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RESEARCH ARTICLE - ENGINEERING

Disc Forming by Friction Stir Consolidation of AA2024 Chips

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Abstract

This work aims to form a disc by recycling AA2024 chips using friction stir consolidation (FSC) technique. Initially, the chips were compacted inside a chamber by an applied pressure of 20.7 MPa. Different chips weights and two process parameters were studied in the FSC process: pre-heating time and plunging depth of the tool. The process was carried out at 1400 RPM. Effect of the process parameters and chips weight on chips quality was analyzed by design of the experiments method. The discs formed with a fully consolidated (FC) volume fraction range of 14.5-22.4%. The plunging depth was the most effective factor on surface finishing and grain size of the discs, while the chips weight was the most effective factor on the FC volume. Increasing the chips weight and plunging depth increased the FC volume. The average grain size of the disks ranged between 6.3 to 11 µm.

Keywords: Friction Stir Consolidation; AA2024; Chips Recycling; Design of Experiments.

1. Introduction

Recycling of metals is used to reduce waste, pollution and consumption of wrought materials. Materials scrap recycling is classified into two methods: the conventional and direct method. The conventional method is carried out by re-melting the scarp, while the direct method involves recycling the scrap without re-melting [1]. The conventional method is carried out by multi-steps: cleaning, re-fining, re-melting the scrap, and casting it into the required die. Those steps requires a higher power and losses a higher amount of material, and involves a pollution of the environment by the oxidation during the re-melting process [2]. To reduce cost of materials recycling, maintain a friendly environment and prevent loss of material during the re-melting process, the direct recycling method was proposed in 1945 by Stern [3]. The direct method included using the extruding and compression of scrap or chips at moderate or room temperature [4]. Friction stir (FS) technique was used to recycling scraps as a solid state technique [5]. This technique was used to produce wires by friction stir extruding (FSE) method, and billets and discs by friction stir consolidation method.

FSE process was used to produce a full consolidated wire from aluminium alloy chips type AA2050 and AA2195. The produced wires contained cold and hot cracks. The microstructure examination indicated to presence of equiaxed and re-crystallized grains. The grain sizes increased with increasing rotating speed of die. The transverse cross-section of wire exhibited a homogenous micro-hardness [6]. Mg chips were recycled into wires by the FSE technique. Fine homogenous microstructure with good surface quality was observed in the produced Mg wires. The corrosion resistance of the produced wires is highly affected by the grain size [7]. Effect of extruded force, rotating speed of die and FSE process temperature on the extruded wires (from AA2050 chips) was studied. The results indicated that excessive extrusion force and rotating speed cause higher hot cracking and grain growth [8]. AZ31 chips were recycled into a wires using FSE. The results revealed that the extrusion rate increased with the extrusion force. The process temperature depended on the heat input and process time. Wire quality increased with decreasing the extrusion rate [9].

Nomenclature

AA	Aluminium Alloy	FSC	Friction Stir Consolidation
FSE	Friction Stir Extruding	FC	Fully Consolidated
FEM	Finite Element Model	PC	partially consolidated
HRC	Hardness Rockwell C	HSS	High-Speed Steel
DOE	Design of the Experiments	mm	Millimetre

The composite material concept was used to product a wire from AA2024 chips by recycling it using FSE. A silicon carbide powder was used as particles to reinforce solid state matrix of AA2024 chips during the process. Inter-granular conglomerate occurred by excessive amount of the powder which resulted in a non-homogenous mechanical properties of the extruded wires [10]. A continuous wire production by the FSE was achieved by [11] to overcome the discontinuity of extruded wire. The designed machine exhibited an acceptable wire quality. Chips of pure aluminium AA1090 was recycled by FSE. Initially, the chips were compacted with a suitable load (150kN), and then the compacted billets were extruded. The produced wires were of good surface quality, non- homogenous microstructure [12].
FSC method to produce billets from irregular pieces of pure aluminium AA1050 of sizes ranged from 5- 10 mm with a thickness of 1mm. The produced billets had a non-homogenous morphology. The hardness of upper surface of billets was higher than those of the base material, which decreased gradually toward lower surface of the billets [13]. AA6061 chips were recycled into discs by FSC. A fully consolidated zone was appeared like a bowl of a recrystallized equiaxed grain structure. This shape expanded under effect of increasing heat input, but not reach lower surface of the disc [14]. AA6061 chips of an average thickness of 76 µm were recycled into discs using the FSC method. In this study, a finite element model (FEM) was proposed to predict quality of the produced discs. Relative density, temperature and strain distribution of the proposed model exhibited an acceptable results [15]. However, analysing effect of process parameters and chips weight on formation of disc using FSC is an important criterion on disc quality. In this study, effect of plunging depth, pre-heating time and chips weight on the consolidated volume and microstructure of formed disc by recycling an aluminium alloy was studied.

