Materials Science. Power Engineering, Vol. 27, No. 4, 2021
Материаловедение. Энергетика. Том 27, № 4, 2021

Metallurgy and Materials
Металлургия и материаловедение

Review article
UDC 669
DOI: https://doi.org/10.18721/JEST.27407

S. Patil ✉

G.H. Raisoni College of Engineering and management,
Pune, India

✉ patilsurajpsb@gmail.com

CONSTRAINED GROOVE PRESSING OF ALUMINIUM ALLOYS – A REVIEW

Abstract. Constrained groove pressing (CGP) is a modern process for the formation of ultrafine grain in metallic sheets with high mechanical properties. During CGP, the sheet metal are subjected to repetitive corrugating and straightening under the plane strain deformation condition by utilizing alternate pressing with the asymmetrically grooved dies and flat dies. This leads to an increase in the degree of plastic strain of the sheet metal without changing its original dimensions. CGP can effectively refine the grain structure to a sub-micron level. Materials processed by CGP have a very high strength, high hardness and many other required properties. This review focuses mainly on CGP process technology, especially the number of passes, as well as the study of microstructure changes. Most of the scientific results were obtained experimentally.

Keywords: CGP, Microstructural change, mechanical properties.

Citation:

S. Patil, Constrained groove pressing of aluminium alloys – a review, Materials Science. Power Engineering, 27 (04) (2021) 96–105, DOI: https://doi.org/10.18721/JEST.27407

Обзорная статья
DOI: https://doi.org/10.18721/JEST.27407

Сурадж Б. Патил ✉
Колледж инженерии и менеджмента Г.Х. Райзони,
Пуна, Индия
✉ patilsurajpsb@gmail.com

НАПРЯЖЕННОЕ ГОФРИРОВАНИЕ ПРЕССОВАНИЕМ АЛЛЮМИНИЕВЫХ СПЛАВОВ – ОБЗОР

Аннотация. Гофрирование в напряженном состоянии прессованием (НГП) – это современный процесс растягивания сверхмелких зерен в листовых металлических структурах для получения хороших свойств материалов. При НГП образец листового металла подвергается циклическому рифлению и выпрямлению в условиях плоской деформации при помощи поочередного обжатия между парами пресс-форм – с ассиметричными пазами и плоскими пластинами. Это приводит к увеличению пластической деформации в образце листового металла без изменения его первоначальных размеров. НГП способно значительно измельчить зернистую структуру до субмикронного уровня. Материалы, полученные посредством НГП, обладают крайне высокими значениями прочности, высокой твердостью и многими другими полезными свойствами. Данный обзор, в основном, сосредоточен на процессе НГП и микроструктурных изменениях относительно числа обжатий при НГП. Большинство научных результатов было получено на практике.

Ключевые слова: гофрирование в напряженном состоянии прессованием (НГП), микроструктурные изменения, механические свойства.

Для цитирования:

Сурадж Б. Патил. Напряженное гофрирование прессованием аллюминиевых сплавов – обзор // Материаловедение. Энергетика. 2021. Т. 27, № 4. С. 96–105. DOI: https://doi.org/10.18721/JEST.27407

Introduction. Upgrading the mechanical properties of metals and their alloys has drawn increasing interest from materials scientists over several decades to respond to the growing demand from such areas as automotive, aerospace and military industries. Manufacturing metals and their alloys with ultra-fine grain (UFG) structures is one of the approaches used to enhance mechanical properties and increase the strength-to-weight ratio, which will again enable the material weight required for a certain strength value in an application to be reduced. This property is highly significant, mainly in the transportation system industry, where the reduction in fuel consumption and the resulting pollution both are prioritized. Two methods are used to produce UFG materials: bottom-up and top-down approaches. The bottom-up approach is not suitable for industrial manufacturing as this process gives a porous structure, while the top-down approach will give a bulk structure material that could be widely used in many applications. Severe plastic deformation (SPD) is a very effective technique to manufacture UFG materials via the top-down approach [1].

