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To cite this article: A Latif *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1270** 012096

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Forgeability characterization of multi-material based functionally graded materials manufactured through friction stir consolidation

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Abstract. Solid state recycling allows direct recycling of metal chips into semi-finished products. This process category proved to lower the environmental impact of metals recycling. Friction stir consolidation (FSC) is a new solid-state technique taking advantage of friction heat generation and severe plastic deformation to consolidate chips into billets. The new frontier of FSC process could be its evolution from recycling techniques towards the concept of upcycling technique: reuse (discarded objects or material) in such a way as to create a product of higher quality or value than the original. The authors have recently successfully applied FSC for producing multi-material based functionally graded materials (FGM). In this paper, the forgeability of the billet consolidated out of two dissimilar aluminium alloys AA 7075 and AA 2011-T3 chips, was analyzed. A proper forging test was designed, and mechanical and metallurgical properties of the forged parts were assessed through Vickers hardness measurements.

1. Introduction

Over the last decade, solid state recycling (SSR) processes have been analysed as a viable alternative for recycling metals scraps [1]. Different variants have been proposed for recycling metal chips: direct hot extrusion [2], equal channel angular pressing (ECAP) extrusion [3], screw extrusion [4], spark plasma sintering (SPS) [5], friction stir extrusion (FSE) [6] and friction stir consolidation [7]. This process category along with high quality recycled semi-finished products, has proved its energy and resource efficiency. In fact, by skipping the melting phase, permanent losses due to oxidation are avoided. Duflou et al. [8] have proved that ECAP and SPS outperform conventional remelting based routes under the environmental impact perspective. Baffari et al. [9] and Buffa et al. [10] proved the energy efficiency of FSE and FSC over conventional recycling, respectively.

The new frontier of SSR processes could be their application for manufacturing multi-material functional grade semifinished products. The advancement from recycling processes towards upcycling ones, chips processing offers excellent control of microstructure and mechanical properties. The ability to manipulate the material composition by simply changing chips mixtures could give designers and researchers tremendous freedom for producing semifinished products with graded properties. At the same time, there is an urgent need to find manufacturing solutions for getting multi-material components. As far as aluminium alloys are concerned, this material has been successfully joined with magnesium alloys in clad, duplex, and bimetallic ring applications [11-13] through casting-rolling, hot pressing, diffusion welding, and friction stir forging. Similarly, aluminium alloys were joined with steel to fabricate lightweight composite shafts for automotive application [14, 15] through deep drawing-forging and extrusion processes. In this respect, relying on a semifinished component with embedded graded properties would ease the manufacturing of multi-material components with graded properties. Graded



components are nowadays crucial for improving the performance of the product under mechanical, electrical, and environmental angles [16].

The authors have recently successfully applied FSC for producing multi-material based functionally graded materials (FGM) [17]. 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. The authors, in their previous research, have successfully obtained bimetallic billet in a multilayer approach starting from AA 7075 and AA 2011-T3 chips. In the present paper, a further step of the process chain is analysed. To be more specific, the forgeability of the multi-material billet is analysed. The results of the upsetting and forging tests area are discussed. The results are compared with mono-material FSCed billet.

2. Methodology

2.1. Material and process set-up

Machining swarf with an average size of 1-2 mm was obtained from aluminium alloys AA 7075 and AA 2011-T3 through turning and milling operations, respectively. The scraps were kept submerged in acetone up to 15 minutes for effective cleaning. Billets of mono and bi materials were produced. For mono-material billet, 15 g chips of one kind of aluminium alloys (AA 7075 or AA 2011-T3) were loaded in a cylindrical die with a nominal diameter of 25.4 mm. The chips were compacted at 5 kN load using ESAB LEGIO (a dedicated friction stir welding machine) and H13 steel cylindrical tool with 25mm diameter and then consolidated by applying 20 kN punch force with rotational tool speed of 1500 rpm for 30 s (figure 1). In the case of bi-materials billet, initially, 5g of AA 2011-T3 were charged in the die and compacted at the same 5kN preload. Then, 10 g AA 7075 chips were added, and the whole charge was compacted at 5kN force. In the final consolidation stage, the same process parameters were adopted as used in the case of mono-material billets. Overall, a set of three experiments were developed, as shown in table 1.

