Friction Stir Consolidation of Aluminum AA5052 Alloy Machining Wastes

Samuel Kefeyalew Abebe
Adama Science and Technology University
Desalegn Wogaso Wolla (desalegnalem@gmail.com)
Addis Ababa Institute of Technology https://orcid.org/0000-0002-0476-656X

Original Article

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

Posted Date: October 12th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-961579/v1

Friction Stir Consolidation of Aluminum AA5052 Alloy Machining Wastes

Samuel Kefyalew[a], Desalegn Wogaso Wolla[b, *]

[a] Department of Mechanical Engineering, Adama Science & Technology University, Adama, Ethiopia.

[b] School of Mechanical and Industrial Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia, 385.

[*]Corresponding author's email: desalegnalem@gmail.com or desalegnnitw@gmail.com

Abstract

The purpose of this paper is to develop aluminum AA5052 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 for better performance characteristics. At first, the required dedicated tooling are designed and built for the specific process. Then, the solid discs are fabricated from aluminum AA5052 alloy machining chips through FSC process in which the experimental parameters 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). Based on the experiment, the compressive strength, hardness and microstructure of the consolidated solid disc are evaluated. Taguchi's L_9 orthogonal array is used to analyze and optimize the process. The results revealed that solid disc is successfully fabricated using FSC process using dedicated tooling, and rotational speed (500 rpm), compact aspect ratio (25.4/3) and processing time (60 sec) are optimal FSC processing conditions. The microsturcture of the solid disk shows finer and fully recrystallized grains in axial cross section orientation of the disc particularly in the central region. Moreover, the results show, the 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 method that adjusts the mechanical properties and microstructure of the material in a single pass to attain maximum performance with less manufacturing cost and time using cheaper and simple tool. It uses a non-consumable rotating die to create frictional heat and plastic deformation resulting in particulate bonding and microstructural modification. Originally, FSC was developed for processing of aluminum and magnesium based structural alloys because of their lower melting point and high application. Among the light weight structural metals, aluminum and its alloys have got much attention as important materials in construction, automobile, and aerospace industries because of their high strength-to-weight ratio and good formability. In addition, these alloys are preferable for engineering applications because of their excellent physical properties such as high specific strength, low density, high specific stiffness, high thermal conductivity, and good manufacturability for machining and casting.

Manufacturing operation namely, traditional machining and metal cutting usually produce considerable amounts of metallic wastes in the form of scraps or chips [1]. There are two primary techniques of recycling of non-ferrous metals (i.e. aluminum and its alloys) machining chips to get a useful product: the so-called 'conventional' technique and the direct conversion technique [2-3]. The conventional methods require melting of the material to be recycled and hot extrusion of the billet to form the final 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 reach 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 creation of thick oxide skin 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 researchers. It can minimize cost of energy consumption and environmental protection as compared to the conventional recycling. In addition, significant amount of carbon footprint also can be cut down. 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 shows that demand for energy in secondary aluminum processing through re-melting is increased significantly. Although there have been several perfect efforts to improve energy efficiency of melting furnaces since the 1980s, however, the energy requirement for secondary aluminum production can still go up to 20 GJ/ton depending on the way of production facilities, aluminum scrap and processes [9]. Thus, conventional recycling technique is considered as unfavorable due to a significant metal and energy losses. For instance, conventional recycling of aluminum turnings caused to approximately 45% losses in the metal [9]. These losses result in increase of labor cost, expenditures and energy without undermining its negative effect on the environment. The direct recycling of aluminum and its alloy involves minimum intermediate processing steps and suitable of improving products performance characteristics with better recovery efficiency [9].

Among the direct recycling techniques, friction stir welding (FSW) and friction stir processing (FSP) are solid phase or solid state processes for joining and microstructure modification, respectively. Both of them depend on plastic dissipation for heat creation or generation, and may be taken as severe plastic deformation processes (SPD). FSW was patented by the Welding Institute, UK, in 1991 [10]. In both technologies, a rotating non-consumable tool, processing and welding, is used to generate a plasticized surface which undergoes heating and severe plastic deformation. In general, FSP results in finer grains in the processed zone due to the application of temperature and sever plastic deformation.

Generally, nowadays, during manufacturing of aluminium and its alloy components, much of the original material is rejected as a waste in the form of scraps or metal chips. These machining chips are not convenient to recycle it using conventional techniques like 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 provides better material yield and have lesser processing steps. Recently, a potential alternative has emerged which is friction stir consolidation. FSC is also preferable due to its environmentally friendliness, minimum number of defects and wastages over conventional techniques. Therefore, this paper 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 in the present investigation was aluminum AA5052 alloy machining chips with an average thickness of 76 μm and its standard chemical composition according to ASTM is given in Table 1. AA5052 alloy is a common aluminum alloy with medium strength and usually used in a wide variety of structures like in boat hulls, gangplanks, and other products exposed to marine environments [11].