Several methods of SPD have been introduced in last decades for bulk as well as sheet metal deformation to enhance the mechanical properties of metallic materials by producing UFG structures. Accumulative roll bonding (ARB), asymmetric rolling (ASR), cryorolling, repetitive corrugation and straightening (RCS), constrained groove rolling (CGR) and constrained groove pressing (CGP) are used to manufacture sheet-shaped materials [2]. Among these methods, CGP is the most versatile method for manufacturing

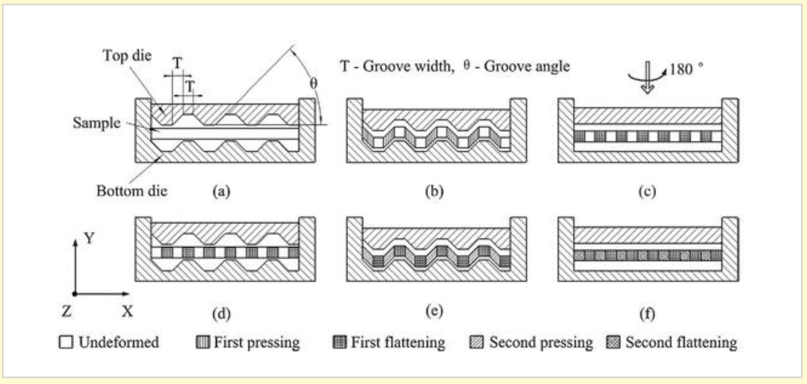

Fig. 1. Schematic of constrained groove pressing (CGP)

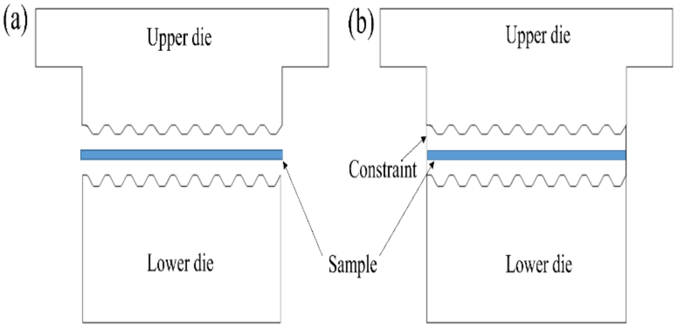

Fig. 2. Repetitive corrugating and straightening (a), and constrained groove pressing (b)

of sheet metals with a UFG structure and that is why it has outstanding, unique and desirable properties. Constrained groove pressing (CGP) is a promising route to produce the UFG structure without changing the overall dimensions of the samples. The authors in [3] initially developed a constrained groove pressing technique in which a sheetmetal is subjected to repetitive shear deformation under plane strain condition. The schematic illustration of the CGP process is presented in Fig. 1.

In the CGP process, a blank is subjected to repetitive shear deformation by deforming the specimen alternately between asymmetrically aligned grooving and flattening dies under plane strain condition. Each pass consists of four stages, two in a grooving die and two in a straightening die. In this technique, the gap between the upper die and the lower die is identical to the sample thickness, and therefore, during the grooving operation, the inclined part located in the groove is subjected to pure shear deformation with an effective plastic strain of 0.58 [4]. In the straightening operation, the deformed regions are subjected to a reverse shear deformation resulting in another effective strain of 0.58 in the reverse direction, causing a total effective strain of 1.16 in the deformed regions [5]. After the second stage, the specimen is rotated by 180° around the axis perpendicular to the sheet plane, as shown in Fig. 1. This allows the undeformed regions to be deformed by further pressing due to the asymmetry of the grooved die, and finally, after the second straightening step, an overall uniform strain of 1.16 is imposed throughout the specimen [6].

Advantages of CGP:

- More homogeneous strain distribution without changing the dimensions of the sample.
- The CGP process is not limited to specific materials and can be used for microstructural refinement in a wide range of metallic materials.
- Fabrication of dies is very simple when compared to some other SPD processes like ECAP.

Limitations of CGP:

- It is a highly discontinuous process owing to a number of stages required for corrugating and flattening.
- The maximum strain that can be achieved by this process is less than other SPD processes.

In the CGP process, the gap between the upper die and the lower die is equal to the thickness of the material resulting in pure shear deformation in the inclined groove region. In CGP, it is possible to impart a larger plastic strain compared to other SPD techniques in sheet metal processing. CGP is almost equivalent to the process of repetitive corrugating and straightening (RCS) except that the material is constrained from expanding laterally in all directions, leading to better homogeneity of material properties. Fig. 2 shows the schematic difference between RCS and CGP.

