Investigation of microstructure and mechanical properties of commercially pure aluminum produced by RCS process

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Abstract

Severe plastic deformation (SPD) process is capable of developing the submicron grain structures in metallic alloys and to improve the Mechanical properties. Repetitive corrugation and straightening (RCS) processes are widely used in industries to compensate the high strength metal plates components used in automobiles. In the present work an attempt has been made to study the influence of RCS parameters like strain rate, number of passes and plate thickness to predict the degree of importance on grain size, micro hardness and tensile strength of RCS specimens. The results indicated that the number of passes has a major influence on the fine-grain refinement, followed by Al plate thickness and strain rate.

Key words: Sever plastic deformation, RCS, Microstructure, Mechanical properties

1. Introduction

The process of severe plastic deformation (SPD) is gaining great interest in material science because it is useful to refine microstructures to the sub micrometer or nanometer levels [1]. In Al based alloys, it is generally difficult to reduce the grain size below 10μm through the conventional recrystallization process following thermo-mechanical treatments. This difficult arises from the inherent nature of Al alloys that the staking fault energy is relatively large so that it is easy for the recovery of dislocation to occur [2]. One of these advantages is a capability of producing large samples that are free from any residual porosity and readily amenable to mechanical testing and forming operations [3]. Among the various SPD techniques proposed for processing bulk materials; very few methods like accumulative roll bonding(ARB)[4,5], constrained groove pressing(CGP) [6,7], and repetitive corrugation and straightening (RCS) [8,9] are capable of processing sheet materials. RCS process was invented recently [10] and it is promising method for producing fine grain sheet material for structural applications. In the RCS process, a work-piece is repetitively bent and straightened without significantly changing the cross-section geometry of the work-piece, during which large plastic strains are imparted into the materials, which leads to the refinement of microstructure. Although many researchers worked on RCS [11] but none of them study thoroughly on process parameters such as strain rate, number of passes and thickness of the metal plate. They are influence on different micro-structural evolution and mechanical properties of RSC specimens.

In present study the morphological and mechanical behavior were predicted through statistical analysis of the measured grain size, microhardness, tensile strength at different conditions and find the effects of strain rate, number of passes and plate thickness to find the percentage of influence of various factors and its interaction on the physical behavior of RCS specimens.

2. Experimental Studies

In order to achieve the RCS on Al test specimen corrugated and flat dies are used in the present research work. Theses dies are designed using analytical method on the basis of loading parameters and test specimen specifications. CATIA V5 tool was used for modeling of the dies according to design specifications. Technical specifications of the die are cross sectional area of corrugated die is 250 × 250 mm^2, Radius of the corrugated groves is 20 mm, depth of the groove is 5 mm, cross sectional area of flat die is 250 × 250 mm^2, material to be forged is aluminum having maximum yield strength 145 MPa, thickness of the test specimens to be forged are 3mm, 4mm and 5mm, cross sectional area of the test specimens to be forged is 20 × 100 mm^2, die material to be used is mild steel, overall tolerance of the geometry is ±1mm. The components of the dies are designed on the basis of loading conditions and test specimen specifications. The key components of the dies are one pair of corrugated die, one pair of flat die, one pair of backup plates to absorb excess loads, eight allen screws and one pair of bevel pins for proper alignment. Final assembly is made by combining male and female dies along with the backup plates. The pressing is performed in a 250T oil hydraulic press at pressing speeds of 1 mm/min, 1.5 mm/min and 2 mm/min. In RCS process, plate material is subjected to repetitive shear deformation under plane strain conditions by pressing the sheet alternately between asymmetric grooved dies and flat dies. The sheets are subjected to total number of five passes of RCS and further processing could not be continued beyond due to cracking of plate. Specimens were prepared for microstructure, hardness and tensile specimen.

Polishing of the test specimens were conducted with different grade silicon carbide papers using automatic polishing machine on one side of the mounted Al specimens. The polishing procedure starts from polishing paper grade of 80, 100, 200, 400, 600, 800 and 1000 to get fine surface finish. To obtain mirror finish on the polished surface diamond paste having grade 0-0.5 and 2 were used. The Keller's reagent was used as the etchant and the chemical composition is 2 ml Hydrofluoric acid (HF), 3ml Hydrochloric acid (HCl) and 5ml Nitric acid (HNO_3).After surface preparation, microstructure analysis was carried out on all the specimens using optical microscope. 500X magnification used for the analysis and the grain size was calculated in accordance with ASTM-E112. The Vickers hardness (HV) of the test specimens were calculated using Micromet-5101 device, with a load of 200g and loading period of 20 seconds. Tensile tests were performed at room temperature with Universal testing machine at cross head speed of 0.5 mm/min. The size of gauge part of the tensile specimen was 5 mm width and 40 mm length. The tensile test specimens were prepared as per dimensions using milling machine.

3. Plan of experiments

A standard Taguchi experimental plan with notation L_{27} (3^3) was chosen as shown in Table.1.Three factors and three levels used in the experiment.

Table 1: Control Factors and levels

Factors	Factors and Levels		
	1	2	3
A. Strain rate (mm/min)	1.00	1.50	2.00
B. Number of passes	1	3	5
C. Plate thickness (mm)	3.00	4.00	5.00

From the Taguchi Orthogonal Array (OA) technique, the designed experimental layout yielded in to the following response values of grain size, Micro-hardness and tensile strengths, Table 2.