2. The Process Details

2.1. Materials

Aluminium alloy AA2024 (Al-4.3Cu-1.2Mg-0.6Mn- 0.35Fe-0.17Si-0.15Zn) was used to produce chips from a plate of wrought material, as shown in Fig. 1. The chips were prepared by a milling machine with a feed rate of 0.5 mm/tooth and a cutting speed of 200mm/min. The produced chips were of an average size of 0.33mm thickness and 20mm length.

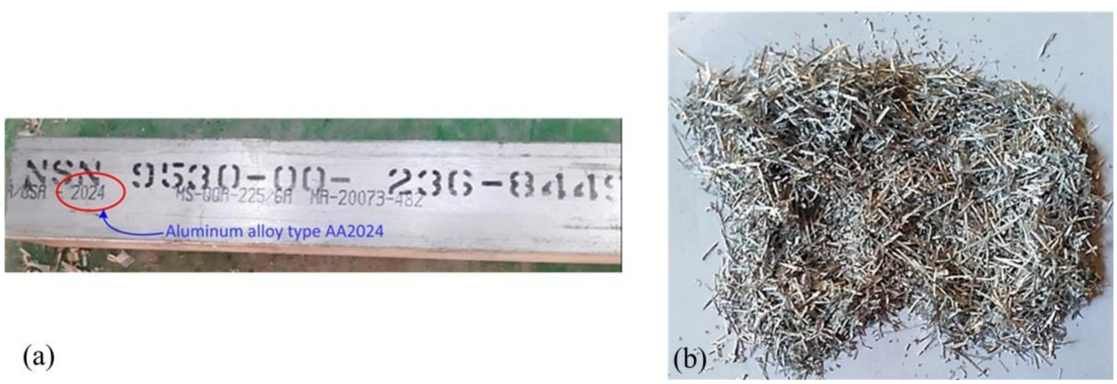

Fig 1. Aluminium alloy AA2024 (a) wrought material plate (b) chips

2.2. Apparatus

The FSC process was carried out with the aid of the following parts: backing plate, chamber die and tool, as shown in Fig. 2. A rotating tool of 25mm diameter was fabricated from high speed steel (HSS) material to overcome the higher heat input and applied pressure during recycling process. The tool was used to compact and stir chips inside a chamber. AISI H13 material of 50HRC hardness was selected to fabricate die of the chamber. Inner and outer diameters of the chamber were 50, 60 mm, respectively. The chamber was fixed on a backing plate.

