Effect of Plunge Depth on Weld Integrity of Friction Stir Welds of Dissimilar Aluminium and Copper

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***Abstract*— This paper presents the effects of plunge depth on the weld integrities of Friction Stir lap welds of aluminium and copper. 3 mm sheets of aluminium and copper were joined using the Friction Stir Welding (FSW) technique. The study focuses on understanding the relationship between the defects and the process parameters. The produced welds were characterized using visual inspection, microstructural evaluation and microhardness profiling. It was found that while all the typical FSW microstructural zones were present in the welds, the sizes of the voids observed in the welds were dependent on the plunge depth employed. Optimization of the processing parameters is in view.**

***Index Terms*—defect, dissimilar, Friction Stir Welding, plunge depth, lap**

I. INTRODUCTION

THE Friction Stir Welding (FSW) process has been recently described as the technology of the future with potential to become a fully commercialized welding technology in many industries [1], [2]. Friction Stir Welding (FSW) technique has revolutionized the welding community and changed the face of metal and plastic joining significantly. While the process is easily employed in the joining of similar metals, FSW towers above other means of joining as it has the ability to join dissimilar metals with more ease and much less problems compared to other metal joining technologies such as fusion welding.

Both aluminium and copper have received lots of attention from researchers globally. The interest derived from the properties of both metals include versatility, malleability, high electrical conductivity, universality, good corrosion resistivity, recyclability, aesthetics, antibacterial properties and lightweight among others.

Combining both aluminium and copper promises to be of great importance due to the different and important properties of both metals. Much effort had been put into the joining of aluminium and copper before the invention of FSW with little success [3]. Welding aluminium and copper has found important applications such as in bimetal cable plugs and lugs, inline connectors, contact adapters, heat sinks, battery tabs and in electrical vehicle batteries.

However, it is becoming increasingly possible to join aluminium and copper with much less problems using FSW. The method was used at the earlier stages in the joining of similar aluminium alloys in butt configuration and proved to be successful. Research proceeded to the joining of similar copper alloys also with notable success. With successes in the similar welding of both aluminium and copper alloys, over the years, research studies were also conducted on dissimilar materials and various levels of successes have been recorded [4], [5], [6], [7]. However, joining aluminium to copper has come with mixed results especially using the lap welding configuration [10], [11], [12].

The relationship between the surface area of the FSW defects and plunge depth has not been a subject of much interest in the research community. This is because a lot of previous studies focused on the use of a single plunge depth throughout most welding procedures. This present work reports the results from the Friction Stir lap welds of 3 mm sheets of aluminium and copper produced by varying the traverse speed and the plunge depth. The weld integrities were evaluated for microstructure and microhardness and the results are reported and discussed.

II. METHOD

3 mm sheets of aluminium and copper were welded in the lap welding configuration as shown in Fig 1 using the Intelligent Stir Welding for Industry and Research (I-STIR) Process Development System (PDS) FSW Machine by MTS Systems Corporation after the surface had been cleaned with acetone to remove impurities. The aluminium sheet was placed on top while the copper sheet was placed below the aluminium.

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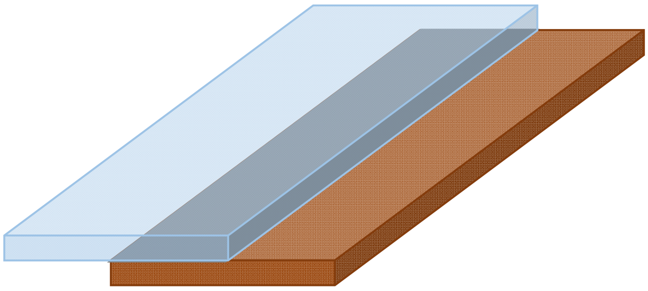

Fig 1: The lap weld configuration

Welding was done at 900 rpm while the traverse speed and the plunge depth were varied. The welds were produced as shown in Table 1.

TABLE 1
WELDING PROCESSING PARAMETERS

Weld Designation	Rotational Speed (rpm)	Traverse Speed (mm/min)	Plunge Depth (mm)
4.5_1	900	50	4.5
4.5_2	900	150	4.5
4.5_3	900	250	4.5
4.8_1	900	50	4.8
4.8_2	900	150	4.8
4.8_3	900	250	4.8

The welds were sectioned using a water jet cut-off machine in order to preserve the weld integrity and avoid any form of post weld heating. This is necessary in order to ensure that the microstructural integrity is maintained. Microstructural samples of 20 x 5 mm were mounted inside a polyfast thermoplastic hot mounted resin and etched before observations were made on the optical microscope. The copper was etched using a freshly prepared solution of Ammonia, Distilled Water and Hydrogen Peroxide, 3%, in the ratio 5:5:1 for 5 seconds while the aluminium was etched for 25 seconds using Flick's reagent. Microhardness profiling was done using a Vickers microhardness testing machine with a load of 200g for 15s across the weld interface. The results are presented in the next section.

III. RESULTS

A. Visual inspection

All the welds were observed to have voids. This is due to the material flow of the faying surfaces of both the aluminium and copper during the welding operation. A macrograph of one of the welds is presented in Fig. 2 and shows the typical hook and the kissing bond defect movement expected in FSLW as observed by Yazdanian and Chen [13] and Wang et al. [14]. However, the sizes of the cross sections of the areas with defects vary with varying process parameters.

