RESEARCH ARTICLE

INTERNATIONAL RESEARCH JOURNAL OF
MULTIDISCIPLINARY TECHNOVATION

DOI: 10.54392/irjmt2331

Aluminum Alloy Chips Recycling using Friction Stir Consolidation

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DOI: https://doi.org/10.54392/irjmt2331
Received: 27-01-2023; Revised: 13-02-2023; Accepted: 19-02-2023; Published: 20-03-2023

Abstract: The purpose of this paper is to develop AA5052 aluminum alloy solid disc from machining wastes via friction stir consolidation (FSC) process & optimize its parameters: die rotational speed, pre-compact aspect ratio and processing time. At first, the required dedicated tooling is designed and built. Then, solid discs are fabricated from AA5052 aluminum alloy chips using FSC process. Taguchi L_9 orthogonal array is used to analyze and optimize the process. Experimental parameters and their levels considered are rotational speed (315, 400 and 500 rpm), pre-compact aspect ratio (25.4/7, 25.4/5 and 25.4/3) and processing time (30, 45 and 60 sec). Using standard tests, compressive strength, hardness and microstructure of the consolidated solid disc are evaluated. The results reveal that solid discs are successfully fabricated using FSC using dedicated tooling, and rotational speed (500 rpm), pre-compact aspect ratio (25.4/3) and processing time (60 sec) are optimal processing conditions. Microstructure examination of the solid disc shows finer and fully recrystallized grains in axial cross section orientation. Moreover, the results show compressive strength and hardness of the solid disc are comparable to that of forged or cast disc and suitable for most engineering structural applications.

Keywords: Machining wastes, Friction stir consolidation, Taguchi methods, Hardness, Compressive strength, Microstructure

1. Introduction

Friction stir consolidation (FSC) is a new and promising thermomechanical processing technique that modifies the mechanical properties and microstructure of the material in a single pass. It uses a non-consumable rotating die to create frictional heat and plastic deformation which results in particulate bonding during consolidation. Formerly, FSC was developed for processing of aluminum and magnesium based structural alloys due to their lower melting point and wide applications. Manufacturing operation namely, traditional machining usually produces considerable amounts of metallic wastes in the form of scraps or chips [1]. There are two primary techniques for recycling of non-ferrous metals machining wastes: the so-called 'conventional' and the direct conversion techniques [2-3]. The conventional method requires melting of the waste metal and hot extrusion of the billet to form a valuable product in wire or rod form. Studies were conducted in recycling non-ferrous metal wastes particularly aluminum and magnesium alloy wastes through melting in a furnace [4-5]. However, their findings indicate using conventional techniques, material yield hardly reaches to 50%. In addition, these techniques involve multi-processing steps causing them not efficient for modern manufacturing applications. One of direct recycling technique is hot extrusion which was first proposed and patented by Stern in 1945 [6]. In addition, Gronostajski and Matuszak milled and compacted aluminum chips followed by conventional hot extrusion process [7]. These solid state processes eliminate formation of thick oxide layers so that the scrap can be changed to a final product without requiring additional processing steps. Compared with conventional recycling techniques, the direct conversion of aluminum scraps into compact metal may result in 26–31% energy, 40% material and 16–60% labor savings [8]. The benefits of direct or solid phase recycling of aluminum are perceived to be important by most researchers. It can minimize cost of energy consumption and environmental protection over the conventional recycling.

In secondary aluminum metal processing, energy about 10 GJ/ton of the material is required which comprises about 5-10% of the energy in the primary aluminum output, and the trend is growing for the subsequent years. In 2030, a recycling rate of 50% will be expected [9]. The percentage figures show that demand for energy in secondary aluminum metal processing via re-melting is increased significantly. Although there have been several perfect efforts to improve energy efficiency of melting furnaces since 1980s, the energy requirement for secondary aluminum production is still increasing to 20 GJ/ton [9]. Thus, conventional recycling technique is considered as unfavorable due to a significant metal and energy losses.