Table 2: The experimental lay out and results of the micro hardness, tensile strength and grain size testing process

Expt. No.	Experimental condition matrix			Micro-hardness Hv	Tensile strength MPa	Grain size in microns
	Strain rate (mm/min)	No. of passes	Thickness in mm			
01	1	1	3	44.48	94.82	7.7
02	1	1	4	43.27	97.31	7.9
03	1	1	5	43.02	76.38	8.0
04	1	3	3	46.17	105.96	6.5
05	1	3	4	45.50	109.81	6.4
06	1	3	5	45.70	89.29	5.6
07	1	5	3	49.20	113.00	3.8
08	1	5	4	48.65	120.00	3.1
09	1	5	5	47.98	96.00	4.0
10	1.5	1	3	46.01	97.70	8.0
11	1.5	1	4	44.38	96.92	7.2
12	1.5	1	5	42.79	79.07	6.7
13	1.5	3	3	47.62	104.95	6.7

14	1.5	3	4	46.19	109.58	5.8
15	1.5	3	5	45.45	91.10	5.0
16	1.5	5	3	52.78	114.7	4.2
17	1.5	5	4	52.73	119.01	3.5
18	1.5	5	5	50.08	96.25	4.7
19	2	1	3	46.33	95.92	8.0
20	2	1	4	44.82	96.09	7.6
21	2	1	5	42.33	78.69	6.4
22	2	3	3	47.91	104.51	6.3
23	2	3	4	46.02	112.10	5.6
24	2	3	5	44.18	88.44	5.1
25	2	5	3	52.13	115.13	4.2
26	2	5	4	52.23	121.94	3.8
27	2	5	5	49.63	97.10	4.6

4. Result and discussion

4.1 Microstructure

Figs. 4.1 a, b and c show grain boundaries of as cast specimen (without SPD pressing) for 3 mm, 4mm and 5 mm thickness respectively. The average grain size for 3 mm thickness and 4 mm thickness specimens have 10µm and 5 mm thickness specimen has 9.4 µm.

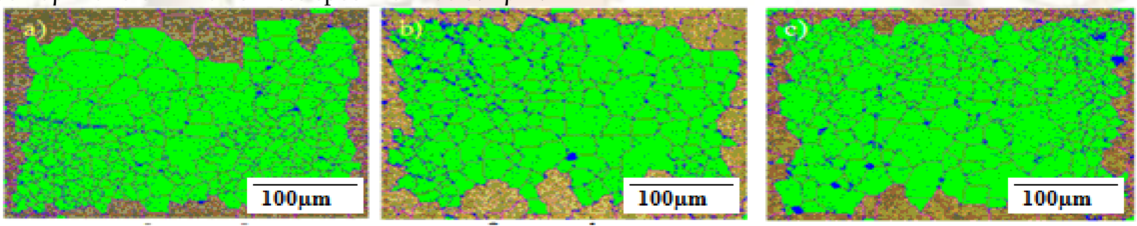

Fig. 4.1: Optical micrographs of as extruded specimen grain structure
a) 3 mm, b) 4 mm and c) 5 mm

