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Fabrication of Billet from Aluminum Alloys AA 2011-T3/7075 Chips through Friction Stir Consolidation

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Abstract. Recently evolving Solid-State Recycling (SSR) techniques have shown promising features to recycle metals scraps more efficiently compared to remelting-based approaches. Among these SSR methods, Friction Stir Consolidation (FSC) has been successfully tested to transform metals chips directly into semi or final solid products. Therefore, researchers explored FSC critical process parameters and their subsequent effects on quality in terms of the mechanical and metallurgical properties of the billet. All the previous studies of FSC were limited to developing billet of mono materials. Therefore, in this research, an attempt was made to go beyond the idea of recycling; in fact, a billet of two dissimilar aluminum alloys AA 7075 and AA 2011-T3 out of chips was obtained. The mechanical and metallurgical properties were assessed through the Vickers hardness measurements and microstructure analysis. The experimental results of this research illustrate that the FSC process is a feasible approach to develop a billet of dissimilar materials with achieving quality closer to the corresponding billet of mono-material.

Introduction

Materials are the primary building blocks of society, such as buildings, infrastructure, equipment, and goods. They enable businesses to operate and run many services like transport, shelter, and mechanical labor. According to International Energy Agency, global demand for steel has increased by three times, cement by nearly seven times, primary aluminum by nearly six times, and plastics by over ten times since 1971 [1]. However, alongside the benefits of the materials, they are also responsible for the emission of anthropogenic gases that have adverse environmental impacts. In 2017, the industrial sector was noticed to be responsible for nearly 40% of total final energy consumption and nearly one-quarter of direct carbon dioxide emissions.

Aluminum is among the top five primary materials that dominate in the industrial sectors [2]. Although at present, only the percent share of steel is larger than aluminum among the metals in global materials consumption [3]. However, the demands for aluminum are also increasing [4] due to rapidly evolving applications of joining dissimilar materials in ships, aerospace, automobile, and megastructure industries. Some of the typical application includes a ship hull that has an outer layer of AA5083 due to its efficient corrosion resistance to seawater, while AA6063 is used in making the internal structure of the ship because of good workability, good corrosion resistance, lightweight and moderate strength. Similarly, axles of BMW Model 5 are made from dissimilar extruded tubes of AA 5083 and AA 6063, and roof structures of arenas and gymnasiums are usually 6063 or 6061 extruded tubes, covered with 5xxx alloy sheet.

Besides, aluminum alloys have also shown good bonding affinity towards dissimilar metals. For example, aluminum alloys have been successfully joined with magnesium alloys in clad, duplex, and bimetallic ring applications [5-7]. Similarly, aluminum alloys were joined with steel to fabricate lightweight composite shafts for automotive application [8, 9]. These attractive features led to increase the global consumption of aluminum.

However, virgin aluminum is produced from bauxite ore. Nevertheless, the process is very complicated, costly, energy-intensive, and responsible for approximately up to 20% loss of pure aluminum. Besides, large amounts of waste slag are generated, which takes up considerable land resources and pollutes the environment [10]. Therefore, during Rome Summit 2021 [11], environmental policy efforts from G-20 countries greatly stressed green technology that reduces primary resource use, pollution prevention, waste management, and sustainable products.

Therefore, new strategies are explored to minimize mining for new ore and mobilize metals recycling practices without losing their beneficial qualities. According to the European Aluminum Association (EAA, 2020), currently, about 36% demand for aluminum in Europe is met by recycled material. It is expected that the recycling rate will reach to 50 percent of EU demand for aluminum by 2050 [12].

Usually, aluminum is recycled through the conventional remelting route. But processes for conventional methods of recycling and reuse consist of multiple steps of refining, remelting, and casting, which are complex and require considerable labor and power [13]. These methods have further severe implications, especially during recycling aluminum scraps. These kinds of scraps, due to their high surface-to-volume ratio, are prone to oxidation, causing permanent material loss during the melting process. They cause adverse environmental impact, high cost, and significant material loss.

Therefore, the researchers attempted SSR techniques that involve fewer recycling steps [14]. In SSR methods, the scrap metals are first cleaned and then directly converted into bulk products and semi-products by mechanical means or plastic deformation without undergoing remelting phase. Thus, bypassing the melting phase significantly avoids the losses due to oxidation and can save up to 95 % of energy, 59 % of the cost, and 46 % of material compared to the conventional melting process [15].