Among the direct recycling techniques, friction stir welding (FSW) and friction stir processing (FSP) are solid state techniques for joining and modifying microstructure. Both techniques depend on plastic deformation of metal for heat generation and hence, they are considered as severe plastic deformation processes. FSW was patented by the Welding Institute, UK, in 1991 [10]. Solid state processing techniques involve the use of a rotating non-consumable tool which is used to generate a plasticized surface. In general, FSP leads to formation of finer grains in the processed zone due to thermomechanical effect.

Generally, nowadays, during manufacturing of aluminum and its alloy components, there is more amount of material wastage in the form of scraps or chips. These machining wastes are not convenient and economical to recycle them using conventional techniques namely melting in a furnace due to presence of surface contaminates and oxides. The conventional technique is also associated with low material yield (nearly 55%). Ultimately, it is desired to establish a more efficient recycling technique which can provide better material yield and involve lesser processing steps. Recently, a potential alternative has emerged which is friction stir consolidation technique. This technique is also preferable due to its environmentally friendliness and material wastage. Therefore, this research aims at evaluating and optimizing FSC process to fabricate a solid disc with better performance characteristics from AA5032 alloy machining wastes.

2. Experimental Details

The material used was aluminum AA5052 alloy machining chips with an average thickness of 76 μm and its chemical composition is given in Table 1. AA5052 alloy is a common Al-alloy with medium strength and usually used in a wide variety of structural applications including boat hulls, gangplanks and other products used in marine environments [11, 12].

Machining chips with desired thickness were collected by dry milling of the solid block metal using a milling machine model of FU281, and Equation 1 [13] was used to determine the desired chip thickness from initial 8 mm diameter solid block.

$$t_c = \frac{2v}{Nn}\sqrt{d/_D} \qquad (1)$$

Where tc is the average thickness of chip, N is the rotational speed of the cutter, n is the number of teeth on the cutter periphery, d is the depth of cut, D is the cutter diameter, and v is the feed rate. The machining parameters adopted to prepare chips with tc = 76 μm average thickness are given in Table 2. The actual thicknesses of the machined chips were measured using a microscope, and the obtained average value was 75.8 μm with 8.3 μm as standard deviation. The photograph of machining chips prepared using the recommended machining parameters is shown in Figure 1.

Dedicated tooling for the FSC process namely die, chamber, punch, flat backing plate, insert button and fixtures were designed and built. A non- rotating die with a stationary chamber and flat backing plate at the bottom of the chamber was used to consolidate and plasticize machining chips to produce pre-compact discs. Pre-compact aspect ratio (height to diameter) of was selected to be 25.4/3 (8.5), 25.4/5 (5) and 25.4/7 (3.5). Figure 2 shows photographs of pre-compacts of AA5052 alloy machining chips with different aspect ratio. Each of specimens was made to have nearly the same relative density of 75% which is obtained using Archimedes principle. Pre-compact discs with different aspect ratio were inserted into the FSC die chamber and made to consolidate further to obtain the desired sold discs.

The general experimental configuration of FSC is shown in Figure 3. A conventional milling machine was used for the experiment. A consolidation chamber with dimension 25.4 mm in diameter and 50 mm in height was used with metallic insert of 25.38 mm diameter and height of 30 mm with role of supporting the bottom side of pre-compact discs. The metallic insert is also used to provide space for locating the pressure gauge. Moreover, a chamber holder fixture with dimension of 300 mm x 200 mm was used to fix the chamber and maintain the center position of the rotating die. The chamber holding fixture was drilled at the midpoint to allow physical contact for pressure gauge and insert which can establish easiness to measure the applied load. The whole set of tooling used for FSC process is shown in Figure 4.