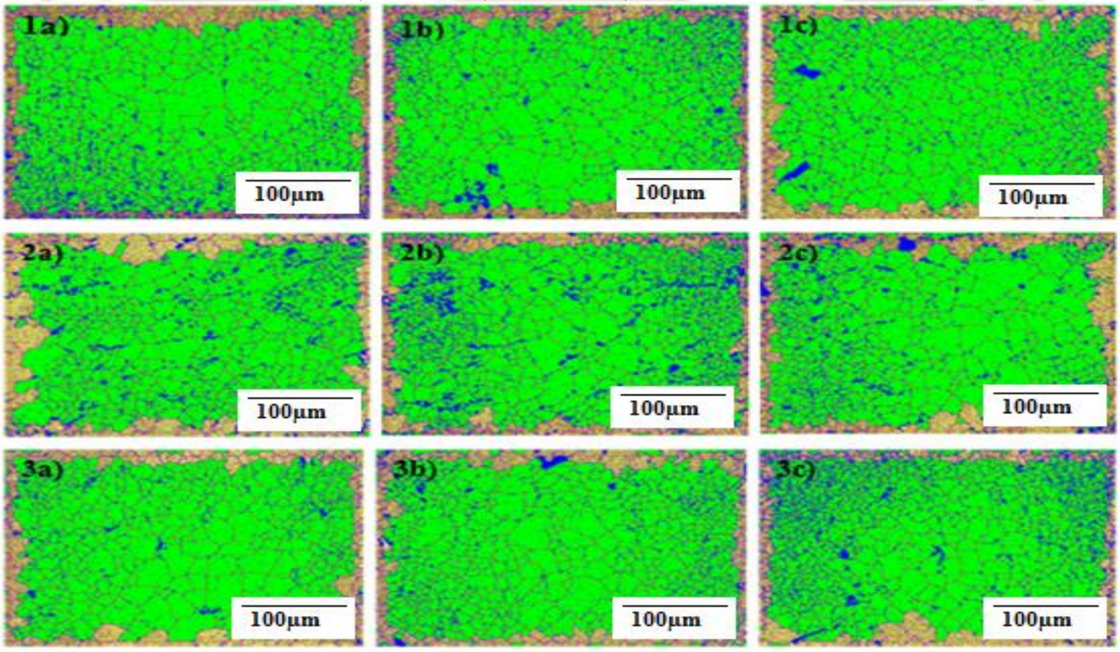

Fig. 4.2 Optical micrographs of grain structure after one pass **1a)** 1mm/min 3 mm, **1b)** 1.5mm/min 3mm, **1c)** 2mm/min 3mm, **2a)** 1mm/min 4 mm, **2b)** 1.5mm/min 4mm, **2c)** 2mm/min 4mm, **3a)** 1mm/min 5mm, **3b)** 1.5mm/min 5mm & **3c)** 2mm/min 5 mm

After one pass of corrugation and straightening of SPD aluminum resulted in the formation of non-uniform and subgrain vary substantially. The presence of subgrains and dislocation cells substructure is evidence that the aluminum in this region has undergone large amount of plastic deformation. The detailed observation over large areas of structure suggests that dislocation behavior relating to the low angle subgrain boundaries formation were effective previously in time of first pass. The development of a deformed substructure developed after first pass is illustrated in Figs.4.2 1a, 1b, 1c,2a,2b,2c,3a,3b and 3c.Total grain refinement of 20-30% was achieved in aluminum specimens after first pressing and the refined grain size of 6.4µm to 8 µm was developed in all the three thickness specimens.

The microstructure resulted from third pass is presented in Figure 4.3. The micrographs shows more finer subgrain structures having grain size 6.7 µm 5 µm, where former in homogeneous grains are fragmented to smaller and more equiaxed subgrains.

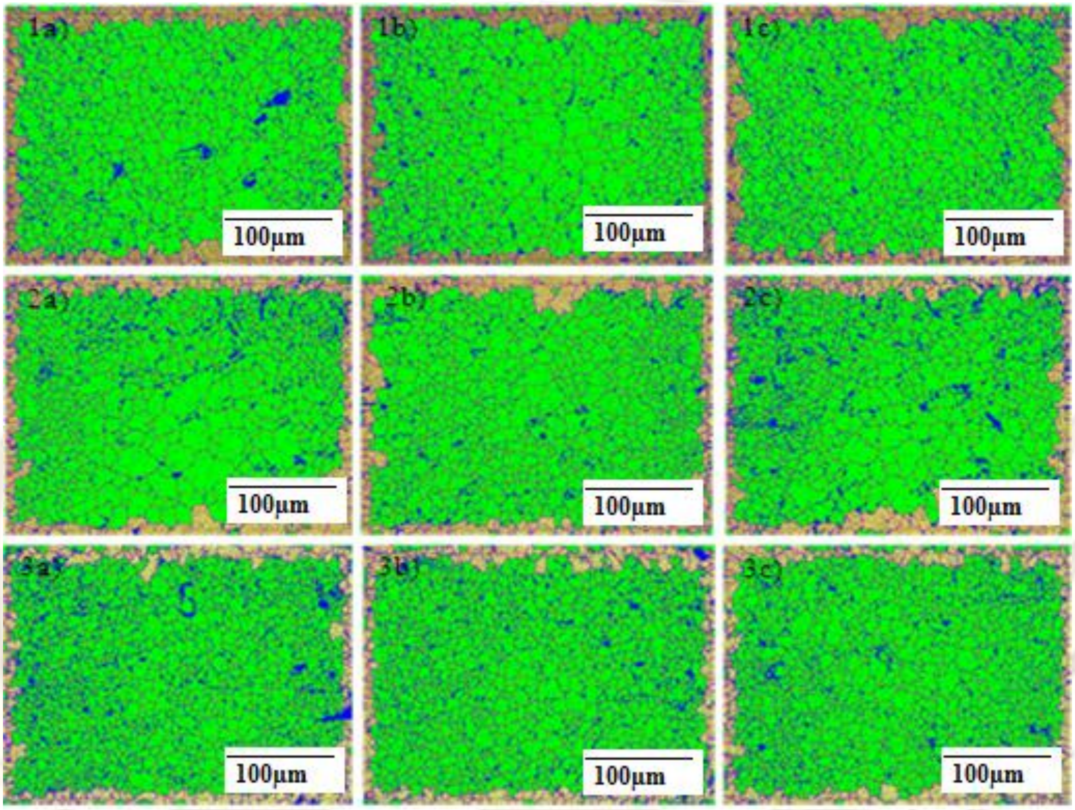

Fig. 4.3: Optical micrographs of grain structure after three pass
1a) 1mm/min 3 mm,**1b)** 1.5mm/min 3mm, **1c)** 2mm/min 3mm, **2a)** 1mm/min 4 mm,
2b) 1.5mm/min 4mm, **2c)** 2mm/min 4mm, **3a)** 1mm/min 5mm, **3b)** 1.5mm/min 5mm and **3c)** 2mm/min 5 mm

The fragmentation of grains after each pass of the process leads to the formation of refined grain structures, which are severely banded due to the dominant shear stress. Inside of such deformed structure the formation of new equiaxed polygonized grains, deposited along the subgrains was observed. The dislocation structure recovery and formation of polygonized grains was observed as local process and is attributed to deformation heterogeneity distribution across the plate.

