Theoretical and Applied Mechanics - AIMETA 2022 Materials Research Forum LLC
Materials Research Proceedings **26** (2023) 713-118 https://doi.org/10.21741/9781644902431-114

Progresses in multi-materials billet manufacturing out of metal scraps through friction stir consolidation

Abdul Latif[1, a], Giuseppe Ingarao[1,b*], Livan Fratini[1,c]and Fabrizio Micari[1,d]

[1]Department of Engineering, University of Palermo, Viale delle Scienze, Palermo, 90128,Italy

[a]abdul.latif@unipa.it, [b*] giuseppe.ingarao@unipa.it , [c]livan.fratini@unipa.it,
[d]fabrizio.micari@unipa.it

Keywords: Friction Stir Consolidation, Solid State Technique, Recycling and Upcycling, Functionally Graded Material, Aluminum Alloys

Abstract. The evolution of Friction Stir Consolidation (FSC) from recycling towards upcycling technique proved to be one of the excellent solid-state methods for manufacturing functionally graded billets. Multi-material Functional Graded Materials (FGMs) represent a novel class of materials characterized by a gradual change in properties and functions which can be tailored to enhance components performance. Manufacturing techniques play a critical role in achieving the designed compositional and microstructural distribution. Specifically, FSC allows the manufacturing of FGM billets out of metallic chips; the mixing of different metallic chips offers mutually exclusive mechanical properties like high hardness and good ductility in a single FSC billet with excellent formability. The present research further explores some challenges while combining dissimilar aluminum alloys chips in different percentages and spatial order, especially in the radial direction. The mechanical and metallurgical properties were assessed through the Vickers hardness measurements and microstructure analysis. The results revealed that new strategies are needed for a better exploitation of FSC as a solid-state method for fabrication of Functionally Graded Material.

Introduction

The demand for aluminum is rapidly increasing due to its growing application. The accelerating consumption is putting immense pressure on industries to increase the production rate [1]. Roughly 100 million metric tons of aluminum are currently produced per year. However, per 1 ton of aluminum production from the primary source, 12-16 tons of greenhouse gas (GHG) are produced. Almost 35 % of the aluminum demand is met by recycling aluminum scraps [2]. The conventional recycling route skips many complex steps of aluminum extraction from the primary source, and therefore it is a highly energy efficient process. However, this method has further limitations, especially during the recycling of aluminum machining chips. Due to their high surface-to-volume ratio, these scraps are prone to oxidation, causing permanent material loss during the melting process. Therefore, the researchers turned to solid-state recycling (SSR) techniques.

SSR methods directly transform metal scraps into finished or semi-finished billet through mechanical means [3]. Recently, SSR processes have proved their energy and resource efficiency [4]. The new frontier of SSR processes could be their application for manufacturing multi-material functional graded semi-finished products. At the same time, there is an urgent need to find manufacturing solutions for obtaining multi-material components. So far, aluminum alloys have been successfully joined with magnesium alloys in bimetallic sheet applications [5]. Graded components are nowadays crucial for enhancing the performance of the product under mechanical, electrical, and environmental angles [6].

The authors have recently successfully applied FSC for producing multi-material based FGMs [7]. FSC has two main steps: compaction and consolidation. During compaction, chips or powder are pressed in a hollow die chamber by applying a specific load through a cylindrical tool. Then compacted materials are further pressed and stirred through high 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 multimaterial approach starting from AA 7075 and AA 2011-T3 chips [7]. Further, a discrete change in hardness profile was noticed, a property that is found in discontinue FGM. In the present research, chips of aluminum alloys AA 7075 and AA 2011-T3 were mixed at different proportions to get a continuous graded hardness profile like continuous FGM. Further, attempts were made to develop multi-materials based shell-core billet by combining the chips along the radial direction of the billet. The purpose was to extend the capabilities of the FSC process in manufacturing FGM. The quality of both continuous FGM and shell-core billets was evaluated by comparing the results with the previous study [7]. Hardness and microstructure are considered the main output criteria.