Table 1 Standard chemical composition limits 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

Machining chips with uniform size as precursors and 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 8mm diameter solid block.

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

where t_c 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 linear speed (feed rate) of the workpiece. The machining parameters adopted to prepare chips with t_c = 76μm average thickness are presented in Table 2. The actual thicknesses of the machined chips were measured using a microscope, and the obtained average value was 75.8μm with 8.3μm as standard deviation. The photograph of machining chips prepared using the recommended machining parameters is shown in Figure 1.

Table 2 The machining parameters used for 76μm thick 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

Dedicated tooling for the experiment 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 were used to consolidate and plasticize machining chips to produce pre-compact disks. The aspect ratio (height to diameter) of pre-compacts 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 machined 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, through adjusting the applied consolidation load. 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.

Figure 2. Pre-compact discs of AA5052 alloy machining chip

The general experimental configuration of FSC is shown in Figure 3. A conventional milling machine was used for the experiment.
A consolidation chamber with the dimension of 25.4 mm in diameter and 50 mm in height was used with metallic insert of 25.38 diameter and height of 30 mm which is used as a support for the bottom side of pre-compact discs. The latter component is also used to provide space for locating the pressure gauge. Moreover, a chamber holder fixture with the dimension of 300 mm x 200 mm was used to fix the chamber and maintain the center position of the rotating die.

Figure 3. Experimental set up for FSC process

The chamber holding fixture was drilled at the midpoint to allow physical contact for pressure gauge and insert which creates easiness to measure the applied load. The whole set of tooling used for FSC set up is shown in Figure 4.

Figure 4. Photographs of tooling used for FSC process

In the experiment, the applied consolidation load was measured using DTZH pressure gauge (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].

$$P = \frac{F}{A} \tag{2}$$

where F is applied force which is 27 kN, A is area of the pressure gauge`s piston which is equal to 900mm$^2$ and $P$ is the pressure gauge`s reading (3 MPa).

Figure 5. The DTZH pressure gauge for controlling applied force

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

Figure 6. A consolidated disc specimen with a) Horizontal cross-section and b) Vertical cross section

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

Figure 7. FSC disc specimens for microstructure analysis

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 technique 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. Factors are independent variables that are expected to affect the response variable whereas levels are the quantitative or qualitative settings which will be tested and one of the main disadvantages is that the optimum combination of process parameters and levels may not be available in the orthogonal array (OA); therefore, it requires additional experimentation for verification. One of the important steps involved in Taguchi's technique is selection of orthogonal array which will further help to conduct experiments to determine the optimum level for each process parameters and establish the relative importance of individual process parameters. An OA is a small set from all possibilities which helps to determine least number of experiments. 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. Further, one of the most disadvantage of Taguchi`s method is that the optimum combination of the process parameters may not be available in the list of OA. Therefore, additional experiments for verification are required. 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.

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

The suitable orthogonal array for the specific experimentation is L_9 array 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. The response variables namely compressive strength and hardness values were determined using mechanical tests.

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

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 or filing. 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.

Figure 8. FSC solid discs with different aspect ratios

Table 5 shows the mean Vickers hardness values of solid discs made under different experimental conditions, and the corresponding calculated S/N ratios (using Equation 3). The hardness values are mean values of three recorded readings of the experimental trails. 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 of higher the better was considered for this analysis.

$$S/_{N}\ ratio = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{{y_u}^2} \tag{3}$$

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

Table 5 Hardness test results 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

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 value (400 rpm) provided higher 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 hardness values. Table 6 also depicts rank of influence of each factor on the hardness and it can be observed 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.

Table 6 Response values for Signal to Noise Ratio (Larger is Better)

Level	Pre-compact aspect ratio	Die rotational speed (rpm)	Time (s)
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**

Figures 9a & b depict the plots of main effect and interaction effect of S/N ratio for different experimental conditions with hardness as required 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.

