Forming A Cylindrical Billet from Aluminium Alloy Chips (AA2024-T3) by using Friction Stir Consolidation Technique

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Abstract

Recently, Friction stir consolidation (FSC) is a solid-state manufacturing and recycling process for metal scrap, hence, becoming much important side to convert the metal scrap into finish or semi-finished products. In contrast with the conventional process or re-melting process, the FSC advantage that lower metal waste, environmentally friendly and low cost. In This research, investigated the feasibility to produce a fully dense cylindrical billet from milling machine chips of aluminium alloy type (AA2024-T3) by using an FSC process, the chips plunged onto a hollow cylindrical die by a rotating tool. The chips softening due to the friction heat generation and subjected to the dynamic recrystallization DRX and high plastic deformation. The process was done with different values of rotation speed tool, plunging depth of the tool and preheating time. A 20 mm diameter coherent cylindrical billet with four highs (20, 25, 30, and 35)mm were obtained. The quality of the obtained billets is evaluated through morphological observation.

1. Introduction

In general, Aluminium and its alloys have high mechanical properties relative to the relatively low density, therefore are used in wide-fields in industry. Additionally, the recyclability of Al-alloys is great, they could be recycled many times without high loss in the mechanical properties [1] due to the aluminium properties the above-mentioned, expected the consumption rate increase to be 4% per year during the next two decades [2], this increase in aluminium demand causes deficiency if the use is limited only to the production of raw aluminium. Moreover, furthermore, the primary aluminium production is effect around 1% of global annual greenhouse gas emissions according to the International Aluminium Institute. Completely, about 40% of the gas emissions come from the production process of aluminium, and the rest approximately 60% is bypass gas emissions resulting from generation the electric power [3]. The recycling processes have an important influence on life-cycle studies, particularly, on materials selection, energy efficiency, environmental and competitive considerations. aluminium production is consumed high energy, recycling processes can save up at 5% of the energy required for aluminium production. Practically, all types of aluminium scrap can be recycled, from old scrap (end of the cycle) to a new scrap (milling, turning, gates and risers, rejections, borings), and the recycled scrap exceeded 90%.[4]. aluminium recycling can be classified into two categories: The conventional method recycling (re-melting and casting method) depends on re-melting the scrap and then casting. However, the chips show very low electrical and thermal conductivity due to their oxidized surfaces; therefore, this process requires high energy, thus, the conventional method needs high cost and results in environmental pollution because of harmful gasses are emitted during the melting process of chips. Because of the previously mentioned circumstance, part of the melted chip turns into different scrap, slag and waste and reduces operating efficiency by 54wt% [5], direct
recycling techniques have been developed with as a purpose to overcome the above-mentioned drawbacks. Solid-State Recycling (Direct Recycling): Is a process which converts the metal scrap into a finished or semi-finished product without re-melting. The process depends on severe plastic deformation (SPD), which defined as the ability to produce ultrafine grains of metals, alloys and intermetallic.[6,7]

In 1945, Stern first suggested and patented hot extrusion as a direct recycling process[8]. In 1997 J. Gronostajski et al. developed the direct recycling processes, used hot extrusion to directly convert aluminium chips into a final product [9]. In 2003 M. Samuel used a solid-state recycling to recycles aluminium chips and compared it with traditional method, the method was based on cold compaction. grinds chips into two size of powder from 0.5 to 2mm and <0.5mm, This method shows high grain density (about 80% before forming),used lower pressure and cost [10], R. Chiba et al. used cold extrusion and cold rolling operation to investigate the applicability of solid-state recycling of aluminium alloy (Al-Si) chips. The initiation step was compact chips into billets and annealed 1 h at 300 °C, after that the billet extruded into a square shaft with rectangular cross-section area, then subjected the shaft into cold rolling to produce strip with 1mm thickness. Mechanical properties tests and microstructure results showed that the specimen had mechanical properties better than the basic aluminium alloy[11], in 2017 D. Baffari, et al., used friction stir extrusion to recycle aluminium alloy AA2024 chips, Investigated the effect of adding different amount of SiC Al chips used numerical simulation to follow the progress of the process. The results were the direct recycling through FSE is possible for AA2024 chips and feasible to produce a product without defect and high initial percentage of reinforce (p>1%) leads to big agglomerates of SiC which due to decrease the quality of product such as cracks and un-uniform mechanical properties [12].