Material and methods

Material and process set-up

Aluminum alloys AA 2xxx and AA 7xxx were considered in the current studies because they are popular alloys in the transport and aerospace manufacturing industries where a good balance between the product in service and scraps [8] exists. The machining scraps were obtained from aluminum alloys AA 7075 and AA 2011-T3 through turning and milling operations, respectively. The scraps were cleaned by submerging them in acetone for 30 minutes. Mono-material billets were developed from chips of both AA 7075 and AA 2011-T3. Then chips of both alloys were combined under proportion (Fig. 1a) and spatial order (Fig .1b) to develop a bi-material billet. However, the overall mass of input material was 15g (constant) in all experiments. First, the chips were loaded in a cylindrical die with a nominal diameter of 25.4 mm and then compacted at 5 kN force by an H13 steel cylindrical tool with a 25 mm diameter. The die and pressing tool system was integrated with ESAB-LEGIO (Fig. 1a), a dedicated friction stir welding machine. The final consolidation step was applied at 20 kN with a high tool rotational speed of 1500 rpm.

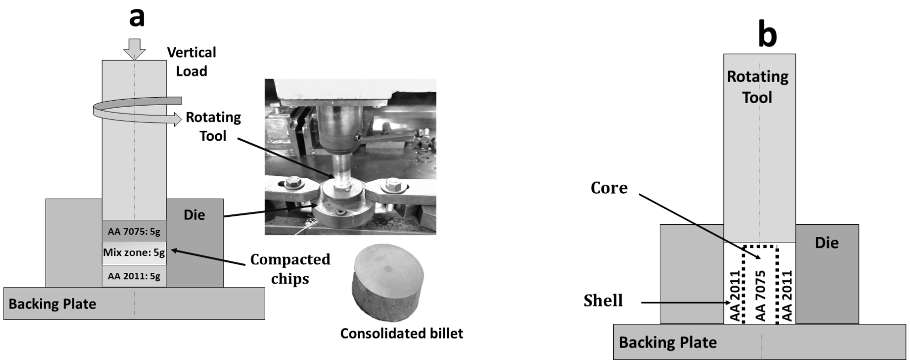

Figure 1. *FSC experimental setup of bi-material billet for (a) mixing chips at various proportion in the mid layer, and (b) chips combining for shell-core manufacturing*

Measured output

The formability of the FSC billet was evaluated with a forging test under cold conditions to turn the billet into near-net shape parts. The forging die and tool were coupled with Galdabini hydraulic press tensile testing machine (Fig. 2), and billets were reduced to 40% of the initial height.

The hardness was evaluated through the Vickers hardness measurement. A load of 49 N (5 kg) was used for 15 seconds. Due to process symmetry, the FSC billet was sectioned along the longitudinal axis, and only four lines were selected along the longitudinal direction, as shown in Fig. 3. Keller’s reagent was also applied to the cross-section to examine the microstructure of the samples.

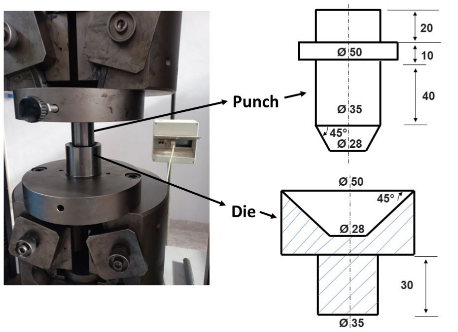

Figure 2. *Forging tool and die setup integrated with Galdabini tensile testing machine*

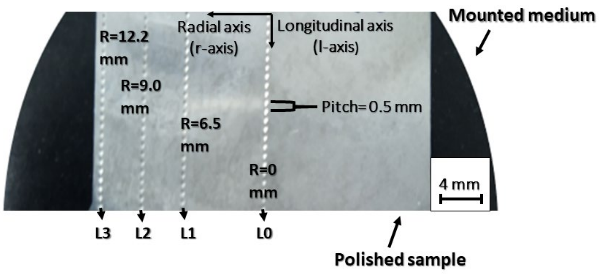

Figure 3. *Sample for Vickers hardness measurement*

Results and discussion

Hardness of the typical FSC bi-material AA 7075/AA 2011-T3 billet

Two factors were found that caused variation in the hardness of the bi-material billet. First was the material aspect, as material retained mechanical properties their properties in the case of bi-material billet [7]. Thus, the part of bi-material that consisted of soft material (AA 2011) showed lower hardness comparing the part that consisted of hard material (AA 7075). Second, a typical FSC mono-material billet is characterized by decaying hardness values along the longitudinal direction and radial direction due to different strain rates and thermal gradients during the FSC process.