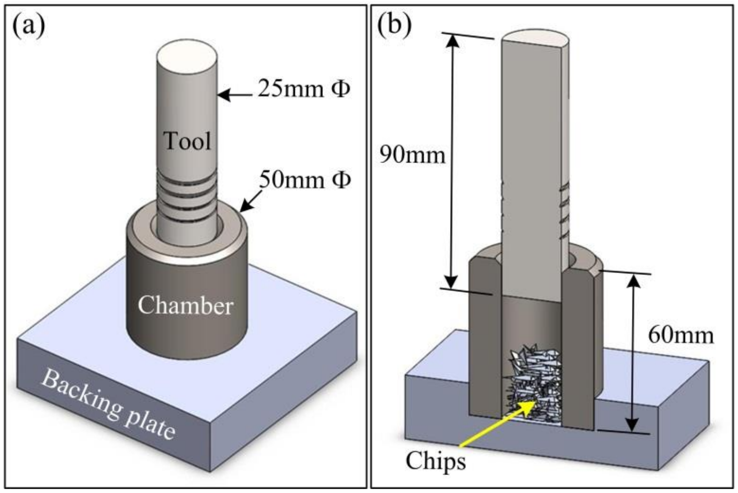

Fig 2. Schematic of apparatus (a) solid (b) cross-section

2.3. FSC process

The discs were carried out by two stages: the first stage was compact the chips, while the second stage was friction stir consolidation the compacted chips. The first stage involved filling the die container by the desired weight chips and pressing it using a suitable hydraulic system, as shown in Fig. 3a. The container die was fixed on the backing plate with a suitable fixture. The chips compacted with a pressure of 20.7 MPa (10.2 kN force) for a period time of 5 seconds. A sample of compacted chips (of 50 mm) diameter is shown in Fig. 3b.

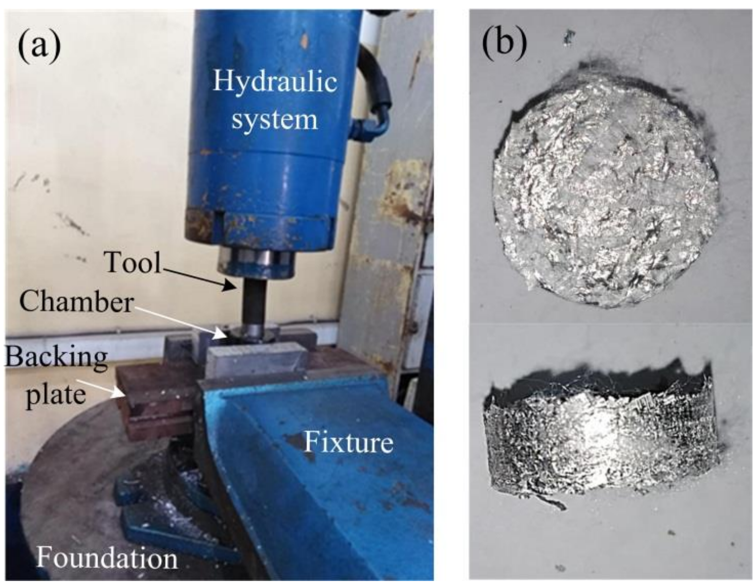

Fig 3. Chips pre-compact (a) compaction machine (b) compacted chips

In the second stage, the same die chamber, backing plate and tool was used to produce final shape of the discs from the compacted chips in the first stage. The FSC process involved fixing the die chamber (included the compact disc in the first stage) with the backing plate on base foundation of a vertical milling machine, as shown in Fig. 4. The tool was rotated and moved down (with desired values) until it touched upper surface of the compacted sample during a periodic time. In this step, the compacted sample was pre-heated and softened. In the second step, the rotated tool was moved inside the chamber with a desired plunged depth to press and stir the compacted disc. The rotation between lower surface of the tool and upper surface of the samples generates a frictional heating which softens the chips sample. Plunging the rotated tool inside the chamber presses the sample. So, combined action of the generated heat and applied load on the compacted sample stirred the softened chips by the rotated tool. At the end of this step, the rotating tool is withdrawn from the die chamber, and the process is terminated. After each experiment, the produced disc is carefully removed from the chamber. During the FSC process, the temperature was recorded by K-type thermocouple which inserted through wall of the die chamber. The temperature was recorded at end of the pre-heating time and consolidation process.