The microstructure resulted from five pass is presented in Figure 4.4. The micrographs shows more finer subgrain structures having grain size of 3.1µm to 4.7µm, where former in homogeneous grains are fragmented to smaller and more equiaxed subgrains.

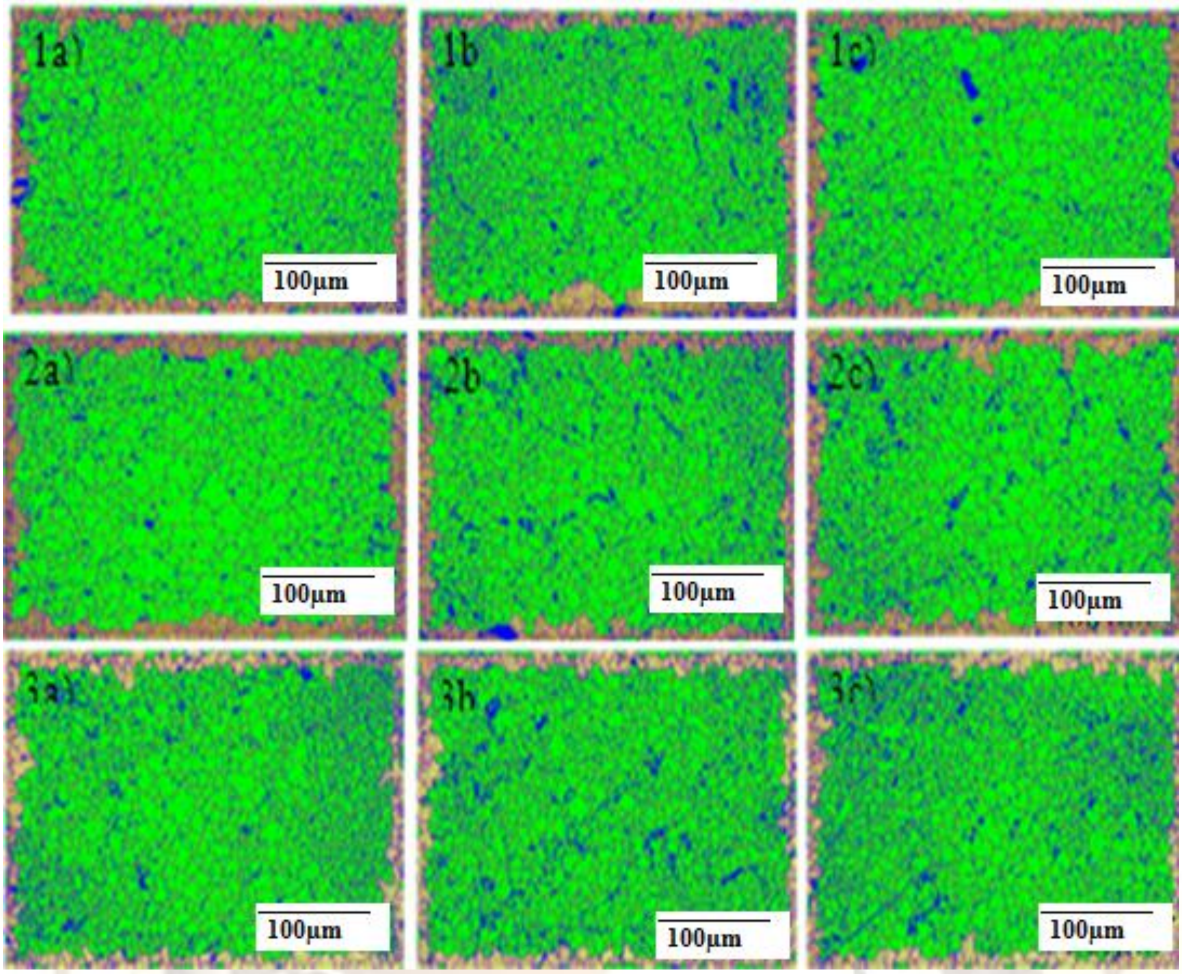

Fig. 4.4 : Optical micrographs of grain structure after five pass **1a)** 1mm/min 3 mm, **1b)** 1.5mm/min 3mm, **1c)** 2mm/min 3mm, **2a)** 1mm/min 4 mm, **2b)** 1.5mm/min 4mm, **2c)** 2mm/min 4mm, **3a)** 1mm/min 5mm, **3b)** 1.5mm/min 5mm and **3c)** 2mm/min 5 mm

An increase in the number of pass of corrugation and straightening to five passes led to the formation of a uniform Ultrafine Grain Structure with an average grain size of 3.1µm to 4.7µm. the overall percentage in grain size refinement after five pass is 40% to 70%.

Achieved microstructure of aluminum after each passes of SPD analyzed through optical microscope. In strain rate one mm/min, after first pass an average of 20% of grain refinement was achieved in 3mm, 4mm and 5mm thickness specimens. But in case of strain rate 1.5 and 2 mm/min, the grain size refinement was varied from 20% to 28%.