The idea of SSR routes for aluminum alloy scrap was first introduced by Stern in 1945 [16]. This discovery led the researchers to focus on ‘meltless’ aluminum scrap recycling and thus various solid-state recycling techniques were developed [17]. Duflou et al. [18] performed an environmental assessment of three different SSR methods and concluded that these methods are more effective approaches for machining scraps recycling.

Friction stir consolidation (FSC) is also one of the SSR process [19] that has efficiently recycled machining chips. FSC has two main steps: compaction and consolidation. In compaction, chips or powder are pressed in a hollow die chamber by applying a specific load through a cylindrical tool. Then materials are further pressed and stirred through the tool's downward force and rotational speed during the consolidation phase.

Baffari et al. [20] numerically modelled the welding of materials chips during FSC to predict bonding parameters. Buffa et al. [21] explored the critical process parameters of FSC and reported that increasing processing time and speed or lowering mass resulted in a better-quality consolidated disc. Li et al. [22] highlighted non-homogeneous mechanical properties of consolidated billet during single-step FSC of aluminum alloy AA6061. However, all the existing literature of FSC [19-22] was focused on developing billets of mono materials only.

The current research is conducted with the goal of exploring the potential of the FSC process to obtain multi-material billets directly out of chips. The main motive is moving from the idea of recycling “Recycling is the reprocessing of recovered materials at the end of product life, returning them into the supply chain [23]” towards the concept of upcycling “reuse (discarded objects or material) in such a way as to create a product of higher quality or value than the original [24]”. In consequence, the idea is starting from chips of two different materials and placing it so that to get tailored billet with enhanced mechanical properties. There are some attractive aspects of these kinds of products, and they can be beneficial in various modern industries such as ships, aerospace, automobile, and constructions applications. Therefore, preliminary experiments are carried out to develop a billet of two dissimilar aluminum alloys AA 7075 and AA 2011-T3. The quality of the billet is evaluated in terms of hardness measurements and microstructure analysis.

Experimental Procedure

Machining swarf of 1-2 mm were produced from AA 7075 round bar of 30 mm diameter and AA 2011-T3 square bar of 25 mm x 25 mm. In the case of AA 7075 chips, a turning operation was adopted with feed rate and cut depth of 4 mm/rev and 1 mm, respectively, while for AA 2011-T3, a milling operation was performed with a feed rate of 28 mm/min and cutting depth of 1 mm. First, the chips were cleaned by submerging in the acetone and shaking them for 15 minutes. Then, 10 g cleaned chips of AA 2011-T3 were loaded in a cylindrical die with nominal diameter around 25.4 mm. Next, ESAB LEGIO (a dedicated friction welding machine) and H13 steel cylindrical tool with 25 mm diameter were used to compact chips at 5 kN force. Then 5g cleaned chips of AA 7075 were added in the same die over AA 2011-T3 chips and again compacted at 5kN load. A 20 kN punch force was applied to consolidate the whole charge at rotational speed of 1000 revolution per minute (rpm) and process time of 30 seconds (sec) as shown in Fig. 1. These process parameters were selected based on previous studies [25] that successfully led to develop a sound billet. Finally, the consolidated billet was removed from the die.

The billet was sectioned along the cylindrical axis in two halves. The cross-section area was properly polished through a series of abrasive papers assisted by alumina lubricant. The surface in contact with tool and backing plate were considered top and bottom surface of the tool respectively. The hardness was measured by the Vickers hardness test. A 49 N (5 kg) load was applied for 15 seconds over the four lines along the longitudinal axis. The lines were at radius, r=0 (central line or L1), 6.50 (L2), 9.00 (L3), and 12.25 mm (near the external surface or L4). On each line, the pitch of the load points was 0.50 mm, as shown in Fig. 2a.

Then microstructure was revealed through Keller reagent and then examined under the OLYMPUS GX51F microscope. The microstructure was analyzed at the interface of two dissimilar aluminum alloys as shown in Fig. 2b.