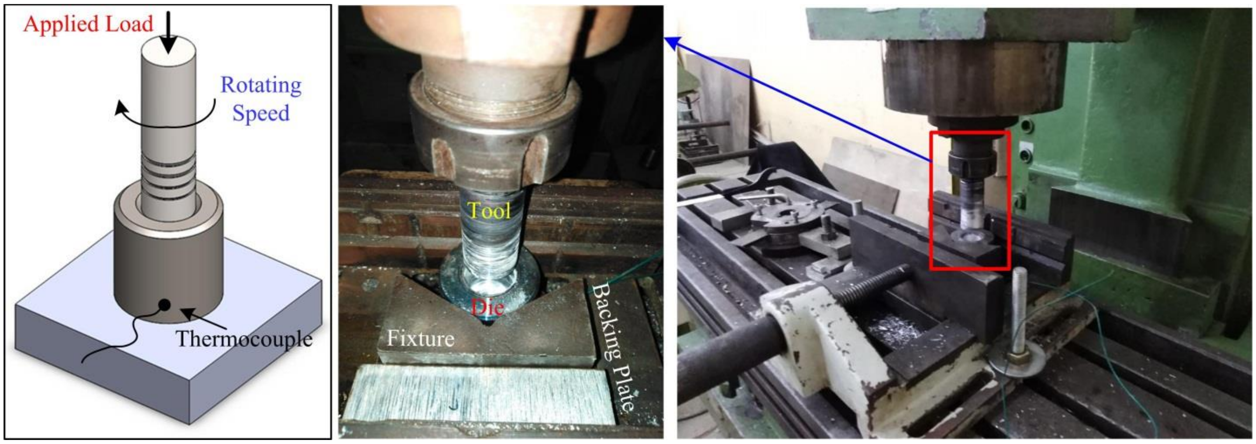

Fig 4. FSC process

2.4. Process parameters

Three process parameters were selected to study their effect on the disc quality: chips weight, pre-heating time and plunging depth of the tool, with four levels for each parameter. The samples were produced at a rotating speed of 1400 RPM. The experiments were designed according to the level of the parameters by the Minitab program using the design of the experiment method, as listed in Table 1.

Table 1 Parameters levels of FSC experiments

Experiment No.	1	2	3	4
Plunging Depth (5mm)	4	5	3	3.5
Pre-heating time (sec.)	30	45	60	75
Chips weight (gm.)	10	12	6	8

3. Results and Discussion

3.1. Formed discs

Fig. 5 shows the formed samples. Top surfaces of the formed indicated that the discs contained a tool trace with different shapes depending on the process parameters. The surface indicated that the chips stirred with thermal plastic deformation due to higher heat input. The sample No.2 revealed to a good surface finishing compared with the other sample. This can be consolidated to the fact that this sample was formed at a higher plunging depth (5mm) compared with the other samples. Increasing the plunging depth of the samples increased the applied pressure which increases the consolidation of the stirred chips. All samples exhibits formation of flash around the discs which can be considered as a loss. The samples 1 and 2 exhibited a good bottom surface finishing compared with the samples 3 and 4. The samples 1 and 2 were formed with a plunging depths more than those of the samples 3 and 4. So, the plunging depth of the tool had the highest effect on the surface finishing of the formed samples.

Fig 5. Formed samples

3.2. Fraction of consolidation

Increasing consolidation of chips of the formed shapes by the FSC is an important challenge [13]. The chips consolidation represents amount of the chips that formed through the sample volume without defect, or formed chips region with fully consolidation. The consolidation region depends on the process parameters that determine the homogeneity of the stirred chips through the volume of the formed sample. The fraction of consolidation is considered as the ratio of fully consolidated region to volume of the solid material [14]. Fig. 6 shows cross-section of the formed discs which polished until the consolidated regions are displayed. The first three samples cross section revealed that samples were formed without defects or cracks. The sample 4 were formed with a higher input heat (pre-heating time) which increase the thermal plastic deformations of chips grain and sheared the material layers.[14]. The samples cross-section revealed that the formed region divided into two main regions: fully and partially consolidated (FC and PC). The FC region lied at the top of the samples, while the PC region lied at the bottom of the samples. This is due to the fact that the heat input at the top of the sample is higher than those at the bottom of the samples. So, the region under the tool surface (which affected by a higher heat input) can be considered as the FC region. Volume of the FC region and PC depend on the process parameters. The PC volume can be reaches the minimum value, but not disappears. The samples formed with different process parameter, so it exhibited different volumes of the FC and PC.