Microstructural Changes

Constrained groove pressing is one of the severe plastic deformation routes, which refines the grain size of the sheet materials to the sub-micrometer range that can even extend up to the nanometre range. The microstructural refinement that takes place during the CGP process is an important phenomenon to understand the mechanical behaviour of sheet materials. Zrnik et al. [7] investigated the CGP of a commercially pure Al plate. The microstructures obtained from the transmission electron microscopy (TEM) analysis are shown in Fig. 3. The microstructure after the first pressing revealed elongated grains with a banded structure (Fig. 3a). Polygonized subgrains with dislocation cells were found within the banded microstructure, and it was due to local adiabatic heat generated at shear deformation. The authors observed that the microstructure after four passes was similar to that of the first pass (Fig. 3b), which is due to the dynamic recovery and polygonization in the deformed structure. The study also revealed equiaxed subgrains with an average grain size of 1μm after four successive passes (Fig. 3c).

Variation of grain size with respect to CGP pass number for different metals and alloys reported by different researchers [8–10] is shown in Fig. 4. Significant grain refinement was observed after the first pass in all the materials, which is similar to other SPD processes [11]. After the first pass, further grain refinement became insignificant at higher strain due to dislocation annihilation through dynamic recovery. Khakbaz and Kazeminezhad [12] showed that it is possible to produce ultrafine-grained sheets by using the CGP technique and studied its effect on mechanical properties. They observed that, after a sudden drop in grain size through first and second passes, the grain refinement became insignificant after the third pass, and the grain size was approximately constant after the fourth pass with a steady-state microstructure. The rate of refinement was reduced due to dynamic recovery.

This trend is consistent with observations in other SPD processes, such as ECAP [13] and ARB [14] carried out on an Al-Mn alloy. Yadav et al. [15] systematically studied the microstructural inhomogeneity in a Cu-Zn alloy sheet deformed by CGP. They showed that the non-uniformity in the microstructure and mechanical properties is mainly due to the strain inhomogeneity generated in the CGP sample. The additional bending strain generated at the intersection of the two grooves was the prime cause of the inhomogeneous microstructure in the CGP sample. The microstructure analysed by EBSD for one pass of the CGP sample is shown in Fig. 5. A larger number of fine grains have been observed in the sample after the first pass compared to the initial sample.

The initial microstructure (Fig. 5a) was homogeneous throughout the sample, while there was a drastic change in the microstructure after the first pass (Fig. 5b). It clearly showed that regions with finer grains deformed more than the other regions.

Lee and Park[16] observed that a single pressing in CGP of pure Al resulted in the formation of a heterogeneous microstructure consisting of equiaxed grains and elongated subgrains or dislocation cells. Though the cell refinement after the first pressing was insignificant, the microstructure became relatively homogeneous after two pressings with equiaxed cells of 0.5 μm.

It was also observed that the grain refinement continued up to six pressings but the grain size after the sixth pressing was only slightly smaller than that after two pressings. This is consistent with the fact that

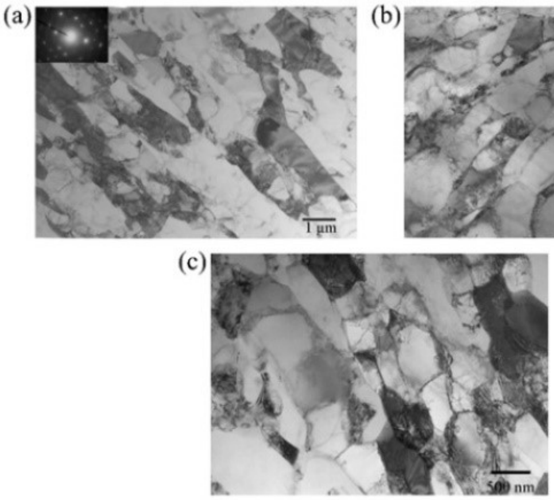

Fig. 3. TEM images of pure aluminium deformed by CGP after first pressing (a), first pass (b), and four passes (c) [7]