In the experiment, the applied consolidation load was measured using DTZH pressure gauge, shown in Figure 5, for each experimental condition. The consolidation force was maintained constant at 27 kN and the pressure level read by the DTZH gauge was converted into equivalent force using Equation 2 [14].

$$P = \frac{F}{A} \qquad (2)$$

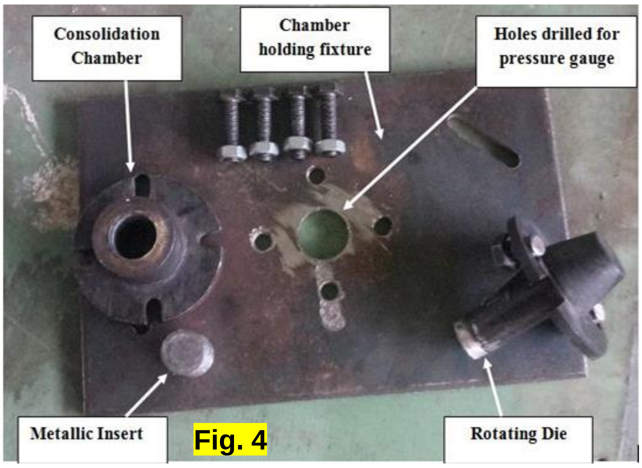
where *F* is applied force which is 27 kN, *A* is area of the pressure gauge`s piston which is equal to 900 mm$^2$ and *P* is the pressure gauge`s reading (3 MPa). For microstructure examination and hardness evaluation, the consolidated solid discs were sectioned by abrasive cutter and the cut part of the specimen was mounted by using hot mounting press. Figures 6a and 6b show disc specimens sectioned in horizontal and vertical directions, respectively.

Table 1 Standard chemical composition of aluminum AA5052 alloy [12]

Composition	Mg	Cr	Cu	Fe	Mn	Si	Zn	Others, each	Others, total	Al
Mass (%)	2.2 -2.8	0.14-0.35	0.1	0.4	0.1	0.25	0.1	0.05	0.15	Reminder

Table 2 Machining parameters used for chip preparation

N (rev/s)	d (mm)	V (mm/s)	D (mm)	Chip length (mm)	n
2.13	0.5	2	19.05	3.18	4



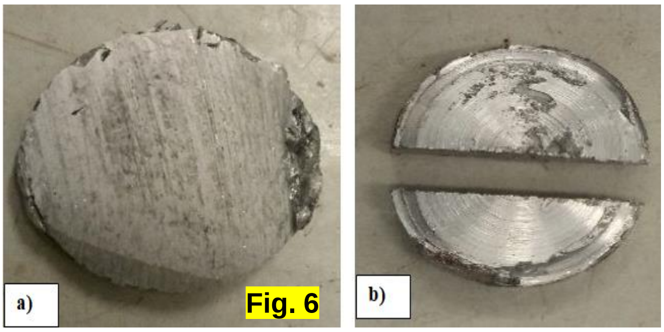


Figure 1. AA5052 alloy machining chips **2.** Pre-compact discs of AA5052 alloy machining chip **3.** Experimental set up for FSC process **4**. Photographs of tooling used for FSC process **5.** The DTZH pressure gauge for controlling applied force **6.** A consolidated disc specimen with a) Horizontal cross-section and b) Vertical cross

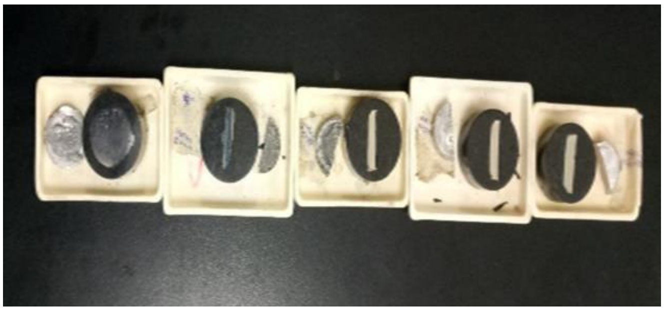


Figure 7. FSC disc specimens for microstructure examination.

The specimens were polished and etched using Keller's etchant namely a solution of water of 190 ml, HCl of 3ml, HF of 2ml and HNO_3 of 5ml.