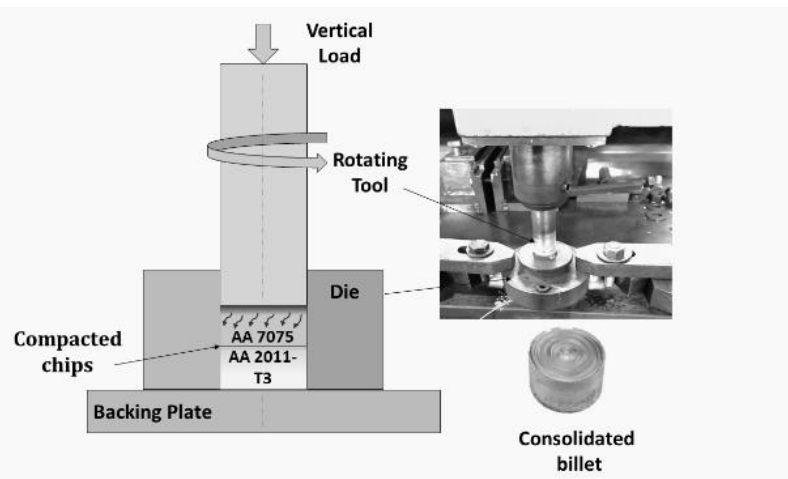


Figure 1. Friction stir consolidation experimental setup

Table 1. Design of experiments

Experiment ID	Billet type	AA 2011-T3, mass (g)	AA 7075, mass (g)
Exp 1	Mono-material	15	0
Exp 2	Mono-material	0	15
Exp 3	Bi-material	5 (at bottom)	10 (on top)

2.2. Measured output

To evaluate the formability of FSC as an SSR recycling process, forging and upsetting operations were performed on the consolidated billets (figure 2) under the cold condition to turn the semi-finished

workpieces into near net shape parts. Galdabini hydraulic press tensile testing machine was used to reduce billet height by 40% of the initial height with 0.1 mm/s punch speed. Forging was performed by designing a special die and punch system (figure 3).

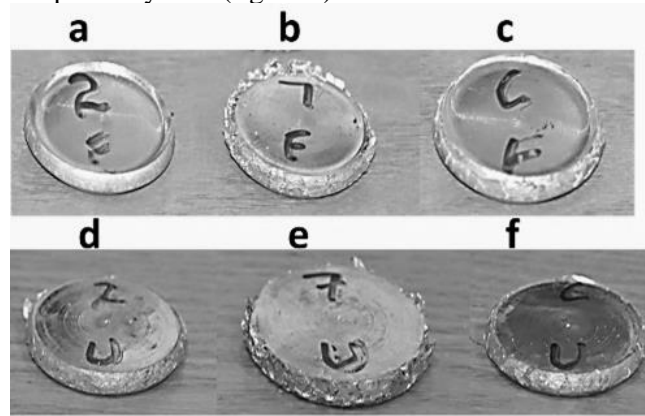


Figure 2. Forged (a) AA 2011-T3 (b) AA 7075 (c) bi-material, and upset (d) AA 2011-T3 (e) AA 7075 (f) bi-material.

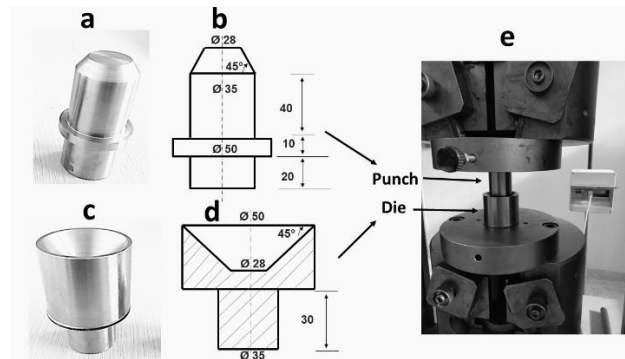


Figure 3. (a) Forging punch, (b) punch 2D view, (c) forging die (d) die 2D sectional view, and (e) forging setup.