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

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 60s, respectively. In addition, from the interaction plots, S/N ratio is lowest at processing time of 30 seconds with pre-compact aspect ratio of 25.4/7, and S/N ratio is highest at processing time of 60s with aspect ratio of 25.4/3. When the aspect ratio increases, the hardness gets better. The result of main effect plots and interaction effect plots for S/N ratios provides 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 contribution values 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 conditions are set for the significant factors and a selected number of experiments are run under specified FSC conditions. 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. The final step of the DOE is the confirmation test, which verifies if the optimum conditions suggested by the matrix experiment do indeed give the improvement projected. The verification experiment is performed by conducting test with optimal setting of factors and levels previously evaluated i.e. 25.4/3, 500 rpm and 60s of aspect ratio, rotational speed and processing time, respectively, in three trials.

Table 7 Confirmation experiment result of hardness

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

Experimental result, depicted in Table 7, indicates that during FSC processing of AA5052 alloy, use of high 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 ratio was obtained to be 53.2 and 34.52 respectively. These values show that the optimum parameter set up is optimum and consistent.

4.3. Compressive Strength of the FSC Solid Disc

Compressive strength test results (mean of trials) 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 60s. On other hand, compressive strength is lowest at experiment with conditions: rotational speed, aspect ratio and processing time of 500rpm, 25.4/7 and 45s, respectively.

Table 8 Compressive strength of solid disc in MPa

No.	Speed	Aspect Ratio	Time	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

4.4. S/N ratio of Compressive strength

Mainly, the main effects is taken from plot of S/N ratios and confirmed by plot of mean because main effect plot for means predicts the compressive strength based on the raw data without considering maximizing the results. 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 60s, 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 9 S/N ratios for compressive strength (Larger is Better)

Level	Rotational speed (rpm)	Aspect ratio	Processing time (s)
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

Main effect and interaction effect plots for S/N ratios of compressive strength are presented in Figures 10 a & b. Pre-compact aspect ratio and die rotational speed have a positive significant 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 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 speed increases, the compressive strength of the consolidated disc also increases. The compressive strength of the consolidated disc increases at time of 60 seconds and 30 seconds but minimum at time 45 seconds and it is due to the condition that at higher consolidation time, sufficient heat will be produced. This heat results in elements of chips at the remote areas of the disc. The stronger the weldment of chip results in increased compressive strength.

The interaction of speed and aspect ratio is analyzed as: at speed of 315 rpm the compressive strength is maximum, medium and minimum at aspect ratios of 25.4/3, 25.4/5 and 25.4/7 respectively. When the speed is 400 rpm the compressive strength is maximum, medium and minimum at aspect ratios of 25.4/3, 25.4/5 and 25.4/7 respectively. At speed of 500 rpm the compressive strength is maximum, medium and minimum at aspect ratios of 25.4/3, 25.4/5 and 25.3/7 respectively. According to the main effect plot for S/N ratio, the optimum set up of three levels and the three factors are determined.

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

The optimum parameter combination predicted by main effect plot for S/N ratios is at the rotational speed, aspect ratio and processing time at 500 rpm, 25.4/3 and 60s respectively.

Similarly, the effect of input parameters on the compressive strength was evaluated using ANOVA. The result shows that all the three process variables; namely, die rotational speed, pre-compact aspect ratio and processing time are statistically significant. From the interaction effects of input process parameters on the compressive strength, it can be also noted that the influence of time versus speed on the compressive strength is highly interrelated and comparable. The higher the speed does not have a significant influence on the improved compressive strength as long as it is possible to fabricate a disc having improved compressive strength with speed of 400 rpm and time 55 seconds. It can also be pointed out that at higher rational speed, compressive strength is better.

4.5. Confirmation Test for Compressive Strength of Sold Disc

The verification experiment is performed by conducting confirmation test with optimal settings of the factors and levels. The confirmation experiments were conducted by adjusting the optimum set ups: aspect ratio of 25.4/3, rotational speed of 500rpm and processing time of 60s in three experimental trials. Table 10 shows the results of confirmation experiment for compressive strength.

Table 10 Verification experiment result on hardness response

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

Verification experimentation result shows that mean compressive strength is 130.64 MPa and signal to noise ratio is calculated to be 42.45 which shows the optimal result is reliable and consistent. In general, the optimum combinations of control factors for compressive strength and hardness are rotational speed of 500 rpm, pre-compact aspect ratio of 25.4/3 and processing time of 60s. In general, the compressive strength and hardness of the FSC disc is comparable to that of forged or cast solid dics as revealed in [16] but it can be further improved using conducting FSC at hot condition which will be one of the area to be research in the future.