In third pass of one mm/min strain rate, an average grain size refinement of 0.8µm to 1.3µm was achieved (8%-13%) in three different thickness specimens. In case of 1.5 mm/min, second and third pass shows decrease in the grain refinement is 0.5µm to 1.1µm which is (5-11%). 2 mm/min strain rate pressing also shows a decrease in grain refinement in second and third pass i.es 0.8µm to 1.2µm (8-12%). The overall decrease in grain size after third pass is 36-44% compared to the initial test specimens.

After five pass of corrugation and straightening, a total of 58% to 69% was achieved in all the three different thickness test specimens. Fig. 4.5 shows distribution of grain refinement after each corrugation and straightening according with different strain rate, thickness and number of pass.

These changes in the grain sizes is due to the extension of pre-existing boundaries in proportion to the strain and also due to the formation of new high angle grain boundaries formed by grain sub dividing.

Fig. 4.6 shows the grain size distribution in 3 mm, 4 mm and 5 mm thickness specimens starting from initial test specimen to five pass specimens with strain rates 1 mm/min, 1.5 mm/min and 2 mm/min. in 1 mm/min the grain refinement of 3 mm specimen has 62% of refinement where as 4 mm and 5 mm specimens shows 69% and 54%. The drop of grain size in 3 mm is 6.2 µm, in 4 mm 6.9 µm and in 5 mm 5.4 µm.

Considering 1.5 mm/min strain rate, grain refinement of 5.8 µm (58%) in 3 mm, 6.5 µm (65%) in 4 mm and 4.7 µm (47%) was achieved. In 2 mm/min strain rate, 3 mm specimen has 5.8 µm µm (62%) and 5 mm specimen has 4.8 µm (48%) grain refinements. The above analysis shows 4 mm (58%), 4 mm specimen has 6.2 specimen has the more grain refinement compared to other two thickness specimens.