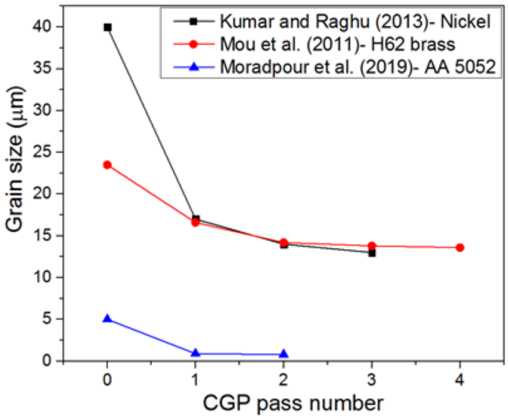

Fig. 4.Variation of grain size with CGP pass number for different materials

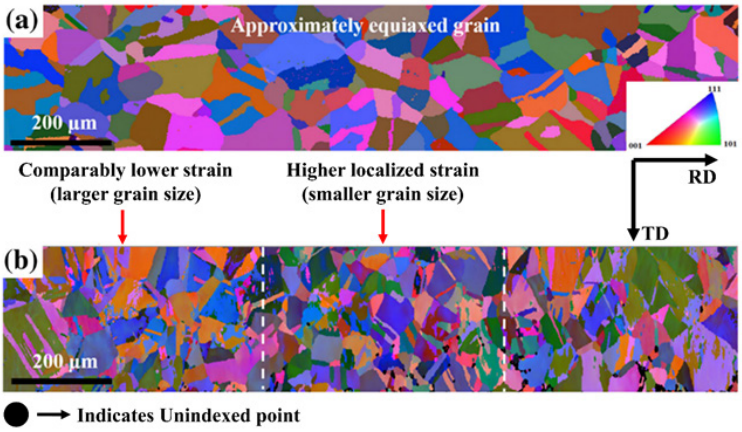

Fig. 5. Microstructure of CGP processed Cu-Zn alloy: initial sample (a) and after first pass (b) [15]

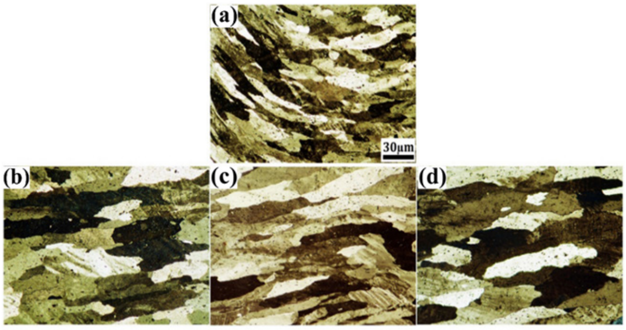

Fig. 6. Optical microstructure of Al-Mn-Si alloy in different conditions: two-pass CGP (a), annealed at 150 °C (b), annealed at 250 °C (c), and annealed at 350 °C (d) [17]

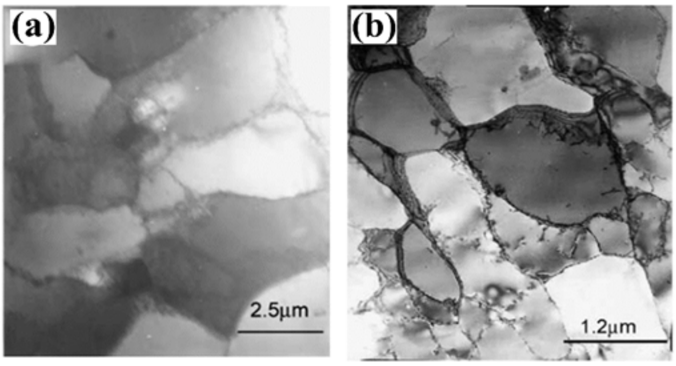

Fig. 7. TEM micrographs of pure aluminium after (a) four CGP passes and (b) annealing at 150 °C [18]

grain refinement gets saturated with the increase in strain.After a few passes, the microstructure consisted of dislocation-free polygonised grains with clear grain boundaries, but the grain size increased to 0.8 μm, which was higher than the grain size after six pressings. Some researchers investigated the effect of post deformation annealing on CGP processed sheets. Fig. 6 shows the optical microstructures of an Al-Mn-Si alloy after two passes of CGP and subsequent annealing at different temperatures [17]. The microstructure after two passes of CGP showed a wavy structure with the accumulation of dislocations due to grooving die geometry and heavy deformation (Fig. 6a).