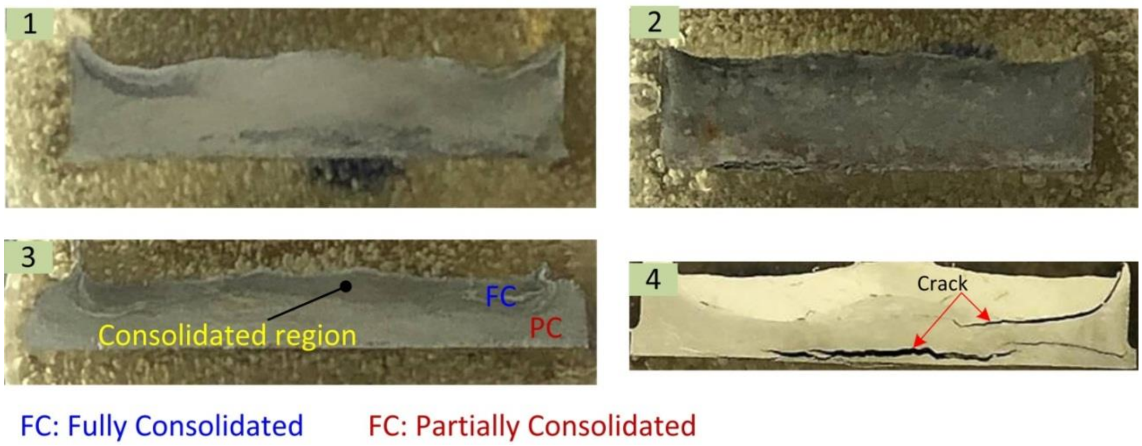

Fig 6. Discs cross-section

The fraction of consolidation is determined according to the following formula [14]:

$$\theta = V\rho_s/m_t \quad (1)$$

Where ρs is the density of the material (2.77 g/cm^3 for AA2024), m_t is mass of the chips, and V is the volume of FC region. The discs were formed with different mass (6, 8, 10, and 12 grams), so to determine the fraction of consolidation of each sample from the Eq.1, it requires evaluating the volume of the FC region. Four steps were considered to evaluate the *V*: assigning boundary of the FC region, assigning coordinate of the FC region boundary, evaluating function of FC region boundary, and evaluate the *V* by integrating the function of FC region. Sample 3 was selected to explain those steps, as shown in Fig. 7. In the first step, the cross-section image was rotated upside down. Y-axis was located at the centre of the FC region, while the x-axis was located at the upper surface of the disc (this surface was assumed as a flat surface). The boundary of the FC region was assigned by a dotted line, as shown in Figure 7a. The second step consisted of finding of coordinates of the FC region curve. Web plot digitizer software was used to locate number of points at the curve. This software calculates the coordinate of the located points (x_n, y_n), as shown in Fig. 7b. Grapher software was used to graph the points (x_n, y_n) with a continuous curve, as shown in Fig. 7c. Curve fitting of FC region boundaries indicated that the calculated coordinates were of a good accuracy. From the grapher software, the fitting equation of the curve was found. A polynomial function mode (with seven degree) was used to give a good fitting of the FC boundaries, as follows:

$$Y = 0.685 + 0.657X - 0.783X^2 + 0.327X^3 - 0.067X^4 + 0.007X^5 - 0.0004X^6 + 9.148*10^{-6} *X^7$$

Where: y is function describing the FC region boundaries. The calculated function was used to evaluate the FC volume (*V*) with the aid of Mathcad software. An element was selected at the FC region to evaluate the volume, as shown in Figure 7d, (*V*) according the following general mathematical equation of volume determination:

$$V = 2\pi \int_0^x xy\, dx$$

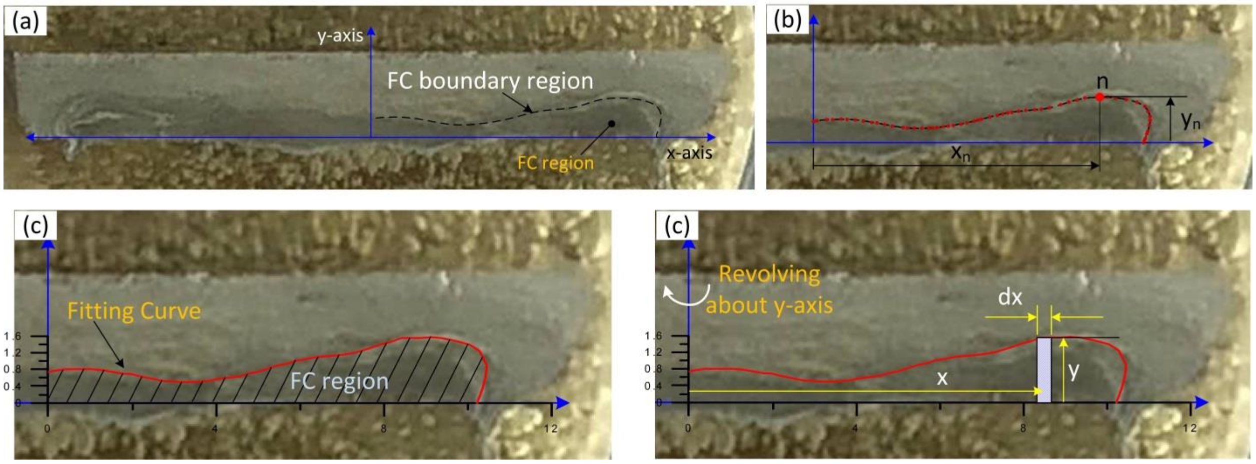

Fig 7. Calculation steps of fraction of consolidation, sample 3

Accordingly, the volume of the FC region of the samples was calculated. The volume of each sample was calculated by dividing its weight by the density of the material. The FC and sample volumes are plotted in Fig. 8a. The FC volume exhibited a minimum and maximum value of 360 and 706 mm^3 in the samples 4 and 1, respectively. Variation of FC and disc volume of the samples was the same. The fraction of consolidation reached a range of 14.5- 22.4%, as shown in Fig. 8b.

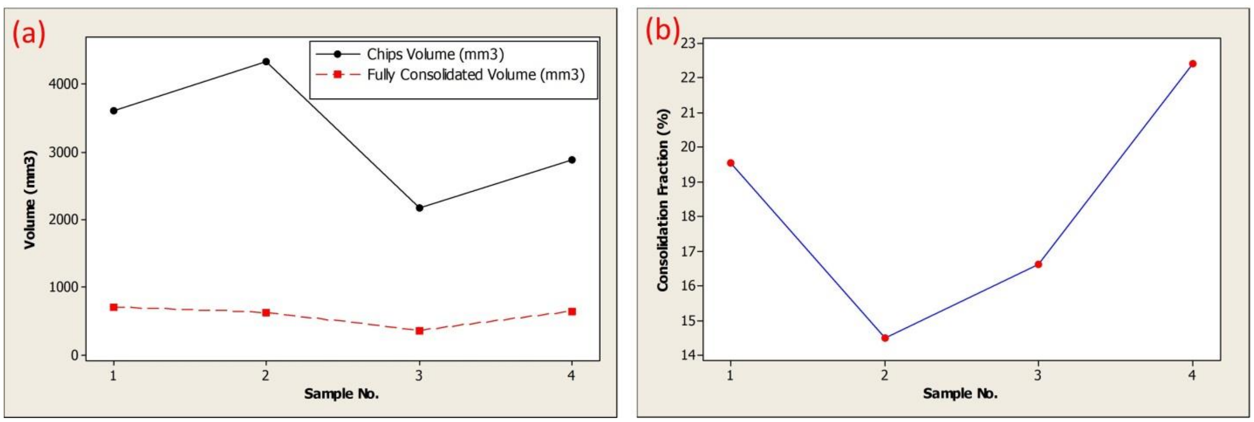

Fig 8. (a) Sample volumes (b) fraction of consolidation

To analyse effect of the process parameters and chips weight on the FC volume, a design of the experiment (DOE) technique by Taguchi method was used with the aid of the Minitab program, as shown in Fig. 9. The Pareto chart, Fig. 9a indicated that the chips weight was the most effective parameter on the FC volume, while the preheating time exhibited the minimum effect. Fig. 9b shows the main effect plot of experiments parameters on the FC volume. Increasing the preheating time decreased the consolidated volume. Increasing the chips weight and plunging depth increased the FC volume. The plunging depth applied the tool pressure which consolidate the chips, and thus increase the FC volume.