Effect of number of passes on grain size

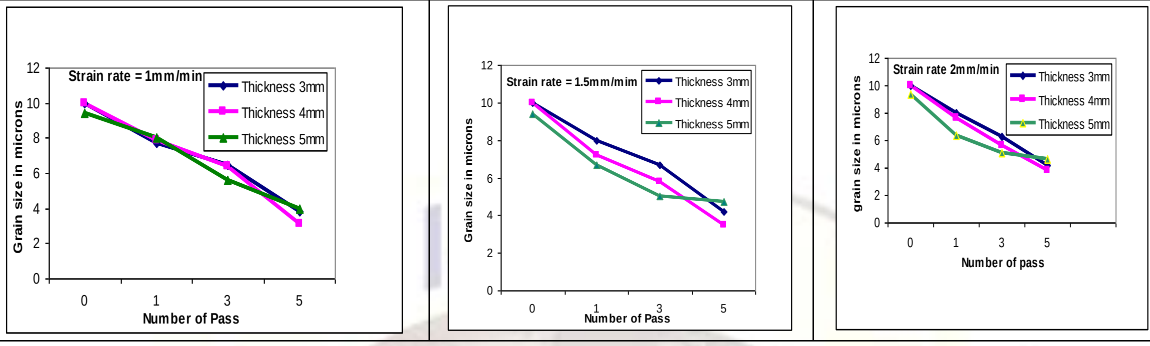

Fig.4.5: Grain refinement according to number of passes

Effect of thickness on grain size

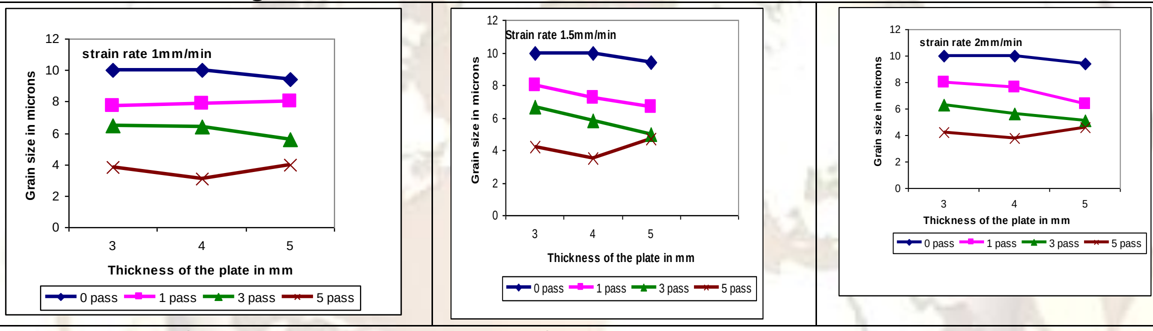

Fig.4.6: Grain refinement according to thickness of the aluminum

Effect of strain rate on grain size

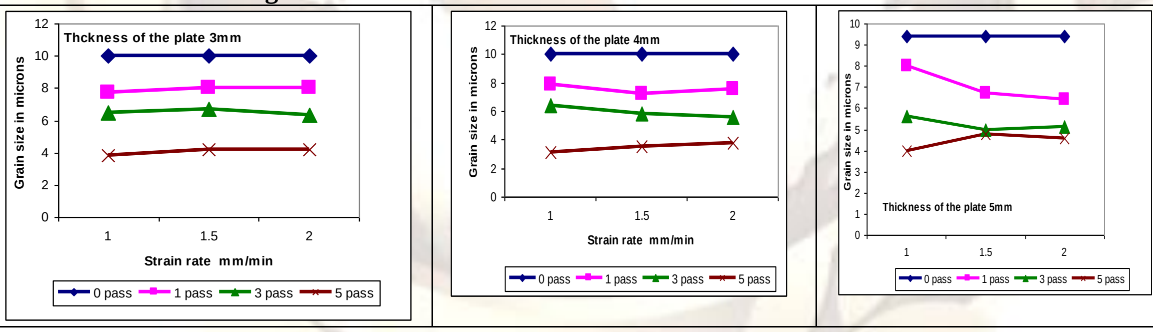

Fig.4.7: Grain refinement according to strain rate of pressing

Fig. 4.7 shows the grain size distribution according to the strain rate of pressing. In 1 mm/min and 1.5 mm/min strain rates, there is an average of 1.9 µm (19%) and 2.5 µm (25%) refinement in grain size was achieved after each pass, where as in 2 mm/min strain rate, 1.2 µm (12%) was achieved. This causes the grain size points of 1 and 1.5 strain rate are after each passes were clearly separate from each other, but in 2 mm/min min strain rate they are nearly grouped towards one point.

The formation of new deformation induced high angle grain boundaries by grain subdivisions at lower strain rates is because, it is energetically easier for a grain to deform if it splits into deformation bands (or cell blocks) that deform on fewer than the slip system required for constrained deformation

4.2 Micro-Hardness after RCS

The initial hardness of the un-deformed specimens has 43.11 HV (3mm thickness specimen), 42.45 HV (4 mm thickness specimen) and 41.16 HV (5 mm thickness specimen). The formation of substructure after one pass led to an increase in hardness to an average of 2 HV in all the three different thickness and strain rates.

The Aluminum structure, which consists of fragmented grains after two, passes of treatment exhibit a further increase in hardness. i.e., average of 1.5 HV (3%) ion all the three different strain rates and thickness of the specimens. After every passes of RCS, the hardness of the specimen shows increasing trend with an average increase in hardness of 1-2 HV in all the specimens.

The hardness was raised however due to dislocations formed in the grains, an important effect which could also affect the final hardness. Through the Hall–Petch equation [1-2] we can see that the grain size decreased more and more giving rise to the better hardness. The grain size would continue to be refined, thereby increasing the hardness during corrugation and straightening process. Fig.4.8 shows the micro hardness distribution according to the number of pass.

Fig.4.9 shows the hardness distribution after each pass of three different thickness specimens. Fig. 4.10 shows the hardness distribution according to strain rate of pressing.