The hardness was determined on both horizontal and radial cross sectioned consolidated discs which are shown in Figure 7, and each specimen was tested at least in five different zones and the average values were recorded. The specimens were passed different preparation steps including, mounting, grinding, polishing and repolishing. The average grain size of the consolidated discs was determined using ASTM E112-13 standard, line intercept method. Finally, compressive strength was determined by using universal testing machine.

3. Design of Experiment

The reason why design of experiment (DOE) was selected over other approaches is it can provide opportunity for systematic planning of experiments. Taguchi technique of DOE has been the most widely used for the last two decades. Its benefit includes the ability to analyze the effect or response of many factors and levels with minimum amount of experimentation.

To obtain optimum process parameters setting, Taguchi proposed a statistical measure of performance called signal to noise ratio [15]. This ratio considers both the mean and the variability of the process. In addition to S/N ratio, ANOVA is used to indicate the interaction influence of process parameters on performance measures. In accordance with the steps that are involved in Taguchi`s method, a series of experiments were conducted and the process parameters considered were die rotational speed, pre-compact aspect ratio and processing time with three levels. Table 3 shows all the factors and the associated levels used for experimentation.

The suitable orthogonal array for the specific experimentation is L_9 and accordingly, experiments were conducted with three factors and three levels, and their values are depicted in Table 4. Each of the 9 experiments was replicated 3 times to account for the variations that may occur due to the noise factors.

4. Results & Discussions

4.1 Hardness of FSC Solid Disc

The fabrication of solid discs through FSC process was successfully performed on a milling machine model FU281. Figure 8 shows photographs of FSC fabricated discs from different pre- compact aspect ratios. Few flashes were observed on the edges of the disc due to the presence of clearance between chamber and rotating die which can be easily removed using polishing. The solid discs were made from three initial pre-compacts with three different aspect ratios (l/d) of 25.4/7, 25.4/5 and 25.4/3, respectively.

Table 3 Selected factors and their levels

Factors	Levels		
	1	2	3
Die rotational speed (rpm)	315	400	500
Pre-compact aspect ratio	8.5	5	3.5
Processing time (sec)	30	45	60

Table 4 Orthogonal array with control factors and their levels

Experiment no.	Control factors		
	Aspect ratio	Die rotational speed (rpm)	Processing Time (sec)
1	25.4/7	500	60
2	25.4/7	400	45
3	25.4/7	315	30
4	25.4/5	500	45
5	25.4/5	400	30
6	25.4/5	315	60
7	25.4/3	500	30
8	25.4/3	400	60
9	25.4/3	315	45

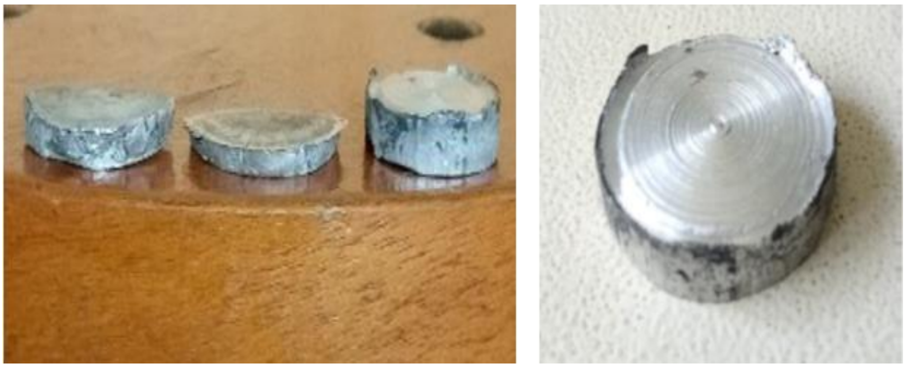


Figure 8. FSC solid discs with different aspect

Table 5 Hardness of FSC discs and S/N ratios

Aspect Ratio	Rotational Speed	Processing Time	Mean	S/N Ratio
25.4/7	500	60	44.27	32.92
25.4/7	400	45	42.13	32.48
25.4/7	315	30	41.20	32.29
25.4/5	500	45	46.70	33.38
25.4/5	400	30	45.03	33.07
25.4/5	315	60	46.03	33.26
25.4/3	500	30	49.23	33.84
25.4/3	400	60	51.43	34.22
25.4/3	315	45	49.20	33.83