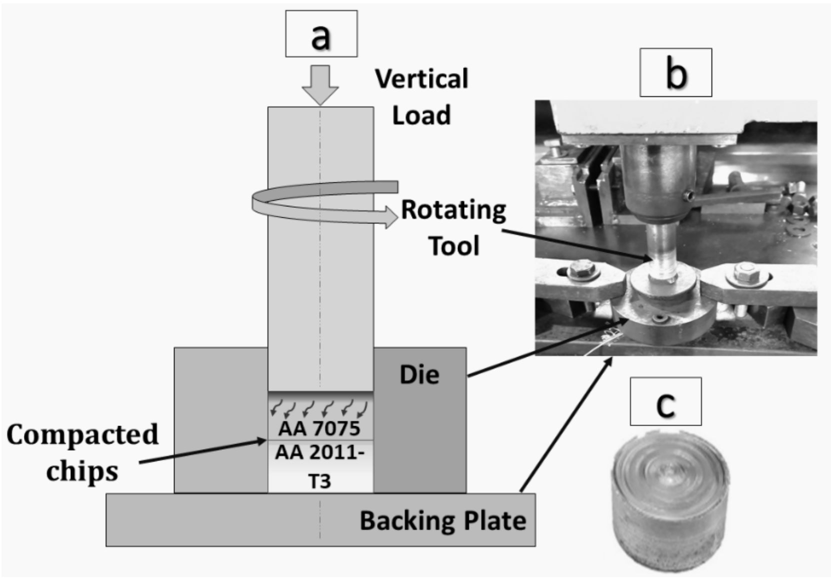

Figure 1. (a) Sketch of the process, (b) utilized fixture, and (c) consolidated billet

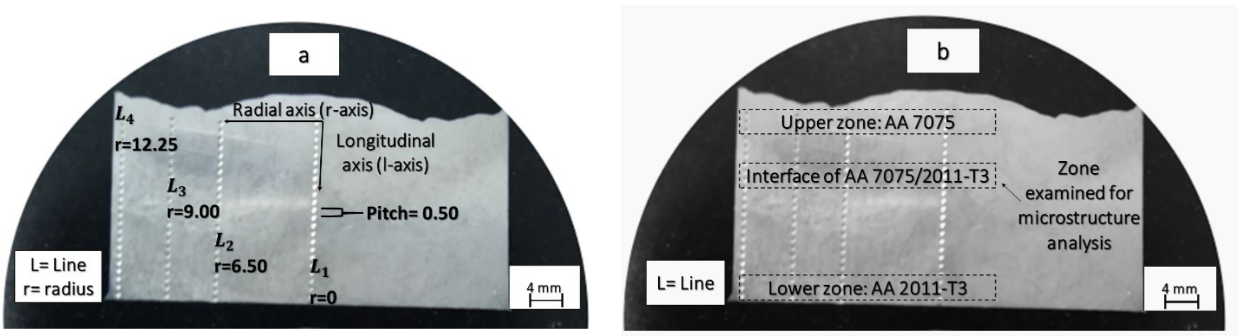

Figure 2. Schematic diagram for (a) Vickers hardness test, and (b) microstructure analysis
Note. All dimensions are in mm

Analysis of Results

This section provides a comprehensive discussion about the hardness profile from two perspectives: the FSC process and material aspects. From the FSC process perspective, the hardness trend was thoroughly examined in the longitudinal and radial directions based on the previous study [24]. On the other hand, the effect of material on hardness profile was also considered based on different material existence along the billet section. Then hardness of dissimilar materials billet was compared to the hardness of corresponding mono-material AA 7075 and AA 2011-T3 billets. The degree of mixability and bonding affinity of two aluminum alloys were further analyzed from micrographs in the mixing zones.

FSC Process Aspect

On analyzing the hardness profile of central line (r=0 mm) along the longitudinal direction, the hardness was noticed to decrease continuously from top to the bottom section of the billet (Fig. 3). The maximum Vickers hardness value (HV) was observed at the top of the billet section around HV 110. The minimum was at the bottom almost HV 50. Similar trend was observed for the other three lines (at r=6.50, 9.00, and 12.25 mm). One of the reasons of dropping hardness value along the longitudinal direction is the nature of FSC process as reported by Li et al [22]. During FSC, heat generates due to rotational speed of tool and contact friction between tool and billet surfaces. The surface of the tool that is in contact with billet is considered the hub of heat from there heat distributes to the whole section of the billet. Therefore, maximum amount of heat is gained by the billet top surface while advancing to the bottom surface its intensity reduces and thereby the bottom surface gets minimum amount of heat. The difference in heat or in other words, the temperature gradient between top and bottom surfaces is a major the factor leading to non-homogenous hardness value.

However, in the radial direction the temperature gradient is relatively constant [22]. Overall, the hardness value also remained more consistent with each other. This radial consistency was more evident at the very top and bottom zones of the billet. This reason is that in the radial direction temperature gradient does not vary significantly. On the other hand, near middle zone, the hardness value though deviates from each other in the radial direction but in this zone material factor plays an important role. This fact is covered in the coming section.