4.6. 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 FSC condition of pre-compact aspect ratio of 25.4/3, die rotational speed of 500 rpm and processing time of 60s was cross-sectioned axially and radially to examine its microstructure details. Figures 1a & b show the microstructure observed in the FSC solid disc cross sectioned in axially and radially orientation, respectively. The grain size was determined using ASTM E112 -13 standards, line intercept method, and it is found that the average grain diameter for axial cross-sectioned disc was $12.4\mu m$ while for radial cross sectioned disc was $12.7\mu m$. The grain sizes along both cross sections show refinement, and this is due to the occurrence 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). Smaller grain size increases the number of grain boundaries which ac as a barrier for dislocation motion during deformation and hence, the material get stronger and harder. The grain size of the disk is finer in its axial cross section as compared to its radial cross section orientation. 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 orientation

5. Conclusion

Solid discs from aluminum AA5052 alloy machining chips were successfully fabricated through FSC process. 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 process. Moreover, design of experiment was employed to determine the optimum FSC processing set up to fabricate a solid disk 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 consolidation 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 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 60s, and it was verified by conducting confirmation tests.
5) The microsturcural characteristics provided more refined grains in the axial orientation cross section over radial orientation. Moreover, the grains are nearly fully recrystalized at center while non-recrystalized and elongated grains were observed at the periphery of the disc.

Declarations:

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

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this research paper.

Available of Data and Materials

All experimental data used in this study are openly available in the library data center of Adama Science and Technology University, Adama, Ethiopia, active archive center at URL: http://localhost:8080/xmlui/handle/123456789/1063 as cited in Samuel K. et al. (2018).

Funding
Not applicable.

Authors' Contributions
Mr. Samuel Kefyalew conducted the experiments and collected data in the laboratories while Desalegn Wogaso (PhD) analyzed, interpreted and was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

Authors' Information
Samuel Kefeyalew is currently graduated with M.Sc degree from Adama Science and Technology, Adama, Ethiopia. His research field is on developing manufacturing processes and characterization of material's properties.

Desalegn Wogaso holds a PhD degree in Mechanical Engineering with Manufacturing Engineering specialization in 2015, and currently has been working as assistant professor in Addis Ababa Institute of Technology, Addis Ababa University. His research concerns are development of advanced materials, processes and technologies for the applications of 21th century industries. He has passionately working and desire to engage on research focusing on advanced materials, modeling and simulation of advanced manufacturing processes, functionally graded materials, and nanomaterials.

References

[1] Jovane, F., Yoshikawa, H., Alting, L., Boër, C.R., Westkamper, E., & Williams, D. (2008). The Incoming Global Technological and IndustrialRevolution Towards Competitive Sustainable Manufacturing. Cirp Annals. Manuf. Technol., 57(2), 641–659.

[2] Tekkaya, Ae., Schikorra, M., Becker, D., Biermann, D., Hammer, N., & Pantke, K.(2009). Hot Profile Extrusion of Aa-6060 Aluminum Chips."Journal of Materials Processing Technology. 209, 3343-50.

[3] Tang, W., & Reynolds, A. (2019). Production of wire via friction extrusion of aluminum alloy machining chips. Journal of Materials Processing Technology. 210 (15), 2231-2237.

[4] Gutowski, T.G., Allwood, J.M., Herrmann, C., & Sahni. S. (2013). Use, Carbon Emissions, and the Potential for Energy Efficiency and Materials Recycling. Annu. Rev. Environ. Resour., 38(1), 81- 106.

[5] Hanko, G., Antrekowitsch, & H., Ebner. (2002). Recycling automotive magnesium scrap. JOM, 54(2), 51–54.

[6] M. Stern. (1945). Method for treating aluminum or aluminum alloy scrap, Google patents. United States Patent office, N.Y. Serial No. 445, p. 190.

[7] Gronostajski, J., & Matuszak, A. (1999). The recycling of metals by plastic deformation: an example of recycling of aluminium and its alloys chips. Journal of Materials Processing Technology, 92, 35-41.

[8] Gronostajski, J., Marciniak, H., & Matuszak, A. (2000). New methods of aluminium and aluminium-alloy chips recycling. Journal of Materials Processing Technology, 106(1-3), 34-39.

[9] Shamsudin, S., Lajis, M. A., & Zhong, Z. W. (2016). Evolutionary in solid state recycling techniques of aluminium: a review. Procedia CIRP, 40, 256-261.

[10] Thomas, W. M., Nicholas, E. D., & Jones, S. B. (1993). Friction extrusion. Metal Working. Google Patents, https://www.google. com/patents/US5262123, Google Scholar.

[11] Oberg, E., Jones, F. D., Horton, H. L., Ryffel, H. H., & Geronimo, J. H. (2016). Machinery's Handbook. Industrial Press, Incorporated, 1207-1209.