Forgeability characteristics of bi-material AA 7075/AA 2011-T3 billet

Analyzing the cross-section of the forged section, a defect-free sample was observed for mono-material AA 2011 billet that showed good forgeability due to its good ductility. However, many defects in the form of debonding chips occurred near the external surface for the AA 7075 billet section (Fig. 4). The reason is that AA 7075 is a poorly ductile material. While combining AA 7075 and AA 2011 in a bi-material billet, the sample showed good forgeability without any defect. The reason was that AA 7075, exploited the good ductility of AA 2011 in the case of bi-material billet. Further, changes due to forging were analyzed by comparing the hardness profile of non-forged and forged bi-material. For the sake of better understanding, only hardness along one line (L0) was considered, as shown in Fig 5. Forged bi-material billet showed an increase in hardness due to strain hardening and a reduction in height compared to unforged billet.

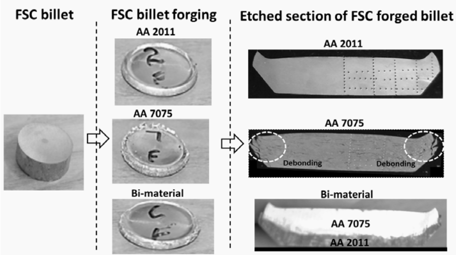

Figure 4. *Forged and etched samples of mono and bi-materials billets*

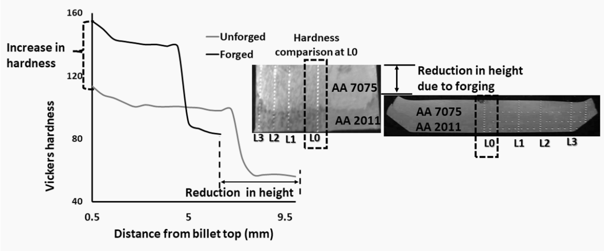

Figure 5. *Hardness profile comparison at L0 for bi-material forged and unforged billets*

Chips mixing of two dissimilar aluminum alloys in the middle zone of the billet

FSC process mechanics and material aspects are the main factors that cause variation in hardness. Comparatively changing material is more dominant than the FSC process mechanics factor. However, the material change causes abrupt variation in hardness and leads to fabricating billet with a hardness profile similar to a discontinuous functionally graded material. Therefore, attempts were made to control hardness based on material mixing and obtain a billet that possessed properties like continuous graded materials. Therefore, a three layers multi-material billet was developed, as shown in Fig. 6a. Each layer has a constant mass of 5g. AA 7075 chips were placed in the top layer, AA 2011-T3 existed in the bottom layer, while in the middle layer, both alloys were mixed at different proportions. For the sake of better understanding, the percentage of AA 2011 in the middle layer was considered a reference. An abrupt drop from higher to lower hardness value was found for 100% (Fig. 6b) and 0% (Fig. 6f) percent AA 2011 composition in the middle layer. In the case of 75 % and 25% the fluctuation trend was noticed in the transition zone, but still, the hardness profile was more inclined towards AA 2011 and AA 7075, respectively. For 50 %, a balance fluctuated hardness profile between AA 2011 and AA 7075 was observed. These results show that continuous hardness variation is not possible based on changing the proportion. The fact is also visible from the etched section (Fig. 7). Actually, the two alloys do not mix with each other to get a uniform solution because FSC is a solid-state process, and the process temperature does not reach to the melting point of aluminum alloys.