Effect of number passes on micro-hardness

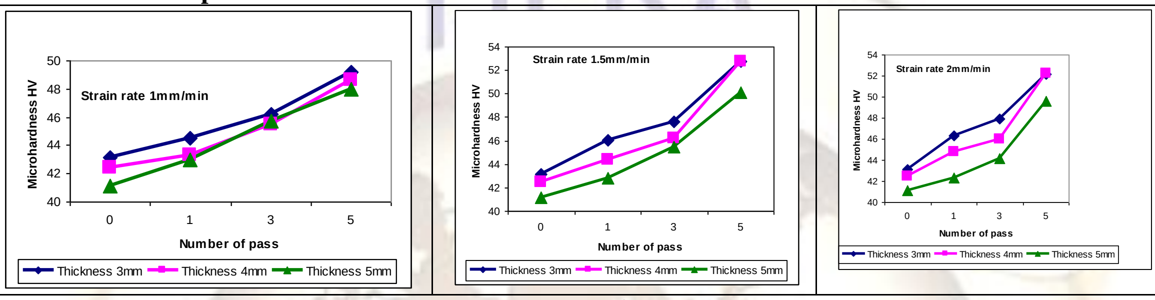

Fig.4.8: Chang in Micro-Hardness according to number of passes

Effect of thickness on micro-hardness

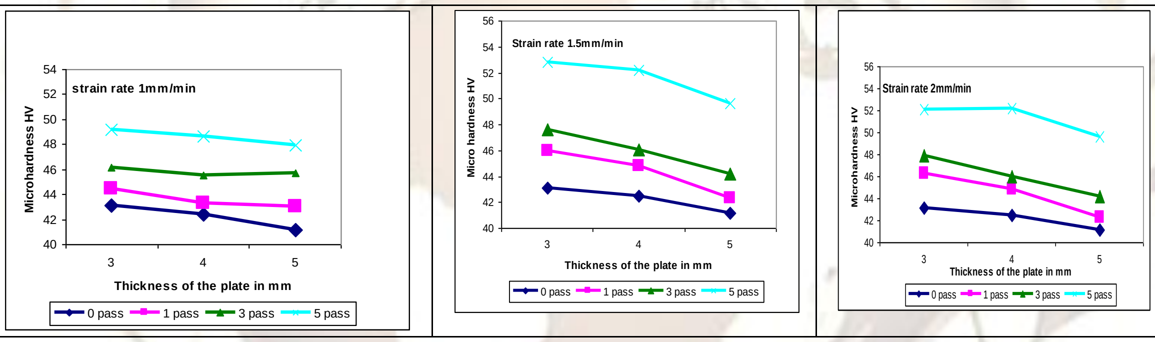

Fig.4.9: Change in Micro-Hardness according to thickness of the specimens

Effect of strain rate on micro-hardness

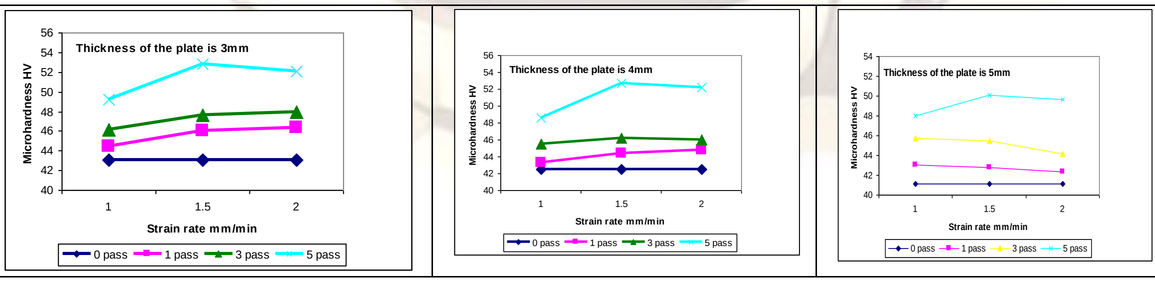

Fig.4.10: Change in Micro-Hardness according to strain rate of pressing

As discussed earlier, higher refinement in the grain size will leads to the in crease in the hardness of the specimens. But the grain refinement strongly influenced by the increase in strain. The above results shows, there is approximately equal amount of increase in hardness values of the specimens pressed using 1, 1.5 and 2 mm/min strain rates. This is due to very little difference in the strain rates. The pattern obtained in Fig. 4.10 is evident for the above reason, which shows all the three graphs follow same patters with a very little variation.

4.3 Tensile Strength

Fig.4.11 shows the distribution of tensile strength values after each pass of the specimens. An average of 6-7 % tensile strength increase was achieved in all the three different strain rates and thickness of the specimens. Overall increase in tensile strength for all strain rates has 21% for 3mm, 35% for 4mm and 15% for 5mm.

Based on the above results, it reveals that the optimum property - highest stress and no remarkable reduction in ductility is produced for a five passes of corrugation and straightening.

Fig. 4.12 shows the tensile strength distribution according to the different specimen thickness. The tensile strength showed very little significant changes with thickness. 4 mm thickness plate shows higher strength compared to 3mm and 5 mm thickness plates. The grain boundaries influence on the tensile strength. Higher the grain size lowers the strength and same time lower the grain size also lower the strength. Hence 5 passes showed decreases.