[12] ASTM B 209. (1996). Standards Specification for Aluminum and Aluminum - Alloy Sheet and Plate. ASTM International. Designation: B 209-96, PA 19428-2959.

[13] Li, X., Baffari, D., & Reynolds, A. P. (2018). Frictions stir consolidation of aluminum machining chips. The International Journal of Advanced Manufacturing Technology, 94(5-8), 2031-42.

[14] Shigley, J. E. (2011). Shigley's Mechanical Engineering Design. Tata McGraw-Hill Education.

[15] Ross, P. J., & Ross, P. J. (1998). Taguchi techniques for quality engineering: loss function, orthogonal experiments, parameter and tolerance design. New York: McGraw-Hill, No. TS156 R12.

[16] Abhijeet Bhowmik & Dilip Mishra.(2016). A Comprehensive Study of an Aluminum Alloy AL-5052. Advance Physics Letter, 3(1), 20-22.

Figures

Figure 1

AA5052 alloy machining chips

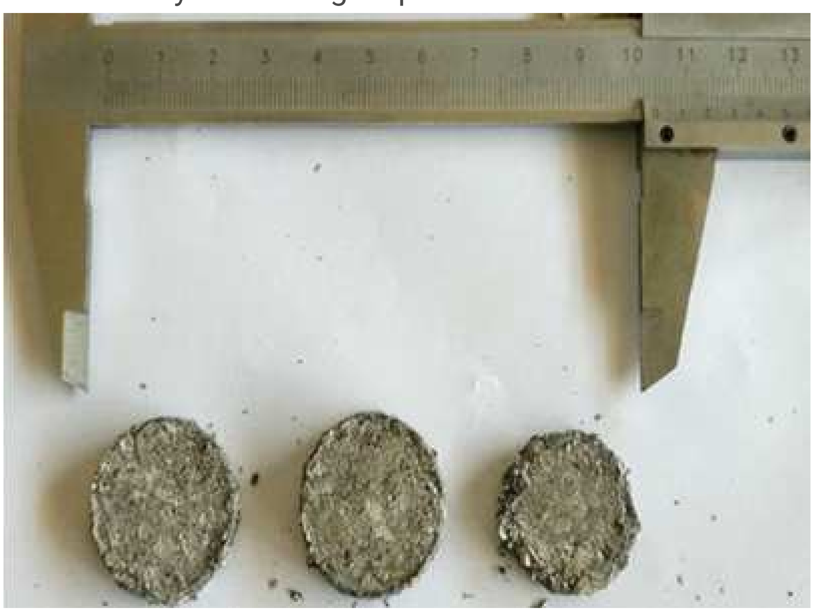

Figure 2

Pre-compact discs of AA5052 alloy machining chip

Figure 3

Experimental set up for FSC process

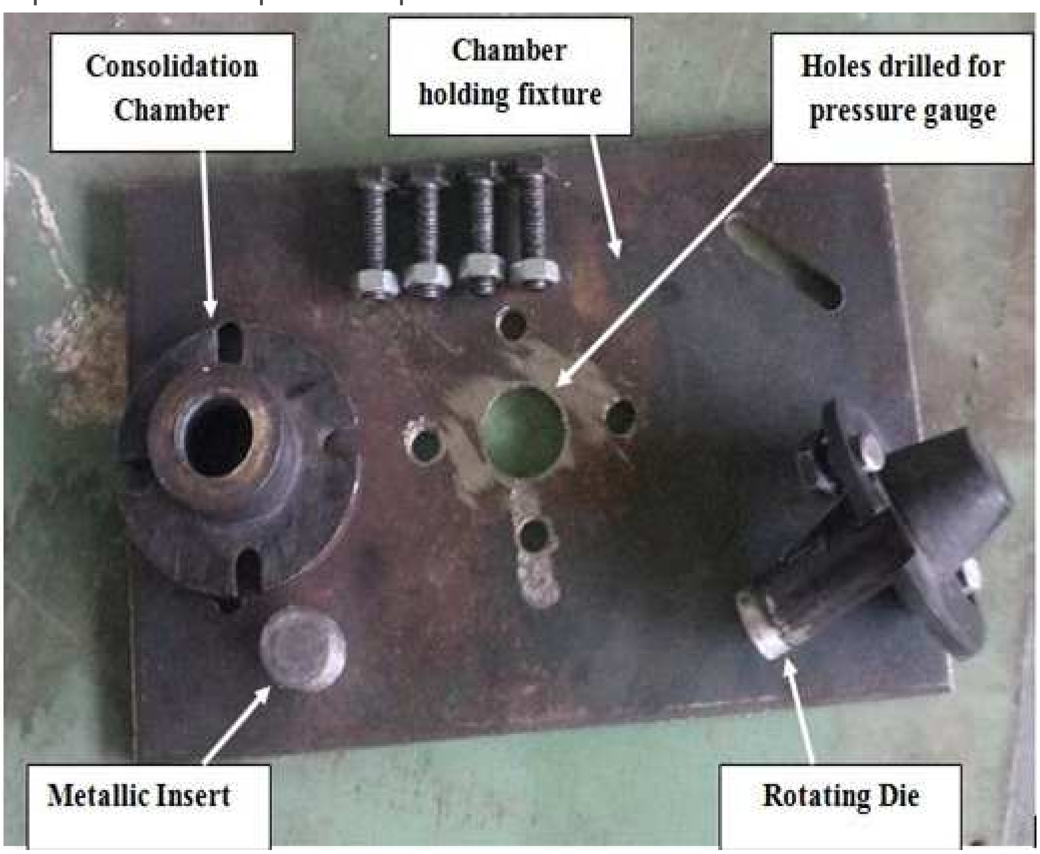

Figure 4

Photographs of tooling used for FSC process

Figure 5

The DTZH pressure gauge for controlling applied force

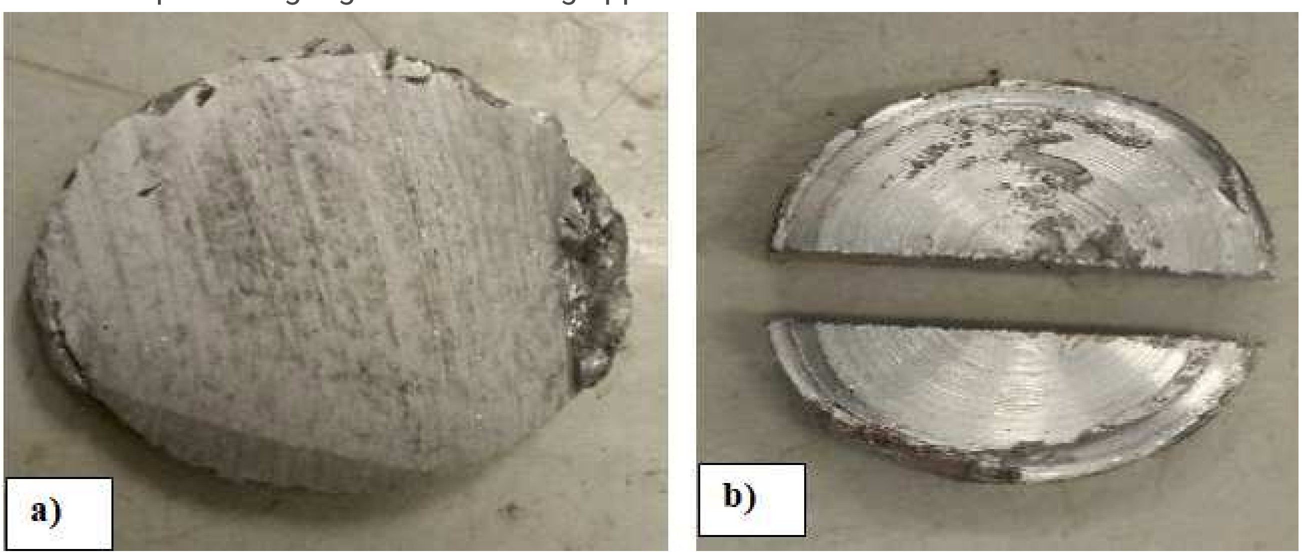

Figure 6

A consolidated disc specimen with a) Horizontal cross-section and b) Vertical cross section