Table 6 Response values for S/N Ratio (Larger is the Better)

Level	Pre-compact aspect ratio	Die rotational speed (rpm)	Time (sec)
1	33.97	33.13	33.07
2	33.24	33.26	33.23
3	32.56	33.38	33.47
Delta	1.40	0.25	0.40
Rank	**1**	**3**	**2**

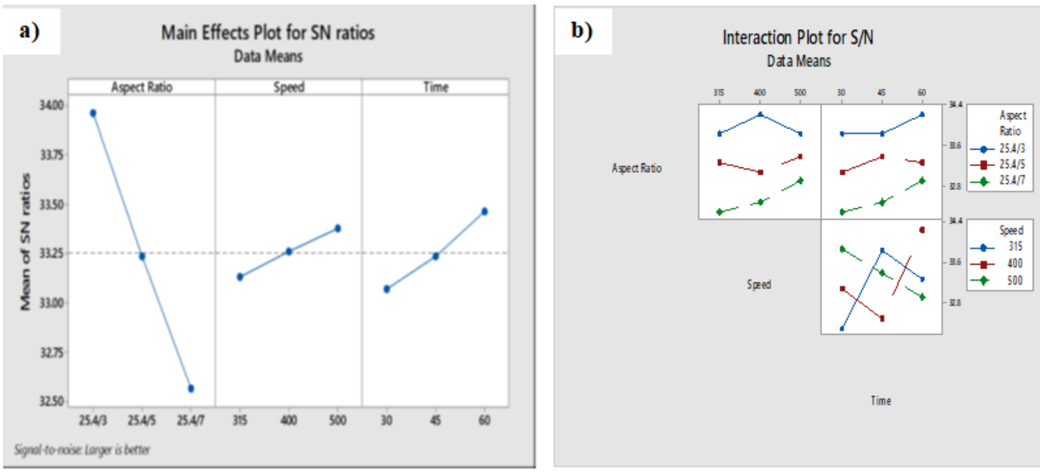


Figure 9. S/N ratio for hardness a) Main effect plot and, b) Interaction effects plot ratios

Table 5 shows the mean Vicker hardness values of solid discs made under different experimental conditions, and the corresponding calculated S/N ratios (using Equation 3). Since the selection of S/N ratio depends on the performance characteristics of the solid discs, higher hardness and compressive strength are preferred in FSC, thus S/N ratio 'larger is the better' was considered for this analysis.

$$S/_N\ ratio = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{{y_i}^2} \qquad (3)$$

where y is response for the given factor level combination, n is number of responses in the factor level combination and $\boldsymbol{y_i}$ is the experimental results.

From Table 5, it is observed that higher pre-compact aspect ratio (25.4/3) and longer processing time (60 sec) with intermediate die rotational speed (400 rpm) provided larger values of S/N ratio (34.22) which is considered to be better performance characteristics of the solid disc. However, decrease in the aspect ratio and processing time resulted in a decreased S/N ratio of the solid disc. Increase in the die rotational speed during consolidation, usually results in improvement of the mechanical properties of the disc, but as observed in this study, it should be controlled at the intermediate stage in combination with the other processing conditions. Increase in hardness values with increase in pre-compact aspect ratio may be due to involvement of more amounts of metals which resulted in a better metal-metal interaction and consolidation. This also indicates that, regardless of processing time and die rotational speed, the variation in pre-compact disc aspect ratio results in variation of hardness values. Table 6 also depicts rank of influence of each factor on the hardness and it can reveal that the effect of pre-compact aspect ratio on the hardness takes the first rank, whereas processing time and die rotational speed acquire the second and third rank, respectively.

Figures 9a & b depict main effect and interaction effect plots of S/N ratio for different experimental conditions with hardness as desired performance characteristic. The experimental result demonstrates that pre-compact aspect ratio and processing time are the significant factors which influence the hardness of the consolidated disc while die rotational speed has lower effect.