Material Aspect

Along the longitudinal direction, the second important reason of the difference in hardness value between the top and bottom section are different materials existence in these zones. The billet top section contained AA 7075 that has somewhat different mechanical properties from AA 2011-T3 that constituted bottom section. Therefore, for better understanding, a billet of only AA 7075 chips and another billet of only AA 2011-T3 chips were developed under same experimental condition as applied for multimaterial billet. Then hardness profile of the multimaterial billet was compared considering the mono material billets as references along the line at r=6.5 mm only as shown in Fig. 4. It was noticed that the average hardness value for mono-material AA 7075 billet was around HV 100 while for AA 2011-T3 billet it was near HV 70. The hardness value of multi-material billet at the top and bottom almost aligned to the hardness value of their corresponding mono materials billets. These results indicated that dissimilar materials still retained their mechanical properties after FSC in multi-material conditions.

In the radial direction, the hardness value is consistent at the top and bottom zones because these zones contained mono material only i.e., AA 7075 in top and AA 2011-T3 in bottom zones. While near the middle section, hardness values significantly deviated from each other that represents that in this zone, mixing of two dissimilar aluminum alloys occurred. It is assumed that the hardness value in the mixed zone is dependent on degree of mixability. It is expected that the area where quantity of AA 7075 surpassed the AA 2011-T3 possessed higher hardness value.

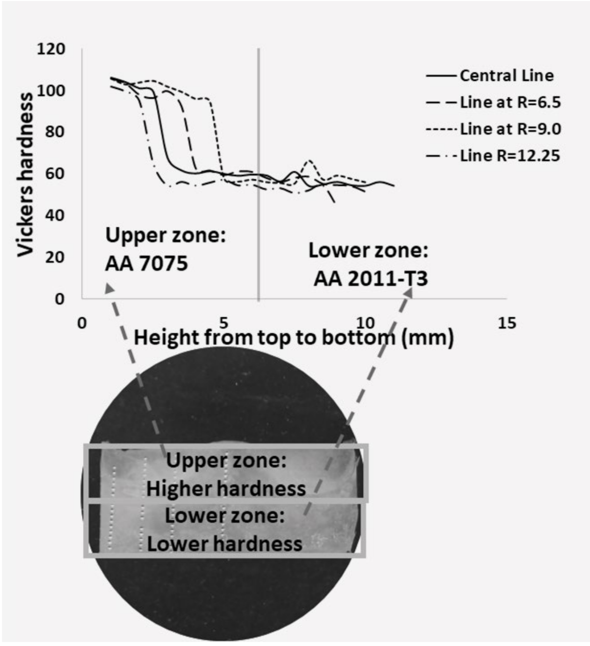

Figure 3. Hardness profile of AA 7075/2011-T3 billet

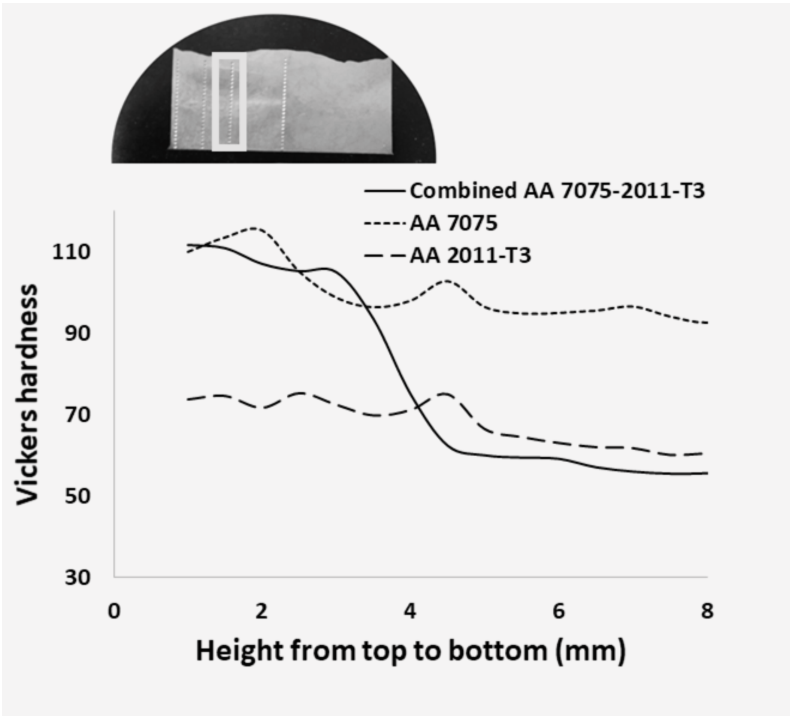

Figure 4. Hardness comparison between multimaterial billet with corresponding mono-materials billets along line at r=6.5 mm (L2)

Microstructure Analysis

The optical microscopy was performed to analyze the microstructure of the mixed zone at central line (Fig. 5). Even though, chips were from two dissimilar aluminum alloys but still no visible boundary was noticed even in the mixed zone. This fact depicts that there is a good bonding affinity of two dissimilar aluminum alloys during FSC.