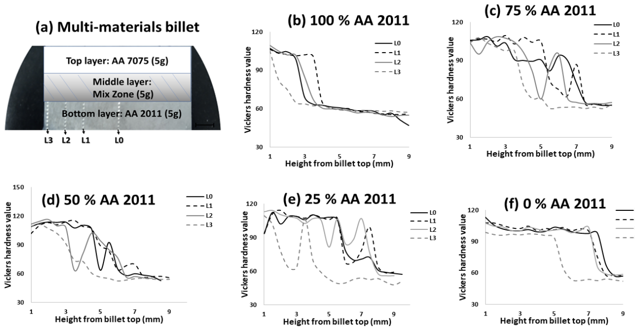

Figure 6. *Three layers multi-material billet (a) schematic, and hardness profile with percentage distribution of AA 2011-T3 in the middle layer (b) 100%, (c) 75 %, (d) 50%, (e) 25 %, and (f) 0%*

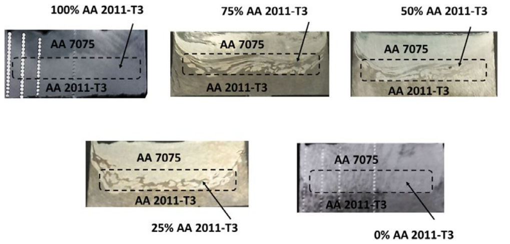

Figure 7. *Eetched section for bi-material billet with 100%, 75 %, 50%, 25 %, and 0% AA 2011-T3 distribution in the middle layer*

Bi-material billet in radial direction

Two different single-step strategies were applied to manufacture multi-material shell-core cylindrical billet from AA 7075 and AA 2011 chips.

Method I

In this method, a hollow flexible thin wall plastic cylinder was placed in the die. The plastic cylinder had a diameter less than the diameter of the die and was concentric with the die. AA 7075 chips were loaded inside the plastic cylinder and surrounded by AA 2011 chips (Fig. 8a). The plastic cylinder was carefully removed after chips compaction. Then the whole charge was consolidated. Keller's reagent was applied to analyze the billet section (Fig. 8b) as this method was previously proved to effectively differentiate the boundary between different aluminum alloys in multi-material billet [7]. Problems like the mixing of chips at the top zone of the billet and an irregular boundary line between the shell and core were found. It is assumed that problems were caused by material flow due to unwanted backward material extrusion, which will be discussed in the following section. Further, this strategy also involves manual steps. So, the next strategy was tested.

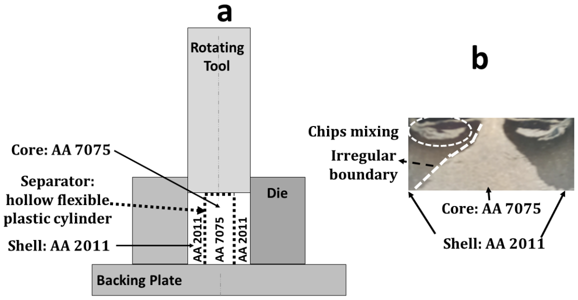

Figure 8. *(a) Method 1 schematic presentation for fabricating of shell-core multi-material billet, and (b) etched section of the shell-core multi-material FSC billet*

Method II

In the second strategy (Fig. 9), a solid cylindrical rod was placed inside the die, and the gap between the rod and the die was filled with AA 7075 chips (shell). Then hollow tool was used to press the chips AA 7075. The purpose of the rod was to develop a hollow shell of AA 7075 and provide support to the internal wall support of the compacted step. The surface of the supporting rod was also very well polished so that chips of the shell did not stick during the compression phase, and the rod could be easily removed. In the next step, cylindrical support was removed, and the cylindrical cavity was then filled with chips of AA 2011 for core development. A tool with a diameter comparable to the diameter of the core was used for chips compaction of the core. Finally, the whole charge was consolidated through the FSC tool. On analyzing the etched cross-section (Fig. 10) of the multi-material core-shell billet, again irregular boundary, chips mixing, and further non-symmetrical (along the longitudinal axis) core material distribution were found. These problems were caused by problems discussed in the previous method.