Effect of number passes on Tensile strength

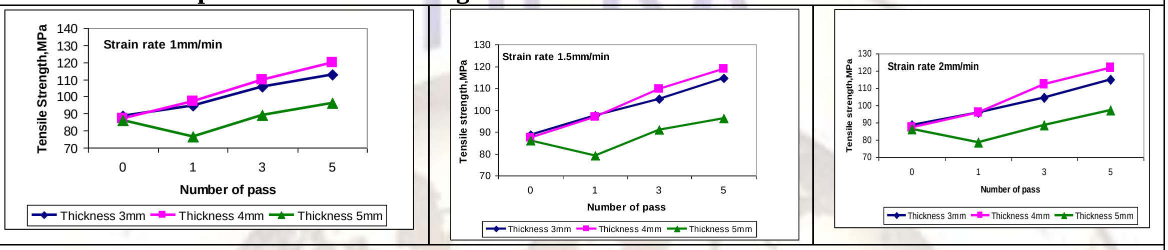

Fig.4.11: Change in Tensile Strength according to number of passes

Effect of thickness on Tensile strength

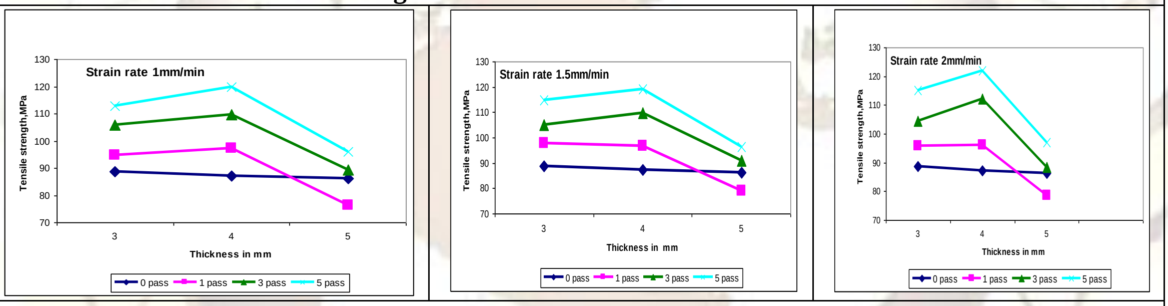

Fig.4.12: Change in Tensile Strength according to thickness of the specimens

Effect of strain rate on Tensile strength

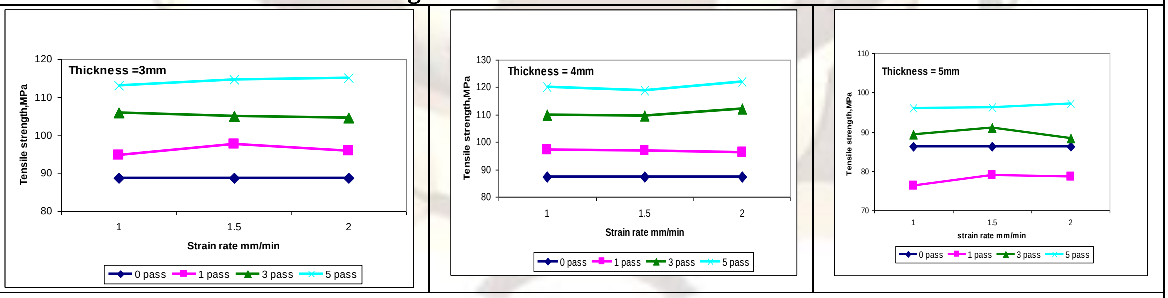

Fig.4.13: Change in Tensile Strength according to strain rate of pressing

Fig.4.13 shows the tensile strength distribution according to the different strain rates. The tensile strength showed no significant changes with strain rate. 3mm thickness plate shows slight decreases along with strain rate but 4 and 5 mm plates show opposite nature. The grain boundaries influence on the tensile strength. Higher the grain size lowers the strength and same time lower the grain size also lower the strength. Hence 5 passes showed decreases.

5. CONCLUSION

- ❖ From the Experiments it is clear that the parameter number of passes (B) has a highest amount of contribution on response values and strain rate (A) has the second highest contribution on the response values.

- Other values of the thickness (C) and interaction factors show a very less amount of contribution.
- From the Taguchi method it is confirmed that the best combination of experiment run which has a highest order and gives highest values on all the response values is experiment number 17
- For 4mm thick Al plate compressed by 1.5 mm/min strain rate up to 5 passes gives the lowest grain size of 3.5µm with hardness 52.73 Hv and tensile strength 119.01 N/mm2.
- From the Taguchi grey relational analysis it is concluded that, at 99% confidence level, the number of pass has the highest contribution toward the response values obtained and the strain rated occupies the second highest contribution rate.

REFERENCES

1. Zenji Horita, Keiichiro Oh-ishi, Kenji Kaneko, Microstructure control using severe plastic deformation, Science and Technology of Advanced Materials , Vol. 7 (2006), PP. 649–654.
2. Z. Horita, T Fujinami, M Nemoto, T G Langdon, Improvement of mechanical properties for Al alloys using equal-channel angular pressing, Journal of Materials Processing Technology, vol.

1 17 (2001), pp.288-292. 3. O.N. Senkov, F.H. Froes, V.V. Stolyarov, R.Z. Valiev and J. Liu, Microstructure of aluminum-iron alloys subjected to severe plastic deformation, Scripta Materialia, Vol. 38, No. 10, (1998) pp. 1511–1516.

4. Saito Y, Tsuji N, Utsunomiya H, Sakai T, Hong RG. Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process. Scripta Mater, vol 39 (1998), pp. 1221–7.
5. Shin DH, Park JJ, Kim YS, Park KT. Constrained groove pressing and its application to grain refinement of aluminium. Mater Sci Eng, vol. 328A (2002), pp. 98–103.
6. Krishnaiah A, Chakkingal U, Venugopal P. Production of ultrafine grain sizes in aluminium sheets by severe plastic deformation using the technique of groove pressing. Scripta Mater 2005;52:1229–33.
7. Krishnaiah A, Chakkingal U, Venugopal P. Applicability of the groove pressing technique for grain refinement in commercial purity copper. Mater Sci Eng, 411A, (2005, pp. 337–40.
8. Zhu YT, Jiang H, Huang JY, Lowe TC. A new route to bulk nanostructured metals. Mater Trans, vol 32A (2001), pp.1559–62.
9. Huang JY, Zhu YT, Jiang H, Lowe TC. Microstructures and dislocation configurations in nanostructured cu processed BY repetitive corrugation and straightening, Acta Mater, vol.49 (2001), pp. 1497–505.
10. J. Y. Huang, Y. T. Zhu, H. Jiang and T. C. Lowe, Microstructures and dislocation configurations In nanostructured cu processed by repetitive Corrugation and straightening, Acta Mater. Vol. 49 (2001) pp. 1497–1505
11. V. Rajinikanth, Gaurav Arora, N. Narasaiah, K. Venkateswarlu, Effect of repetitive corrugation and straightening on Al and Al–0.25Sc alloy, Materials Letters, vol 62 (2008) pp.301–304
12. M. Senthil kumar, s. Natarajan, Analysis of tribological factors on dry sliding wear behaviour of thermally sprayed carbide and ceramic coatings by Taguchi method, International Journal of Engineering Science and Technology,vol. 3 (4) (2011), vol. 3336-3347