Both formed (forged and upset) and non-formed billets were sectioned and polished through a series of abrasive papers assisted by alumina. The hardness was evaluated by the Vickers hardness measurement. A load of 49 N (5 kg) was used for 15 seconds. For the non-formed samples, four lines were selected along the longitudinal direction, i.e., at radius, $r=0$ mm (L0), 6.50 mm, 9.00 mm, and 12.25 mm (L1, L2, and L3, respectively) as shown in figure 4(a). A constant pitch of 0.50 mm was set for the load points on each line. For bi-material forging and upsetting samples, hardness was also measured near the external surface at L4 in the longitudinal direction and three additional lines (L5, L6, L7) in the radial direction (at the interface and zones just above and below the interface), as shown in figure 4(b) and figure 4(c). The idea was to thoroughly examine the forming behaviour of bi-material behaviour near the external surface and at the interface of two different aluminium alloys.

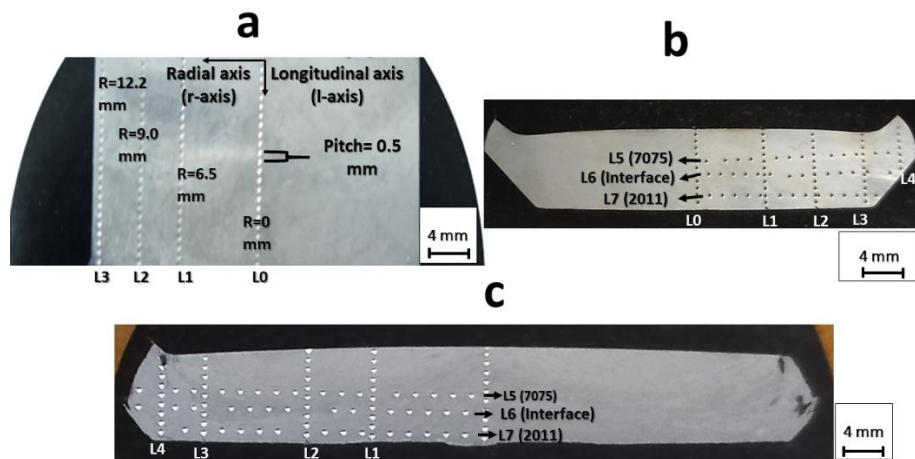


Figure 4. Hardness samples of bi-material. (a) non formed, (b) forged, and (c) upset.

3. Results

3.1. Results for mono-material consolidated billet

In this section, the results of the upsetting and forging test will be analysed for the mono-material billets. Specifically, the hardness, as discussed in the previous section, will be presented and compared to the hardness of the consolidated billet (with no deformation imparted).

3.1.1. Results for AA 2011-T3 mono-material billet. In figure 5, the hardness trends in the axial direction at different measuring loci for the three different configurations (consolidated, forged, and upset) are reported. Overall, it is possible to notice that the hardness values increased both in the upsetting as well as in the forging test. The decreasing trend moving from the top to the bottom is still present in both deformed samples (figure 5(b) and figure 5(c)).

The forging test reveals that the consolidated billet of AA 2011-T3 can be successfully forged and that mechanical properties are further enhanced because of the strain hardening induced by the processes. Concerning upsetting, results reveal fracture/ chips de-bonding close to the outer region (figure 5(f)), where secondary positive mean stress status can occur because of the barrelling phenomenon.