The solid-state recycling process (FSC) for aluminium and aluminium alloys becoming much important side to convert the metal scrap into semi-finished product in contrast with the conventional process or re-melting process, due to the advantages of solid-state recycling being lower metal waste environmentally friendly and low cost, the direct recycling result in 40% of the material, about 26–31% energy, and approximately 16–60% work savings. [13] FSC and FSE techniques are same, But FSC is an advanced technique to a purpose to recycled consolidate the incoherent substances into a fully coherent bulk directly by using simple equipment and with only one action, the process equipment is also similar to FSE with only one difference that the die without extrusion channel, where it consists of three parts: the rotating die, the chamber, and backing plate.[14]

In this paper, the feasibility of the FSC process to recycle milling machine chips of aluminium alloy AA2024-T3 into full dense solid billet is investigated, The quality of the obtained billets is evaluated through morphological observation and calculate the fraction of consolidation.

2. Experimental procedure
1.1. Materials and chips preparation
Aluminium alloy shaft type AA 2024-T3 with 100mm length and 50mm diameter and 240 HV microhardness was used to produce chips. The milling machine was set up on 0.5 mm/tooth feed rate and 200 m/min cutting speed to create chips with about 0.40 mm thickness and length about 22 mm. as shown in figure 1. The chemical composition of the AA2024 is listed in table 1. and the mechanical and physical properties for each material are listed in table 2.

1.2. Formatting author names
The FSC is a solid-phase production process to solidification the materials powder, chips, or scrap into solidified bulk by friction technique. The FSC operation depends on high plastic deformation and solid-state welding [15], the FSC die consists of three parts as shown in figure 2. the first part (the punch) or (the tool) is a cylindrical part with 80 mm length and 20 mm diameter, and then make four grooves on the punch as a mark for four highs (20,25,30,35) mm manufactured of high-speed steel HSS, the second part (the die) or (the chamber) a hollow cylindrical die with 60 mm length, 40mm outer diameter and 20 mm inner diameter manufactured of AISI H13 Chromium hot-work steel.
Figure 1. The material and chips preparation. (a) AA 2024-T3 shaft, (b) milling machine for chips preparation, (c) milling machine chips.

Table 1. Chemical composition of the AA2024-T3

| Element wt.% | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Ni  | Zn  | Ti  | V   | Pb  | Al  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Measured value | 0.068 | 0.216 | 4.38 | 0.546 | 1.62 | 0.0083 | 0.006 | 0.016 | 0.016 | 0.007 | 0.013 | Rem |

Table 2. The properties of AA2024-T3.[16]

| Property                      | Value     |
|-------------------------------|-----------|
| Density at 20 °C              | 2.77 g/cm³|
| Liquids temperature           | 638 °C    |
| Incipient melting temperature | 502 °C    |
| Solidus temperature           | 502 °C    |

1.3. Design of the experiments
The plain of this work is to examine the effect of the process parameters on the consolidation of the chips. Three parameters were selected: (a) rotating speed (rpm), (b) plunging depth (mm), and (c) preheating time (min). And each parameter has four levels. A Taguchi method was used to design the experiments. Table 3 lists the experimental levels of each parameter to produce the specimens.