Based on the main effect plot for S/N ratio, optimum combination is selected as pre-compact aspect ratio, die rotational speed and processing time of 25.4/3, 500 rpm and 60 sec, respectively. In addition, from the interaction plots, S/N ratio is lowest at processing time of 30 sec with pre-compact aspect ratio of 25.4/7, and S/N ratio is the highest at processing time of 60 sec with aspect ratio of 25.4/3. When the aspect ratio increases, the hardness increases. The results of main effect and interaction effect plots for S/N ratio provide the optimum processing condition. However, the optimum experimental condition is not part of the orthogonal array, hence not experimented. Therefore, confirmation experimental runs are required.

The effect of each input parameters on the hardness was evaluated using variance analysis (ANOVA). The result shows that all the three process variables namely, die rotational speed, pre-compact aspect ratio and processing time are statistically significant with contributions of 5.32%, 77.69% and 4.27%, respectively, and error percent of 0.43%. From this, it is observed that pre-compact aspect ratio is most significant as it contributes the highest effect on hardness, and the processing time contributes the lowest value of 4.27%.

4.2 Confirmation test for hardness of the solid disc

The optimal condition is set for the significant factors and selected number of experiments is run under specified processing condition. The average of the results from the confirmation experiment is compared with the predicted average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental results. It was performed by conducting test with optimal setting of factors and levels previously evaluated i.e. 25.4/3, 500 rpm and 60 sec of aspect ratio, rotational speed and processing time, respectively, in three trials.

Experimental result, depicted in Table 7, indicates that during FSC processing of AA5052 alloy, use of high rotational speed, high aspect ratio and extended time are recommended to obtain better hardness for the specific range at rotational speed of 500 rpm, aspect ratio of 25.4/7 and processing time of 60 seconds. Further, the S/N ratio and mean values are calculated using Equation 3 for S/N (larger is better case). The result shows the mean and S/N ratios were obtained to be 53.2 and 34.52 respectively.

4.3 Compressive Strength of the FSC Solid Disc

Compressive strength results and S/N ratios are shown in Table 8. It can be seen that the mean values of compressive strength is highest at processing condition of rational speed of 500 rpm, aspect ratio of 25.4/3 and processing time of 60 sec. On other hand, compressive strength is low at experiment with conditions: rotational speed, aspect ratio and processing time of 500 rpm, 25.4/7 and 45 sec, respectively.

4.4 S/N ratio of compressive strength

From Table 8, it is clearly observed that experimental run 7, with processing condition: rotational speed, pre-compact aspect ratio and processing time of 500 rpm, 25.4/3 and 60 sec, respectively provided the highest S/N ratio (42.30) and the least was observed at experimental run 9. In addition, Table 9 shows the ranks of the significance of each parameters on compressive strength with pre-compact aspect ratio takes the first and processing time the last.

Table 7 Confirmation experiment results of hardness

Exp. no.	Aspect ratio	Speed (rpm)	Time (s)	Mean
1	25.4/3	500	60	53.2

Table 8 Compressive strength of solid disc in MPa

No.	Speed (rpm)	Aspect Ratio	Time (sec)	Mean	S/N
1	315	25.4/3	30	123.39	41.79
2	315	25.4/5	45	118.35	41.46
3	315	25.4/7	60	115.41	41.24
4	400	25.4/3	45	127.72	42.12
5	400	25.4/5	60	120.42	41.61
6	400	25.4/7	30	112.47	41.01
7	500	25.4/3	60	130.44	42.30
8	500	25.4/5	30	128.89	42.20
9	500	25.4/7	45	110.42	40.86

Table 9 S/N ratios for compressive strength (Larger is the Better)

Level	Rotational speed (rpm)	Aspect ratio	Processing time (sec)
1	41.50	42.07	41.62
2	41.58	41.76	41.48
3	41.79	41.03	41.72
Delta	0.29	1.04	0.23
Rank	2	1	3

Table 10 Confirmation test for compressive strength

Exp. No.	Speed (rpm)	Pre-compact aspect ratio	Time (sec)	Mean	S/N ratio
1	500	25.4/3	60	130.64	42.45