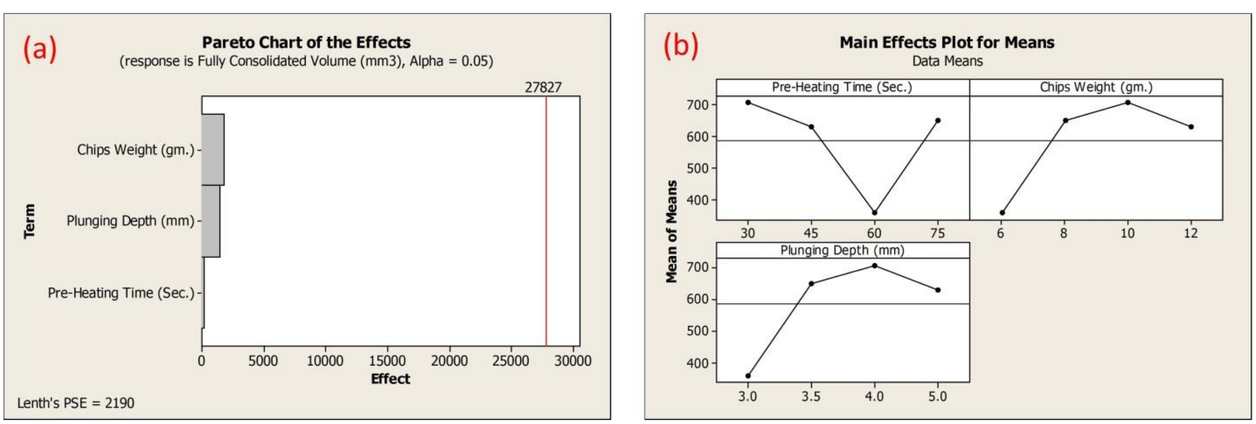

Fig 9. DOE analysis of the FSC (a) Pareto chart (b) Main effect plot

3.3. Microstructure features

The sample 1 was selected to explain the microstructure of the disc, as shown in Fig. 10. The images indicated that the grain recrystallized with a fine structure. Unbounded grains can be observed at the chip boundary or near the gap. This may consolidated to the fact the applied pressure and/or heat input was insufficient to weld the grains along this region. The chip boundary exhibited different interface line width, where the gap between the chips eliminated and the grain recrystallized. Some images revealed that the chips welded without presence of defects such as voids. No cracks were found at the disc microstructure.