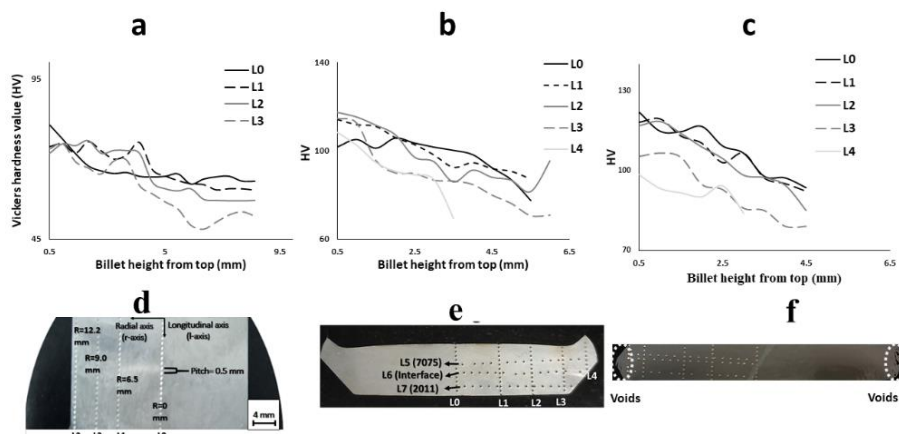


Figure 5. Hardness samples of mono-material AA 2011-T3. (a) non-deformed, (b) forged, and (c) upset and polished section of (d) non-deformed, (e) forged, and (f) upset.

The figure 6 depicts the hardness along the radial direction for the forging and upsetting cases. It is possible to see that hardness decreases when moving from the top to the bottom and from centre towards the outer zone of the analysed cross section. This trend derives from FSC process mechanics [7].

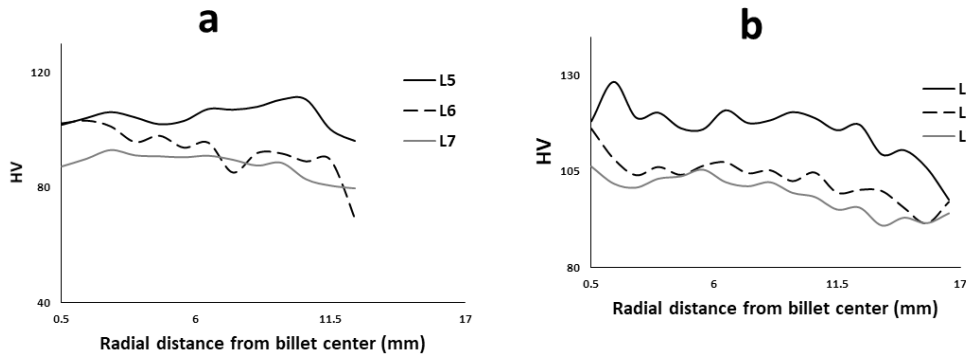


Figure 6. Hardness in radial direction of mono-material AA 2011-T3 (a) forging, and (b) upsetting

3.1.2. Results for AA 7075 mono-material billet. As far as AA 7075 is concerned, different results were observed. As a matter of fact, it is a less ductile material with respect the series 2011 and several defects occurred. In figure 7 the axial hardness values of the analysed samples are reported. In the forging test, many voids due to chips de-bonding can be observed, a defective component was therefore obtained. This is somehow reflected in the oscillating trends of some hardness trends (L2, L3, L4). The upsetting samples exhibits a larger area characterised by fractures with respect the AA 2011-T3 case, although most of the part of the sample still results consolidated and with constant hardness values. This worsening is very well visible in figure 7(f) and figure 8 where the hardness in radial direction of upsetting is reported. Actually, a sudden drop in hardness occurs when moving towards the outer part of the sample.