Annealing after two passes of CGP allowed the restoration phenomena by releasing stored energy and residual stress. The microstructures after annealing at 150 °C, 250 °C, and 350 °C did not show any major difference. However, thermal recrystallization and possible grain growth were observed after 350 °C. Similarly, Krishnaiah et al. [18] studied CGP of pure Al. They annealed the CGP sample deformed up to four passes at 150 °C and observed that the loss of dislocations resulted in the formation of distinct contrast subgrains structure, as shown in Fig. 7. However, no drastic change in grain size was observed after annealing compared to the deformed condition.

Mechanical Properties

Understanding the mechanical properties of sheet metals subjected to the CGP process such as strength, ductility, and toughness is important for the sheet metal forming applications. Many researchers investigated the effect of the CGP process on the strength and ductility of different alloys. It is reported that the sheet metals subjected to CGP have superior strength when compared to the initial condition of the sample [2]. The trend in the variation of strength with respect to the number of CGP

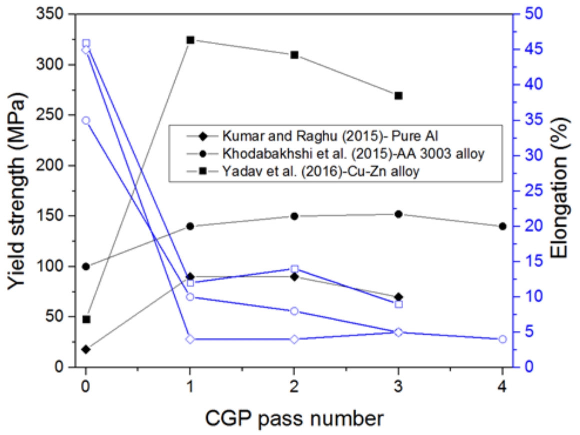

Fig. 8. Variation of yield strength and ductility with CGP pass for different materials [15, 19, 20]

passes is different for different materials. However, strength increases for the initial number of passes (generally two) and then decreases or saturates in the further passes. Fig. 8 shows the variation of mechanical properties (yield strength and ductility) with CGP pass numbers for different materials [15, 19, 20]. It can be observed from Fig. 8 that the trends of yield strength variation in pure Al and Cu-Zn alloy are similar in which the strength increased after the first pass and then decreased during further passes, while in the case of AA 3003 alloy, the strength increased after the first pass and then saturated during second and third passes. Kumar et al. [21] reported similar results in a pure nickel sheet, where marginal strength drop was observed after three passes of CGP along with slight improvement in strain hardening ability and uniform elongation.

It was also found that the role of grain size in strength improvement was more than that of dislocation density because three passes of CGP were found to be enough to obtain good mechanical properties through grain refinement. Krishnaiah et al. [18] deformed pure aluminum by CGP at room and cryogenic temperatures. They observed that the ultimate tensile strength (UTS) increased from 79 MPa to 96 MPa after two passes of CGP at cryogenic temperature, which was reasonably higher than at room temperature deformation in which UTS was observed around 85 MPa after two passes. The higher improvement in strength was mainly due to the suppression of dynamic recovery at cryogenic temperature. The tensile properties of pure Al deformed after CGP at cryogenic temperature were similar to the properties of cryorolled AA 5083 alloy reported previously [22].

Peng et al. [23] deformed H62 brass sample using CGP under partially and fully constrained conditions. The study reported that a partially constrained CGP process reduces the equivalent strain by 40% when compared to the fully constrained condition. However, more deformation occurred in the interior of the CGP sample than the surface region under a fully constrained condition. Khodabakhshi et al. [24] studied the CGP of low carbon steel and concluded that after one pass, inhomogeneity in the sample increased compared to the initial material. In general, the CGP sample exhibits an uneven surface even after repetitive flattening. The surface unevenness is mainly due to repetitive grooving, and hence groove marks are developed on the CGP sample with a rough surface. It is difficult to characterize the mechanical properties and formability of CGP samples due to uneven surface, and it also makes the sheet subjected to CGP unsuitable for subsequent forming applications. In addition to this, CGP leads to non-uniformity in mechanical properties due to strain inhomogeneity and microstructural inhomogeneity.Recently, Kumar et al. [25] studied the inhomogeneity factor (IF) of low carbon steel and commercial aluminum materials deformed by CGP. The inhomogeneity factor is used to quantify non-uniformity in hardness distribution. They observed that IF value is more in commercial aluminum than low carbon steel and showed that more inhomogeneity in the properties of the commercial aluminum.