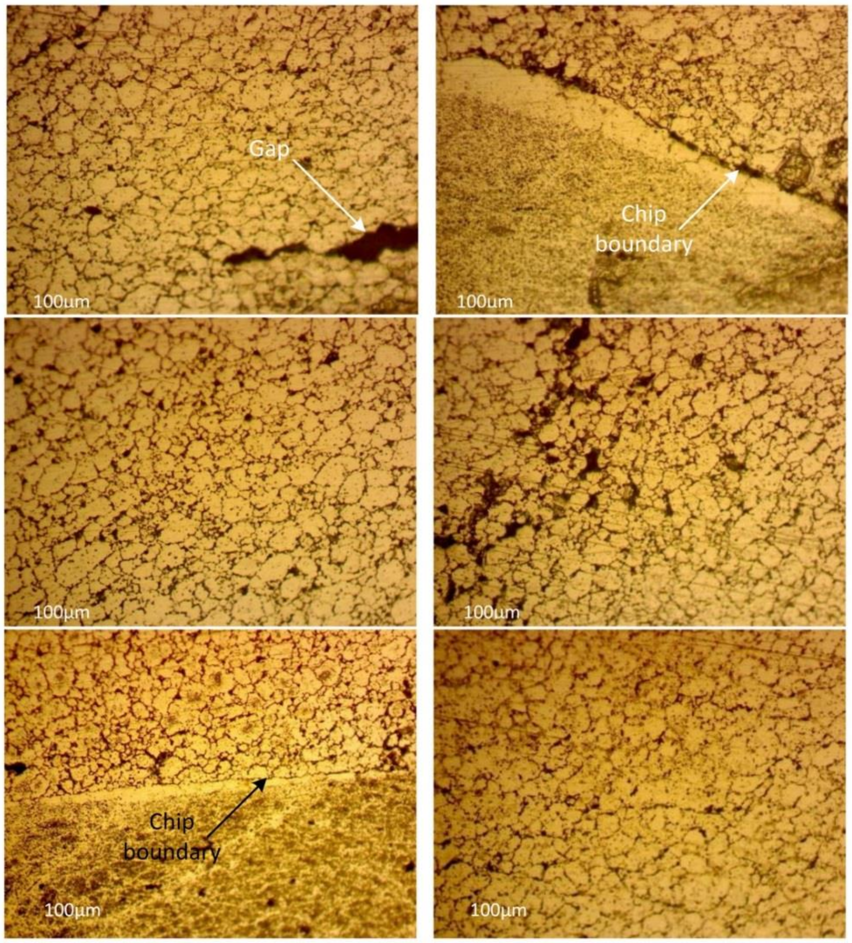

Fig 10. Microstructure of the disc, sample 1

The average grain size was calculated for each sample, and reached minimum and maximum values of 6.3 and 11 mm. To analyse the effect of the experiments parameters on the average grain size, the DOE method was used, as shown in Fig. 11. The Pareto chart indicated that the plunging depth exhibited the highest effect on the grain size of the samples, followed by chips weight and pre-heating time, as shown in Fig. 11a. Increasing the chips weight and plunging depth increased the grain size, as shown in Fig. 11b.

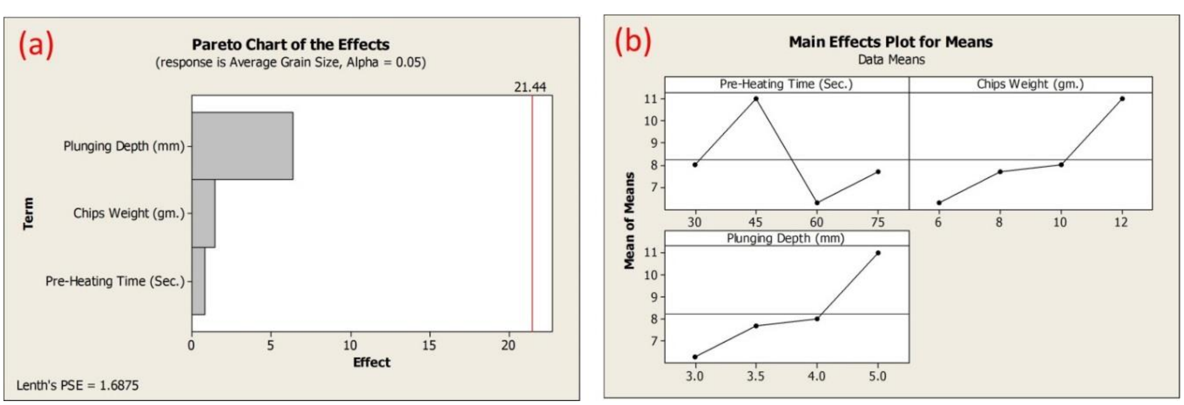

Fig 11. DOE analysis of the grain size (a) Pareto chart (b) Main effect plot

4. Conclusion

Four discs were formed by recycling AA2024 using friction stir consolidation process. Effect of the pre-heating time, chips weight and plunging depth of the tool were analysed. The following conclusion can be drawn:

1. Increasing plunging depth increase the surface finishing of the discs.
2. A higher input heat increase crack formation along the disc region.
3. The formed samples exhibited the same variation of the fully consolidated and disc volumes.
4. The fraction of consolidation of the discs ranged from 14.5 to 22.4%.
5. Chips weight was the most effective parameter on the FC volume.
6. Increasing the chips weight and plunging depth of the tool increased the FC volume.
7. The discs were formed with fine recrystallized grains.
8. Increasing the plunging depth and chips weight increased the grain size.
9. The plunging depth exhibited the highest effect on grain size of the disc.
10. The average grain size of the formed disc ranged between 6.3-11 μm.

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