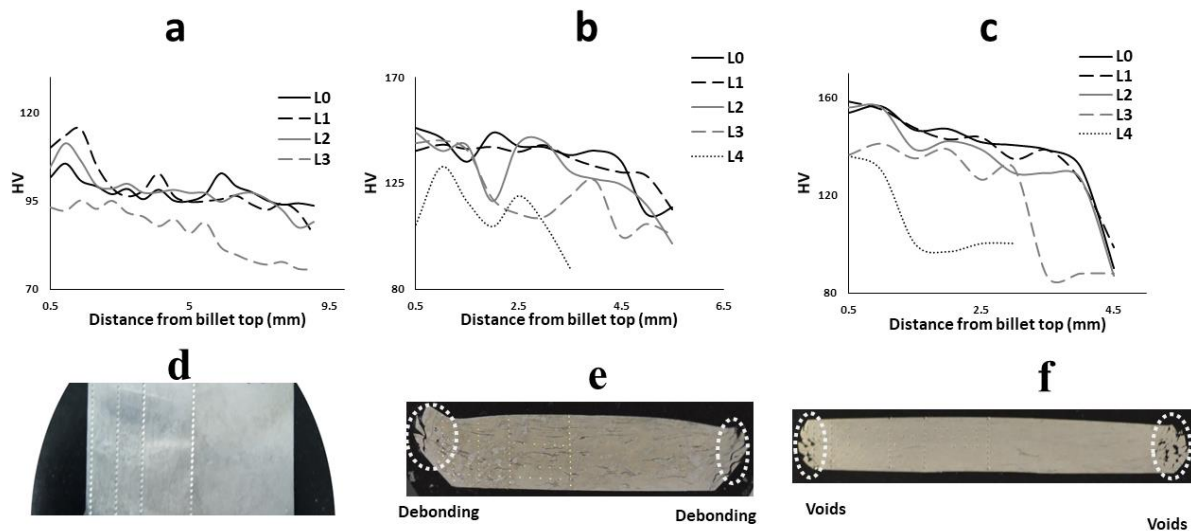


Figure 7. Hardness samples of mono-material AA 7075 (a) non-deformed, (b) forged, and (c) upset and polished section of (d) non-deformed, (e) forged, and (f) upset.

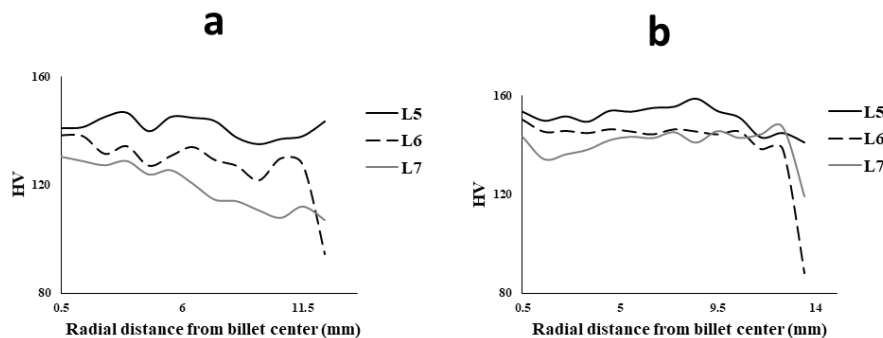


Figure 8. Hardness in radial direction of mono-material AA 7075. (a) forging, and (b) upsetting.

3.2. Results for bi-material billet

The first consideration can be drawn by analysing the hardness profile of the consolidated billets. It is possible to notice that the top part of the billet has a higher hardness value, while in the bottom part lower values were observed. The higher and lower hardness levels correspond to the hardness values of single material AA7075 and AA2011-T3 FSCed mono-material billet, respectively. In other words, in the non-mixing zones of multi-material billet, dissimilar materials retained their mechanical properties. In figure 9, the different trend at loci L3 is due to material flow occurring because of unavoidable backward extrusion. This phenomenon enables outer material moving upwards and extruding from the clearance between the punch and the die. This phenomenon, therefore, causes the upward flow of the AA 2011-T3 at the bottom of the billet, producing an early drop of hardness values. This aspect is well visible in figure 10 where the hardness in radial direction is reported. The drop in hardness of the interface trend is, in fact, due to the upward flow of AA 2011-T3. In the upsetting test, again an increase of hardness values is observed and again fractures can be observed in the very external area of the sample. The most interesting results concern the forging test, though; in fact, a sound sample was observed. No fracture or voids are visible and hardness profile with no oscillating values were collected, this is a quite unexpected result. In fact, large part of the billet is made of AA 7075 that exhibited a poor behaviour under forging conditions. This phenomenon can be explained by assuming that AA 2011-T3, being a material with lower mechanical properties (but better ductility) contributes significantly to the deformation mechanics preventing fracture or de-bonding phenomena occurring in the AA 7075.