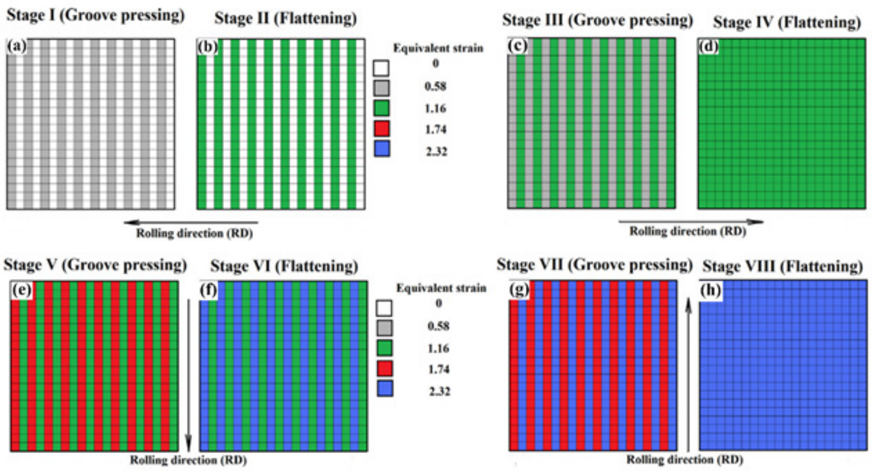

Fig. 9. Eight stages of CGP-CR process for one pass

In the initial two CGP passes, IF value increased, and then it is either consistent or slightly decreased in the remaining passes. In this work, tensile properties were also studied in two different directions by testing samplesparallel and perpendicular to the groove. It was observed that strength and elongation of the CGP samples were higher in parallel to the groove than in perpendicular toit.

Khodabakhshi et al. [26] proposed a modified route of constrained groove pressing to improve the homogeneity of the deformed sheets. The proposed route was called constrained groove pressing – cross route (CGP-CR) in which the sheet sample should have a square cross-section, and each pass consists of eight stages – four corrugating and four straightening. Fig. 9 shows the eight stages of the proposed CGP-CR process for one pass. Initially, in the first two stages (Fig. 9a and b), sheet was subjected to grooving and flattening such that the rolling direction of the sample was perpendicular to the groove direction. After two stages, the sheet sample was rotated by 180° around the axis perpendicular to its plane. Now the rolling direction was again perpendicular to the groove but in the opposite direction. In stage III (Fig. 9c) and stage IV (Fig. 9d), the sheet sample was again deformed using grooving and flattening dies, respectively.Until now, the process is similar to the conventional CGP process. After stage IV, the sheet was rotated by 90° such that the rolling direction was parallel to the groove direction and again the four stages were repeated.

These eight stages complete one pass in the CGP-CR process. The major advantage of this process is a high magnitude of plastic strain of about 2.32 imparted in one pass, which is two times higher than that of the conventional CGP process. Peng et al. [9] studied the effect of equivalent strain on the mechanical properties of a brass sheet subjected to multi-pass CGP. The non-uniform distribution of the equivalent strain caused non-uniform distribution of grain size and hardness. The surface region where high equivalent strains were present had finer grains and higher hardness than the interior.