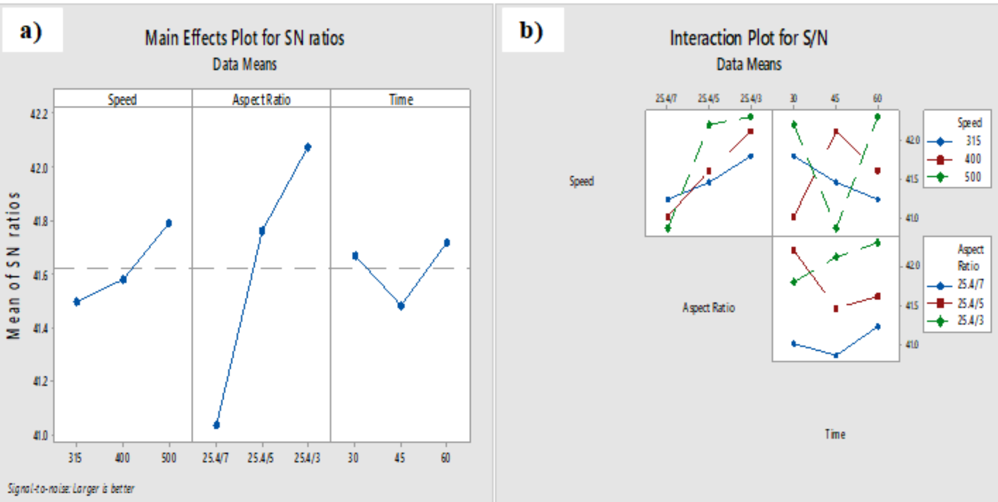


Figure 10. a) Main effect plot for S/N ratio, b) Interaction effect plot for S/N ratio of compressive strength

Main effect and interaction effect plots for S/N ratios of compressive strength are presented in Figures 10 a & b, respectively. Pre-compact aspect ratio and die rotational speed have a positive effect on the compressive strength while the processing time has less significance. Further, pre-compact aspect ratio increases the compressive strength of the consolidated disc. This is due to the fact that heat can easily be transfer from the top surface of the disc to the remote areas of the disc and strong inter-chip bonding maintained at the bottom surface of the disc. When the rotational speed increases, the compressive strength of the consolidated disc also increases. The compressive strength of the consolidated disc is increased at processing time of 60 sec and 30 sec, but minimum at 45 sec and this is due to the condition that at higher consolidation time, sufficient heat can be generated. This heat results in elements of chips at the remote areas of the disc to be consolidated. The stronger the weldment of chips the better the compressive strength. In addition, the main and interaction effects of factors were evaluated and depicted in figure 10.

The optimum parameter combination predicted by main effect plot for S/N ratios is at the rotational speed, aspect ratio and processing time of 500 rpm, 25.4/3 and 60 sec, respectively. Similarly, the effect of input parameters on the compressive strength was evaluated using ANOVA. The result shows that all the three factors are statistically significant. From the interaction effects of factors, it can be also noted that the influence of processing time versus rotational speed on the compressive strength is highly interrelated and comparable.

4.5 Confirmation test for compressive strength of solid disc

The confirmation test was performed with optimal settings of the factors and levels mainly aspect ratio of 25.4/3, rotational speed of 500 rpm and processing time of 60 sec. Table 10 shows the results of confirmation test.

The result shows that mean compressive strength is 130.64 MPa and S/N ratio is calculated to be 42.45 which show that optimal condition is reliable and consistent. In general, the optimum combinations of control factors for compressive strength and hardness are found to be rotational speed of 500 rpm, pre-compact aspect ratio of 25.4/3 and processing time of 60 sec. In general, the compressive strength and hardness of the FSC disc obtained in this research are comparable to that of forged or cast solid disc presented in [16], but the performance of the FSC solid disc can be further enhanced by conducting FSC process at warm and/or hot condition which will be one of the future research areas.