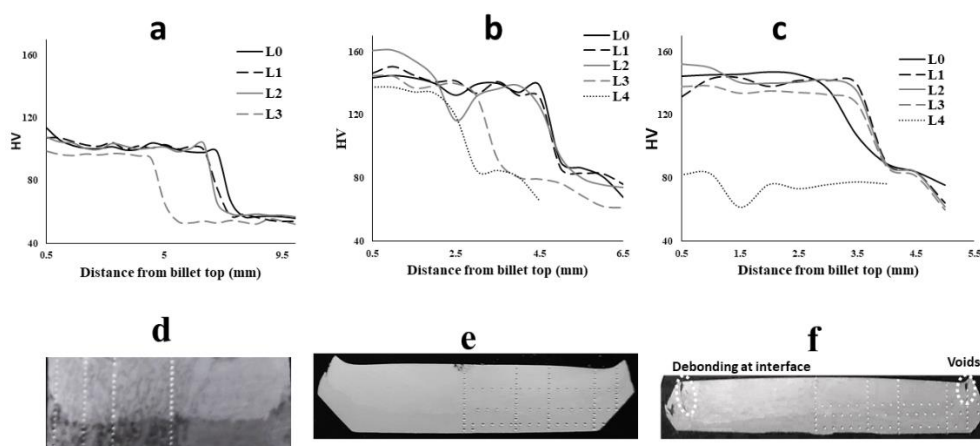


Figure 9. Hardness samples of bi-material AA 7075-AA 2011-T3. (a) non-deformed, (b) forged, and (c) upset and polished section of (d) non-deformed, (e) forged, and (f) upset.

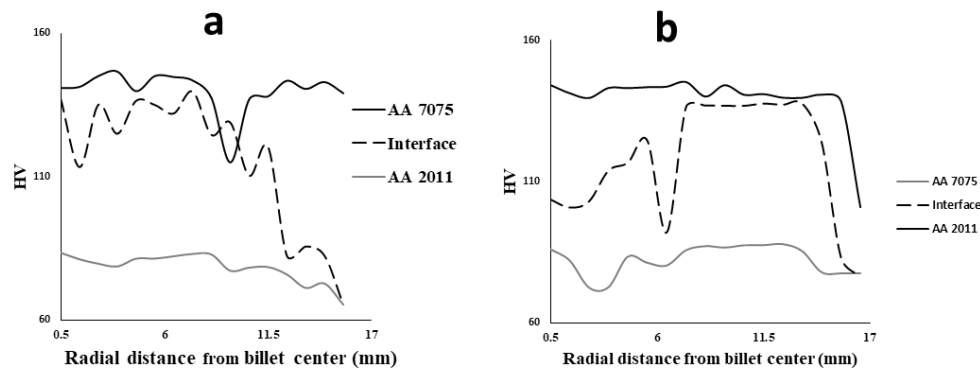


Figure 10. Hardness in radial direction of bi-material AA 7075-AA 2011-T3 (a) forging, and (b) upsetting.

4. Conclusions

In this paper, the forgeability of friction stir consolidated billets was analysed. Mono and bi-material billets were manufactured from two different aluminium alloys: AA 7075-AA 2011-T3 and tested by upsetting and forging. Based on the post-analysis of experimental data, the following conclusions are drawn:

1. Hardness of the FSCed billets significantly improved with forging and upsetting.
2. Crack in the form of debonding occurred at the outer external surface in the case of upsetting for mono-material billets. However, in the case of AA 2011-T3, very good results were observed, proving the effectiveness of the FSC process.
3. Overall, poor results were obtained for the AA-7075. This is due to the poor formability of the considered alloy. In this respect, the other alloys or an improved FSC approach should be analyzed in the future.
4. For bi-material billet, the detachment occurred at the interface of the two materials during upsetting. It has been proved that the FSCed billets possess good forgeability features. Furthermore, the bi-material billet performed better than the AA-7075 mono-material one. This result should be better explored by using numerical simulation to better understand the process mechanics.

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