Figure 7

FSC disc specimens for microstructure analysis

Figure 8

FSC solid discs with different aspect ratios

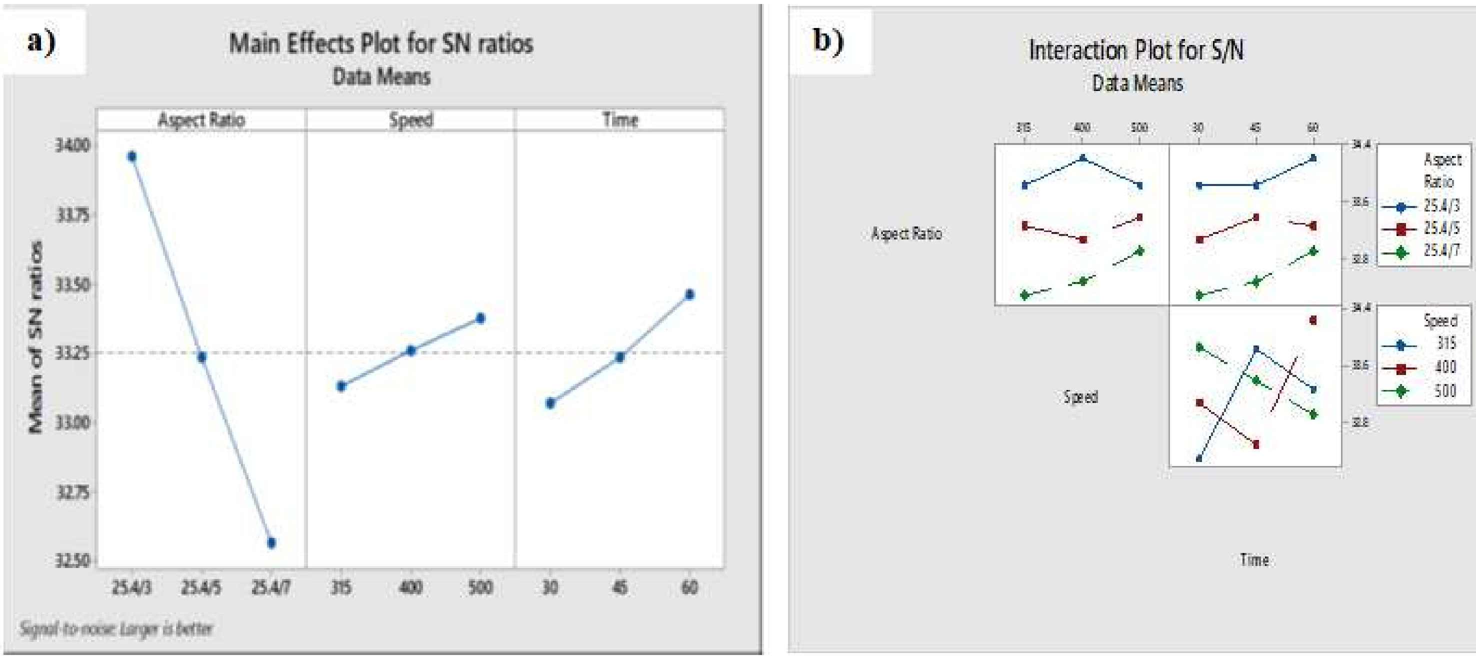

Figure 9

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