5. Microstructural Characteristics

In general, the mechanical properties of materials mainly depend on the microstructural characteristics, particularly grain size. The disc fabricated using FSC process at optimal set up of pre-compact aspect ratio of 25.4/3, die rotational speed of 500 rpm and processing time of 60 sec was cross-sectioned axially and radially to examine its microstructure details. Figures 11a & b show the microstructure observed for solid disc cross sectioned in axially and radially direction, respectively. The grain size was determined using ASTM E112 -13 standard line intercept method, and it is found that the average grain size for axial cross-sectioned disc was 12.4 μm while for radial cross sectioned disc was 12.7 μm. The grain sizes along both cross sections show refinement, and this is due to the existence of severe plastic deformation during processing and the effect gets higher at optimal FSC set up (higher die rotational speed and pre-compact aspect ratio and longer processing time). Small grain size can increase the number of grain boundaries which can act as a barrier for dislocation motion during deformation and hence, the material get stronger and harder. The grain size of the solid disk is finer in its axial cross section as compared to radial cross section. Moreover, the center of the disc shows fully recrystallized equiaxed grains whereas the peripheral area contains non recrystallized grains elongated in the circumferential direction.

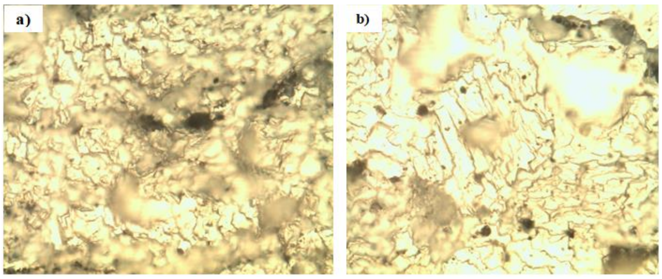


Figure 11. Microstructure of FSC disc cross sectioned in a) radial and, b) axial direction.

5. Conclusion

Solid discs from aluminum AA5052 alloy machining chips were successfully fabricated through FSC process using dedicated tooling. The results namely hardness, compressive strength and microstructural characteristics reveal that the specific material is clearly consolidable and effectively processed into a useful product through FSC technique. Moreover, design of experiment was employed to determine the optimum FSC processing set up to fabricate a solid disc with acceptable performance characteristics of compressive strength and hardness. Based on post-analysis of experimental data, and consolidated discs, the following conclusions are drawn:

1) The dedicated FSC process of metal machining chips involves two distinct stages: chip

compaction and consolidation. In the compaction stage, the material is easily compressed with very low level of chip consolidation. In the second stage, consolidation, the material further densifies because of the better bonding of chips due to severe plastic deformation and heat generation because of metal-metal particle interaction.

2) With a combination of generated heat and severe plastic deformation, chip consolidation was formed at the tip of chip charge as the process progresses. Better consolidation was observed near to the interface between die tool and the metal over the central region of the specimen due to increased frictional force which generates more heat.

3) Increase in the values of pre-compact aspect ratio, consolidating time and die rotational speed increases the performance of the solid disc in terms of compressive strength and hardness due to grain refinement caused by large amount of plastic deformation and heat generation.

4) The optimal FSC process set up for better performance of the disc was found to be pre-compact aspect ratio of 25.4/3, die rotational speed of 500 rpm, and processing time of 60 sec, and it was verified by conducting confirmation tests.

The microstructural characteristics provided more refined grains in the axial direction over radial direction on the cross sectioned specimens. Moreover, the grains are nearly fully recrystallized at center while non-recrystallized and elongated grains were observed at the periphery of the disc.

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Acknowledgement

The Authors would like to thank Adama Science & Technology University for providing access to the research facilities to conduct the experimental work.

Conflict of interest

The Authors has no conflicts of interest to declare that they are relevant to the content of this article.

Does this article screened for similarity?

Yes

Authors' Contributions

Mr. Samuel Kefyalew conducted the experiments, collected data and contributed in writing the manuscript while Desalegn Wogaso (PhD) supervised and contributed in developing the manuscript. All authors read and approved the final manuscript.