Kumar Gupta et al. [2] have done an extensive review of CGP and explained all the parameters influencing the mechanical properties and microstructure of CGP processed materials. In the CGP process, the interface distance between the grooves and groove width should be equal. Therefore, in the grooving stage, sheet metal is subjected to pure shear deformation [27]. Groove width was equal to the sheet thickness in all the investigations, but the groove angle was different. However, the groove angle of 45° was used in most of the studies. Groove angle is an important parameter that purely depends on the material type. Borhani and Djavanroodi [28] studied the influence of groove angle on the mechanical properties and microstructure of commercially pure aluminum processed by rubber pad-CGP. CGP experiments were carried out using two different dies- one with a groove angle of 45° and another with a groove angle of 50°. CGP dies with 50° angle were more effective in terms of grain refinement and enhanced strength and hardness. The grain size observed after six passes using a 45° angle and after four passes, using a 50° angle was 842 nm and 833 nm, respectively. Similarly, Sajadi et al. [29] also observed that dies with a smaller groove angle enabled more number of passes. They used two dies with groove angles of 53° and 45° and observed that the die with 45o groove angle allowed four passes while the 53° groove angle die allowed only three passes.

Conclusion

CGP is a severe plastic deformation (SPD) strengthening technique used for sheet metals. It is possible to produce ultrafine-grained sheets by using the CGP technique and its mechanical properties will improves. The sheet metals subjected to CGP have superior strength when compared to the initial condition of the sample. Strength increases for the initial number of passes (generally two) and then decreases or saturates in the further passes.

M238 steel alloy was selected for manufacturing the upper and lower installation plates and die holders, while K110 steel alloy was selected for manufacturing the upper and lower flat and corrugated dies.

REFERENCES

[1 **A.N. Thangapandian, S. Balasivanandha Prabu,** The Role of Corrugation Die Parameters on the Mechanical Properties of Aluminum Alloy (AA 5083) Processed by Repetitive Corrugation and Straightening. Journal of Materials Science and Chemical Engineering, 3 (2015), 208–212. DOI: 10.4236/msce.2015.37028

[2] **A.K. Gupta, T.S. Maddukuri, S.K. Singh,** Constrained groove pressing for sheet metal processing. Progress in Materials Science, 84 (2016), 403–462. DOI: 10.1016/j.pmatsci.2016.09.008

[3] **D.H. Shin, J.J. Park, Y.S. Kim, K.T. Park,** Constrained groove pressing and its application to grain refinement of aluminum, Mater. Sci. Eng. A 328 (2002) 98–103.

[4] **H. Alihosseini, K. Dehghani,** Bake hardening of ultra-fine grained low carbon steel produced by constrained groove pressing, Mater. Sci. Eng. A 549 (2012) 157–162.

[5] **Z.S. Wang, Y.J. Guan, G.C. Wang, C.K. Zhong,** Influences of die structure on constrained groove pressing of commercially pure Ni sheets, J. Mater. Process. Technol. 215 (2015) 205–218.

[6] **S.S. Satheesh Kumar, T. Raghu,** Structural and mechanical behaviour of severe plastically deformed high purity aluminium sheets processed by constrained groove pressing technique, Mater. Des. 57 (2014) 114–120.

[7] **J. Zrnik, T. Kovarik, Z. Novy, M. Cieslar,** Ultrafine-grained structure development and deformation behavior of aluminium processed by constrained groove pressing, Mater. Sci. Eng. A 503 (2009) 126–129.

[8] **S.S. Satheesh Kumar, T. Raghu,** Mechanical behaviour and microstructural evolution of constrained groove pressed nickel sheets, J. Mater. Process. Technol. 213 (2013) 214–220.

[9] **K. Peng, X. Mou, J. Zeng, L.L. Shaw, K.W. Qian,** The influence of the equivalent strain on the microstructure and hardness of H62 brass subjected to multi-cycle constrained groove pressing, J. Mater. Process. Technol. 211 (2011) 590–596.

[10] **M. Moradpour, F. Khodabakhshi, H. Eskandari,** Dynamic strain aging behavior of an ultra-fine grained Al-Mg alloy (AA5052) processed via classical constrained groove pressing, J. Mater. Res. Technol. 8 (2019) 630–643.

[11] **R.Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov,** Bulk nanostructured materials from severe plastic deformation, Prog. Mater. Sci. 45 (2000) 103–189.

[12] **F. Khakbaz, M. Kazeminezhad,** Work hardening and mechanical properties of severely deformed AA3003 by constrained groove pressing, J. Manuf. Processes 14 (2012) 20–25.

[13] **S. Ferrasse, V.M. Segal, K.T. Hartwig, R.E. Goforth,** Microstructure and properties of copper and aluminum alloy 3003 heavily worked by equal channel angular extrusion, Metall. Mater. Trans. A 28A (1997) 1047–1057.