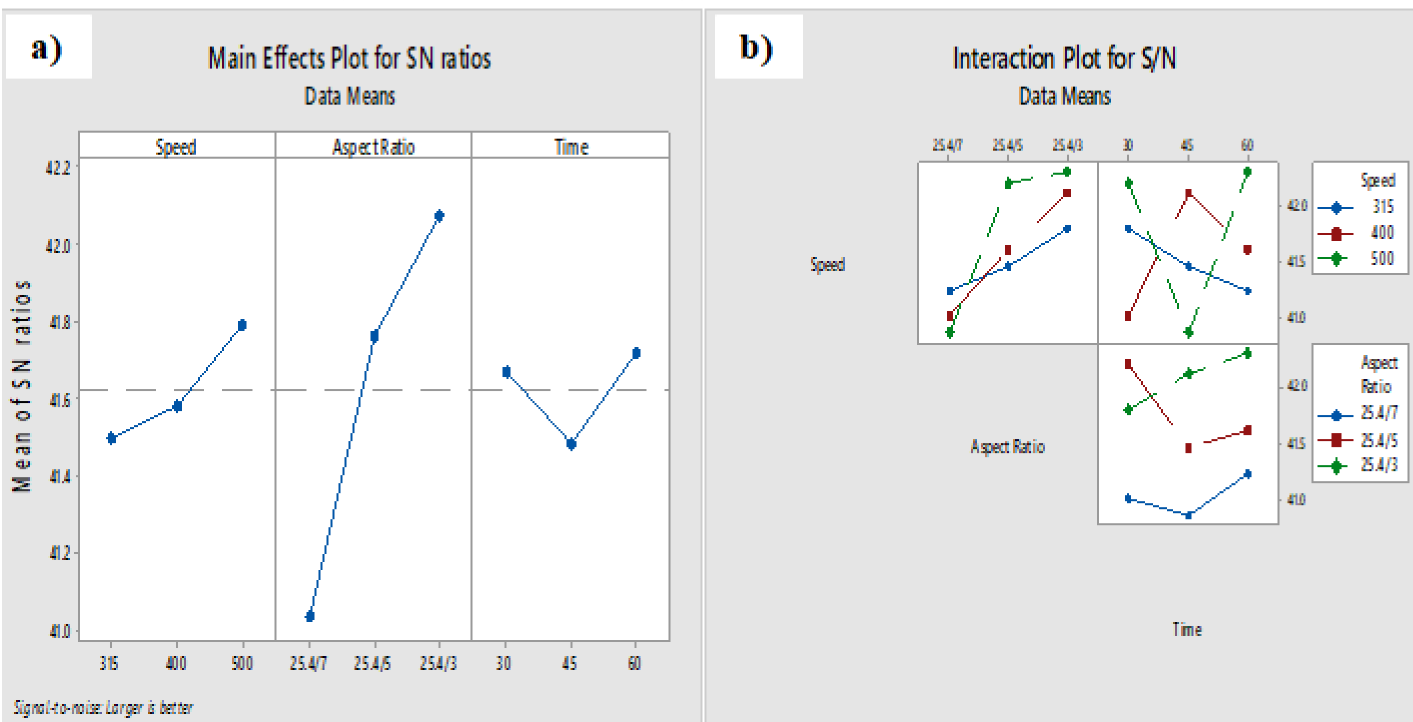

Figure 10

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

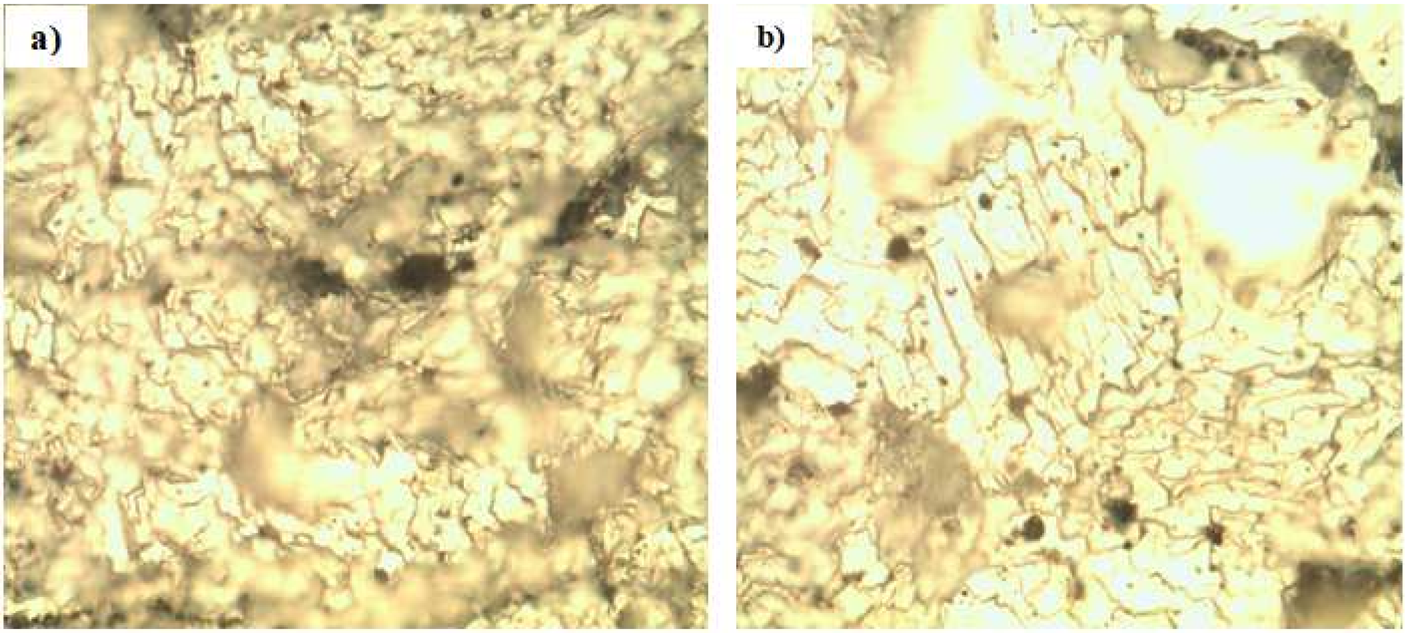

Figure 11

Microstructure of FSC disc cross sectioned in a) radial and, b) axial orientation