Table 3. The experimental levels process parameter

| No. | Rotating speed (RPM) | Plunging depth (mm) | Preheating time (min) |
|-----|-----------------------|---------------------|------------------------|
| 1   | 900                   | 20                  | 1.0                    |
| 2   | 1111                  | 25                  | 1.5                    |
| 3   | 1444                  | 30                  | 2.0                    |
| 4   | 1888                  | 35                  | 2.5                    |
The vertical milling machine was used to achieve the FSC process. Initially, the backing plate and die was aligned with the rotational axis of the milling machine and fixed on the machine table. Load the die with the desired weight of chips. As shown in figure 2, A cylindrical punch plunged into the die and started rotating with the selected rotating speed for a specific preheating time according to the process parameters. After the pre-heating time is over, the punch starts to plunge into the die and continues plunge at the same selected rotating speed until it reaches the specified depth engraved on the punch, at that time, the process is stopped. Finally, the punch is withdrawn from the die and terminate the process.

![Figure 2](image)

**Figure 2.** (a) Sketch of the process, (b) milling machine and fixture

### 3. Results and discussion

#### 3.1 Design of experiment (DOE) results

Billets, 20mm in diameter, with 35, 30, 25, and 20 mm high were obtained. The Minitab program was used to analyse the effect of the process parameters on the temperature of the process and the fraction of consolidation $\Theta$, the fraction of consolidation calculated according to Eq (1) [14]:

$$\Theta = \frac{\rho_{ps}}{m_t}$$

Where $\rho_{ps}$ is the density of basic metal AA2024, $m_t$ is the total mass of billet charge and $v$ is the volume of the fully consolidated region. In table 4, shows the FSC specimens:

The Minitab program was used to analyse the effect of the process parameters on the temperature of the process and The fraction of consolidation $\Theta$. figure 6 illustrated the main effect plot on the billets consolidation and temperature increases, figure 3a indicated that the increasing in the rotating speed and preheating time increased the preheating temperature, while the plunging depth has no effect on the preheating temperature, in figure 3-b indicated that the final temperature increases and highly by increasing the plunging depth. rotating tool affect this increase but the increasing of rotating speed and preheating time have a small effect on the final temperature raising, and in Figure 3c indicates that the consolidation factor increase by increasing the plunging depth until 30mm. the other factors, rotating speed and preheating time, has a small effect on the fraction of consolidation.
Table 4. The FSC specimens

| No. | S1  | S6  | S11 | S16 |
|-----|-----|-----|-----|-----|
| Front view | | | | |
| Top view | | | | |
| Root | | | | |

Table 5. The input and output of FSC process

| No. | Rotating speed (RPM) | Plunging depth (mm) | Preheating time (min) | Preheating temperature (°C) | Final Temperature (°C) | The fraction of consolidation θ (%) |
|-----|----------------------|---------------------|-----------------------|----------------------------|------------------------|-----------------------------------|
| 1   | 900                  | 20                  | 1.0                   | 162                        | 505                    | 62                               |
| 2   | 900                  | 25                  | 1.5                   | 164                        | 530                    | 82                               |
| 3   | 900                  | 30                  | 2.0                   | 165                        | 579                    | 85                               |
| 4   | 900                  | 35                  | 2.5                   | 167                        | 583                    | 78                               |
| 5   | 1120                 | 20                  | 1.5                   | 168                        | 526                    | 71                               |
| 6   | 1120                 | 25                  | 1.0                   | 166                        | 528                    | 75                               |
| 7   | 1120                 | 30                  | 2.5                   | 170                        | 565                    | 90                               |
| 8   | 1120                 | 35                  | 2.0                   | 169                        | 578                    | 75                               |
| 9   | 1400                 | 20                  | 2.0                   | 168                        | 525                    | 71                               |
| 10  | 1400                 | 25                  | 2.5                   | 170                        | 530                    | 88                               |
| 11  | 1400                 | 30                  | 1.0                   | 167                        | 582                    | 91                               |
| 12  | 1400                 | 35                  | 1.5                   | 168                        | 590                    | 77                               |
| 13  | 1800                 | 20                  | 2.5                   | 171                        | 510                    | 65                               |
| 14  | 1800                 | 25                  | 2.0                   | 170                        | 535                    | 81                               |
| 15  | 1800                 | 30                  | 1.5                   | 168                        | 592                    | 87                               |
| 16  | 1800                 | 35                  | 1.0                   | 167                        | 595                    | 78                               |
The Pareto chart gives an indication of the degree of the effective factors of friction stir consolidation parameters on the preheating temperature, final temperature, and the consolidation fraction as shown in figure 4. In general, in figure 4-a, indicate that the preheating time has the highest effect on increasing the preheating temperature while plunging depth exhibited the least effect on this temperature, while the final temperature affected highly by the plunging depth compared with the other factors (rotating speed and preheating time) as shown in figure 4b, finally, The Pareto chart indicates that the most effective factor on increasing the consolidation fraction is the plunging depth which has the highest effect compared with the other factors as shown in figure 4c.

