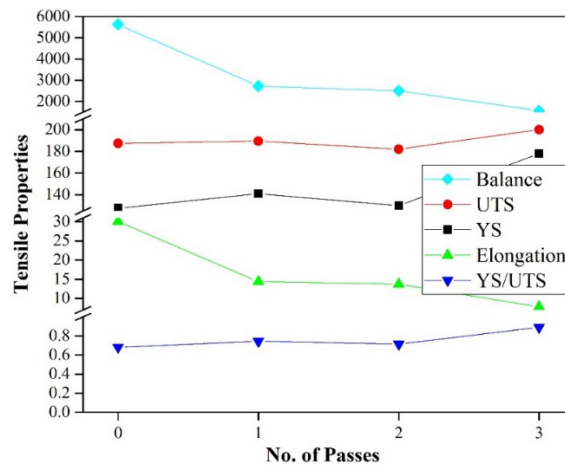
6.8% and 39.6%, respectively. This increase may be due to the presence of Mg and Cr alloying elements in 5052 Al alloy, which usually form precipitates during heat treatment. These precipitates inhibit grain growth during treatment and hence do not permit the strength to decrease. Similar results for 3003 Al alloy were obtained by Krishnaiah et al. [Krishnaiah, Chakkingal and Venugopal (2005)] after groove pressing.

Elongation decreased after the first pass as a result of strain hardening and then increased after the second pass, which may be due to grain refining. A reduction in elongation occurred again after the third pass as a result of micro-crack formation in the CGPed 5052 Al alloy at the final pressing of the third pass.

The change in the balance of strength and ductility in 5052 Al alloy with the number of CGP passes is also shown in Fig. 13. The same behaviour was observed for CGPed pure 1050 Al; the balance between strength and ductility decreased with an increasing number of CGP passes.

Figure 12: Stress-strain curves before and after CGP of 5052 Al alloy

Figure 13: Tensile properties before and after CGP of 5052 Al alloy

4 Conclusions

This work addressed the constrained groove pressing (CGP) of pure 1050 Al and 5052 Al alloy. Al alloys are lightweight materials but unfortunately have low strength. CGP is a severe plastic deformation (SPD) strengthening technique used for sheet metals. Therefore, the current work aimed to improve the strength of two Al-materials to replace heavier steel bodies in automobiles, hence improving the fuel economy and performance of the vehicles. The effect of the number of CGP passes on the microstructure and tensile properties was studied. The following conclusions can be drawn:

1. The optimal design of the CGP die components was attained using the stress analysis tool in SolidWorks SimulationXpress wizard with a safety factor of 2.

2. For pure 1050 Al, the ultimate tensile strength (UTS) increased from 61.79 MPa in the as-received material to 109.27 MPa after the second pass of the CGP process. UTS then decreased to 63.05 MPa after inter-pass annealing and applying the third pass; this decrease is attributed to micro-crack formation, recrystallization, grain coarsening and dislocation annihilation. The yield strength (YS) showed the same trend as UTS. Ductility decreased and the YS/UTS ratio increased with the number of CGP passes.

3. For 5052 Al alloy, UTS increased from 187.37 to 189.44 MPa after the first pass, then decreased to 182.11 MPa after the second pass. After applying inter-pass annealing and the third pass, UTS increased again to 200.11 MPa. YS showed the same behaviour. Variations in elongation and the YS/UTS ratio after different CGP passes were insignificant.

4. The CGP process was accompanied by a decline in the strength-ductility balance as the number of CGP passes increased for both materials.

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