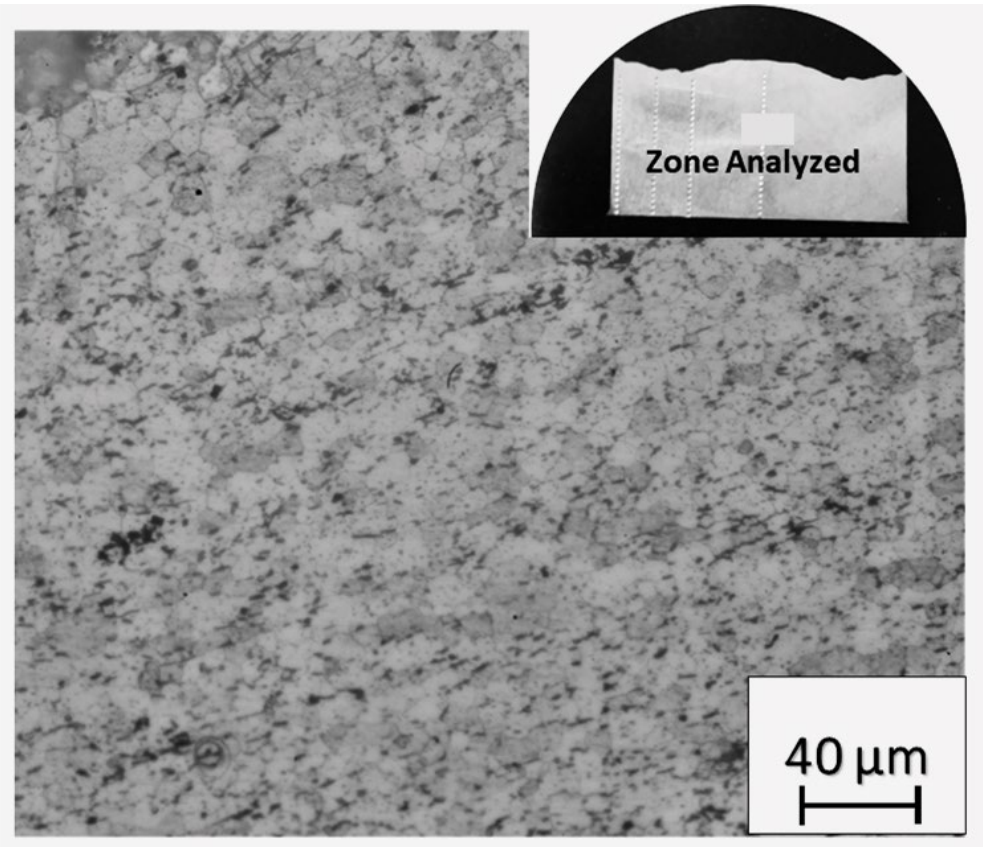

Figure 5. Micrograph of mixed AA 7075/2011-T3 zone at 50x along the central line

Conclusion and Further Development

Based on post-analysis of experimental data, the following conclusions are drawn:

- FSC successfully developed billet from two dissimilar aluminum alloys chips.
- A good bonding affinity existed during FSC of two dissimilar aluminum alloys. In the analyzed microstructure, no visible boundary was noticed even in the mixing zone of two dissimilar aluminum alloys.
- In the non-mixing zones of multimaterial billet, dissimilar materials retained their mechanical properties. That was observed in the top and bottom section of the billet that contained AA 7075 and AA 2011-T3 respectively.
- In the mixed zone, mechanical properties depended on the degree of mixability of materials. However, the mechanical properties are more inclined towards the dominant ingredient.

It has been proved that the FSC process can successfully develop a billet from dissimilar aluminum alloys chips. However, it is also essential to fully explore materials flow, a deep understanding of material distribution through EDX analysis and numerical modeling and simulation of dissimilar aluminum alloys. Further, developing a billet from dissimilar metals chips through FSC can be one of the potential future works.

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