Figure 3. The main effect plot of FSC parameters for: (a) preheating temperature, (b) final temperature, (c) The fraction of consolidation.

3.2. Microstructure Examination

The vertical cross-section of the recycled disks was mounted, ground, polished and etched with Keller reagent in order to highlight the microstructure. After taking an overview of all samples, it was observed that four different regions were formed in the rate of solidification and crystallization. Each sample consists of two or more regions, according to the parameters of each sample. In figure 5, sample No.6 (rotating speed 1120 rpm, plunging depth 25mm, and preheating time 1.0 min) it was observed that there are four combined regions. In the first part, zone (a), it’s a fully consolidated zone, and the FSC producing a flow microstructure consisting of dynamic recrystallized grains and the superplastic solid-state flow phenomena at high temperature that generated from the friction between the bottom of the rotating tool and chips. Since this process is similar to the FSW from the mechanism side, therefore, the DRX is characteristic of all FSW processes examined thus far in all metals [17,18]. In zone (b), there is no direct contact between the tool and metal chips the plunging depth decreases the gaps between chips and the friction will be between only chips, the rotating speed in this area work as a mixing tool. Recrystallization occurs and equiaxed recrystallized grains. In zone (c), the chips welded together without occurring recrystallization In zone (d), there are no consolidation chips with weak welding between chips. While, S11 showed a fully dense billet with only zones A and B are observed.
Figure 4. Pareto chart of the effective factors of FSC: (a) preheating temperature, (b) final temperature, (c) The fraction of consolidation.

Figure 5. S1: 900 rpm, 20 mm, 1.0 min. S6: 1120 rpm, 25 mm, 1.0 min. S11: 1400 rpm, 30 mm, 1.0 min.
In figure 6, shows the effect of rotating speed on dynamic recrystallization, grain size, and superplastic solid-state flow phenomena, the increase in rotating speed leads to an increase in grain size. The flow shape also controlled by rotating speed and the processing time. In the dynamic recrystallization region the grain size that close to the tool increase with temperature increasing, there is no visible difference in grain size between S1 and S6 due to the little increase in temperature (505-528)°C, in S11 the temperature increase into 582°C, which leads to a clear increase in grain size. The solid-state flow characteristic effected by the rotation speed, Where, in S1 900 rpm, the flow as a bow shape, the arch radius decrease when the rotation speed increase until became as a sloping line in S11 1400 rpm.

4. Conclusions
In this work, the FSC process was used to recycle aluminium alloy chips type(AA 2024-T3) into coherent billets. were investigated the process parameters effect on the billet consolidation, The following conclusions can be drawn:

1-Due to the FSC is an asymmetric process, hence, the heat increasing and plunging depth the most responsible effect on the consolidation, therefore, the correctly choosing of the process parameters affect the consolidation, This was evident in S1 62% Ø, when S11 91% Ø.
2-The rotating speed and plunging depth lead to DRX which work on recrystallization in the zone that closes to the tool and create a superplastic solid-state flow phenomena.
3-The friction between chips and rotating tool which increasing the temperature initially, after that the heat generating via the friction between chips jointly with increasing in plunging depth.

Figure 6. S1: 900 rpm, 20 mm, 1.0 min. S6: 1120 rpm, 25 mm, 1.0 min. S11: 1400 rpm, 30 mm, 1.0 min.
4. The grain size in the area that close to the tool increasing with rotating speed and temperature increasing.

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