[14] **Z.P. Xing, S.B. Kang, H.W. Kim,** Structure and properties of AA3003 alloy produced by accumulative roll bonding process, J. Mater. Sci. 37 (2002) 717–722

[15] **P.C. Yadav, A. Sinhal, S. Sahu, A. Roy, S. Shekhar,** Microstructural inhomogeneity in constrained groove pressed Cu-Zn alloy sheet, J. Mater. Eng. Perform. 25 (2016) 2604–2614.

[16] **J.W. Lee, J.J. Park,** Numerical and experimental investigations of constrained groove pressing and rolling for grain refinement, J. Mater. Process. Technol. 130–131 (2002) 208–213.

[17] **H. Pouraliakbar, M.R. Jandaghi, G. Khalaj,** Constrained groove pressing and subsequent annealing of Al-Mn-Si alloy: Microstructure evolutions, crystallographic transformations, mechanical properties, electrical conductivity and corrosion resistance, Mater. Des. 124 (2017) 34–46.

[18] **A. Krishnaiah, U. Chakkingal, P. Venugopal,** Production of ultrafine grain sizes in aluminium sheets by severe plastic deformation using the technique of groove pressing, Scr. Mater. 52 (2005) 1229–1233.

[19] **S.S. Satheesh Kumar, T. Raghu,** Strain path effects on microstructural evolution and mechanical behaviour of constrained groove pressed aluminium sheets, Mater. Des. 88 (2015) 799–809.

[20] **F. Khodabakhshi, M. Haghshenas, H. Eskandari, B. Koohbor,** Hardness-strength relationships in fine and ultra-fine grained metals processed through constrained groove pressing, Mater. Sci. Eng. A 636 (2015) 331–339.

[21] **S.S. Satheesh Kumar, T. Raghu,** Tensile behaviour and strain hardening characteristics of constrained groove pressed nickel sheets, Mater. Des. 32 (2011) 4650–4657.

[22] **Y.B. Lee, D.H. Shin, K.T. Park, W.J. Nam,** Effect of annealing temperature on microstructures and mechanical properties of a 5083 Al alloy deformed at cryogenic temperature, Scri. Mater. 51 (2004) 355–359.

[23[**K. Peng, X. Mou, J. Zeng, L.L. Shaw, K.W. Qian,** Equivalent strain , microstructure and hardness of H62 brass deformed by constrained groove pressing, Comput. Mater. Sci. 50 (2011) 1526–1532.

[24] **F. Khodabakhshi, M. Kazeminezhad, A.H. Kokabi,** Constrained groove pressing of low carbon steel: Nano-structure and mechanical properties, Mater. Sci. Eng. A 527 (2010) 4043–4049.

[25] **S. Kumar, K. Hariharan, R.K. Digavalli, S.K. Paul,** Accounting bauschinger effect in the numerical simulation of constrained groove pressing process, J. Manuf. Processes, 38 (2019) 49–62.

[26] **F. Khodabakhshi, M. Abbaszadeh, H. Eskandari, S.R. Mohebpour,** Application of CGP-cross route process for microstructure refinement and mechanical properties improvement in steel sheets, J. Manuf. Processes 15 (2013) 533–541.

[27] **G.G. Niranjan, U. Chakkingal,** Deep drawability of commercial purity aluminum sheets processed by groove pressing, J. Mater. Process. Technol. 210 (2010) 1511–1516.

[28] **M. Borhani, F. Djavanroodi,** Rubber pad-constrained groove pressing process: Experimental and finite element investigation, Mater. Sci. Eng. A 546 (2012) 1–7.

[29] **A. Sajadi, M. Ebrahimi, F. Djavanroodi,** Experimental and numerical investigation of Al properties fabricated by CGP process, Mater. Sci. Eng. A 552 (2012) 97–103.

THE AUTHOR

PATIL Suraj – *G.H. Raisoni College of Engineering and management.*
E-mail: patilsurajpsb@gmail.com

Статья поступила в редакцию 03.06.2021; одобрена после рецензирования 09.06.2021; принята к публикации 22.11.2021.
The article was submitted 03.06.2021; approved after reviewing 09.06.2021; accepted for publication 22.11.2021.