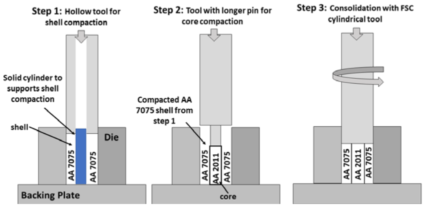

Figure 9. *Method 2 schematic presentation for fabricating of shell-core multi-material billet*

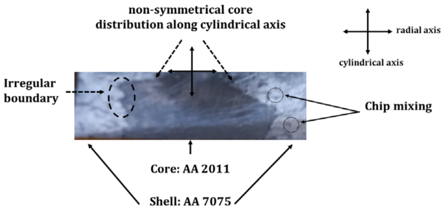

Figure 10. *Method 2 etched section ofthe shell-core multi-material FSC billet*

Additional challenges in manufacturing FSC multi-material billet

During the FSC process, unwanted material flow within the clearance between the tool and the die occurred. It is assumed that by proper selection of process parameters or at a higher technology readiness level (TRL), this unwanted material flow can be controlled [7].

Besides, it is challenging to numerically model a bi-material billet. As assigning two materials to a single billet is possible through phase transformation in Deform 3D software, but it is very difficult to obtain a discrete boundary between materials, even choosing a very refined mesh size.

Conclusion

FSC stir consolidation is an efficient technique to develop multi-material based FGM with excellent control on mechanical properties. Based on the previous discussion, the following conclusion can be drawn.

1. Mixing of different alloy chips at any proportion does not lead to develop continuous FGM. FSC is solid-state process and therefore, materials do not join to mix and form a uniform solution.
2. Multi-material shell-core billet is challenging to develop through a single-step FSC process.

3. Backward extrusion is the drawback of the FSC and can be controlled with a proper selection of key process parameters or at a higher technology readiness level.
4. The existing numerical model needs improvement to bring it closer to the real FSC process for proper modelling.

The future potential research in FSC could concern: 1/advanced mechanical and metallurgical characterization, 2/ numerical modelling and environmental assessment through Life Cycle Assessment methods.

References

[1] T.G. Gutowski, S. Sahni, J.M. Allwood, M.F. Ashby, E. Worrell, The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 371.1986 (2013): 20120003. https://doi.org/10.1098/rsta.2012.0003

[2] D. Raabe et al., Making sustainable aluminum by recycling scrap: The science of "dirty" alloys, Progress in Materials Science. (2022): 100947. https://doi.org/10.1016/j.pmatsci.2022.100947

[3] B. Wan, W. Chen, T. Lu, F. Liu, Z. Jiang, M. Mao, Review of solid state recycling of aluminum chips, Resources, Conservation and Recycling.125 (2017):37-47. https://doi.org/10.1016/j.resconrec.2017.06.004

[4] J.R. Duflou, A.E. Tekkaya, M. Haase, T. Welo, K. Vanmeensel, K Kellens, W Dewulf, D. Paraskevas, Environmental assessment of solid state recycling routes for aluminium alloys: can solid state processes significantly reduce the environmental impact of aluminium recycling?. CIRP Annals (2015) 64(1) pp 37-40. https://doi.org/10.1016/j.cirp.2015.04.051

[5] J.H. Bae, A.P. Rao, K.H. Kim, N.J. Kim, Cladding of Mg alloy with Al by twin-roll casting Scripta Materialia (2011) 64(9) pp 836-9. https://doi.org/10.1016/j.scriptamat.2011.01.013

[6] C. Zhang, F. Chen, Z. Huang, M. Jia, G. Chen, Y. Ye, E.J. Lavernia, Additive manufacturing of functionally graded materials: a review Materials Science and Engineering A (2019) 764 p 138209. https://doi.org/10.1016/j.msea.2019.138209

[7] A. Latif, G. Ingarao, L. Fratini, Multi-material based Functionally Graded billets manufacturing through Friction Stir Consolidation of aluminum alloys chips CIRP ANNALS, in press (2022). https://doi.org/10.1016/j.cirp.2022.03.035

[8] J.M. Allwood, J.M. Cullen, M.A. Carruth, D.R. Cooper, M. McBrien, R.L. Milford, M.C. Moynihan, A.C. Patel, Sustainable materials: with both eyes open, Vol. 2012, Cambridge, UK: UIT Cambridge Limited, 2012.