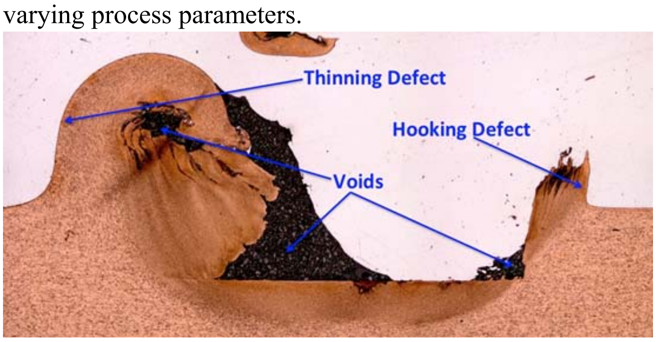

Fig 2: Defects observed and material flow

B. Defect size versus plunge depth

Table 2 presents the surface areas of the voids for each of the welds. It was found that the total surface area of each of the voids in the welds vary with the processing parameters.

TABLE 2
TOTAL SURFACE AREA OF VOIDS IN THE WELDS

Weld Designation	Defect Area (mm^2)
4.5_1	1.82
4.5_2	1.83
4.5_3	0.23
4.8_1	0.70
4.8_2	0.39
4.8_3	0.66

It was observed that the sizes of the surface areas of the voids vary with the plunge depth. An increase in the plunge depth resulted in a decrease in the surface area of the defects. The micrograph showed a better flow for both the copper and aluminium alloys at the higher plunge depth than the lower plunge depth. It is suggested that the higher plunge depth benefits from a higher vertical force of the tool, resulting in the better material flow observed. It is however expected that the good material flow observed eventually peaks at a peak plunge depth, above which the material flow is not anticipated to improve further.

C. Microstructure

Four (4) different microstructural zones were observed for both the aluminum and copper parent materials as normally experienced in typical FSW welds. These are the unaffected Base Material (BM), Heat Affected Zone (HAZ), Thermomechanically Affected Zone (TMAZ) and the Weld (Nugget) Zone (WZ). Figs. 3 and 4 show the microstructural images of the parent materials and the different microstructural zones respectively.

Fig 3: Microstructural images at 50x magnification using the optical microscope showing (a) Cu parent material (b) Al parent material (c) Cu Heat affected zone (HAZ) (d) Cu Thermo-mechanically affected zone (TMAZ)

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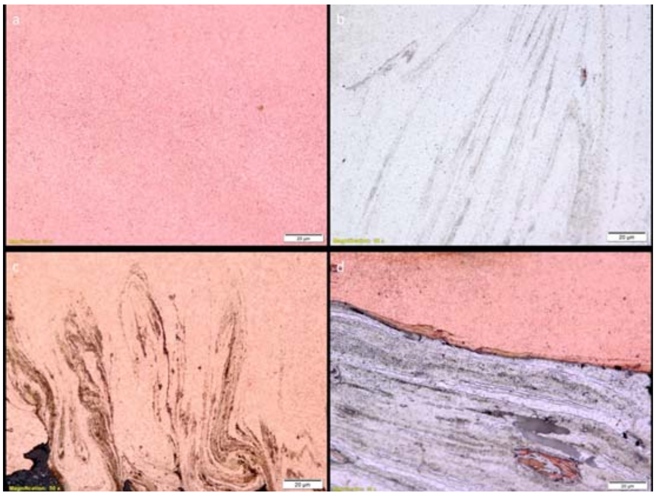

Fig 4: Microstructural images at 50x magnification using the optical microscope showing the weld zones (WZ) of (a) Cu side only (b) Al side only (c) Cu side with material flow (d) Cu and Al sides with material flow

The parent material shows the copper having equiaxed grain structure while the aluminium possessed elongated grains. As a result of the welding, microstructural analysis showed a decrease in the grain sizes in the HAZ, TMAZ and WZ compared to the original parent copper grains. However, the changes in the grain sizes of the aluminium was not significantly different in all the microstructural zones. This is due to the aluminium alloy that was used in the study due to age hardening and manufacturing procedures as explained by Mishra et al. [15].

Grain thinning and elongation were observed in the HAZ of the copper while maintaining the equiaxed structure of the PM. The grains in this zone were larger when compared to the grains of other zones except for the unaffected BM. This same trend was observed by Miličić et al. [16].

The FSW process resulted in grain refinement of the copper due to the heat input during welding process, the effect of the rotating tool and the dynamic recrystallization of the grains at the TMAZ and WZ. However, the basic grain structure of the copper and aluminium grains were maintained.

The distinct interfacial region between the aluminium and copper grains shown in Fig. 4(d) results from the wettability of both aluminum and copper alloys used in the study. While it is normally expected that the grains of both the aluminium and copper will mix freely during welding due to the effects of the rotating tool, the differences in the thermal conductivities and diffusivities of both alloys result in the interfacial region observed. This prevented the proper mixing of the grains of both metals.

D. Microhardness Profiling

While the copper parent material was observed to have a Vickers microhardness value of HV 91.8, the aluminum had a value of HV 37.7. The Vickers microhardness profiles of the welded samples are presented in Fig 5.

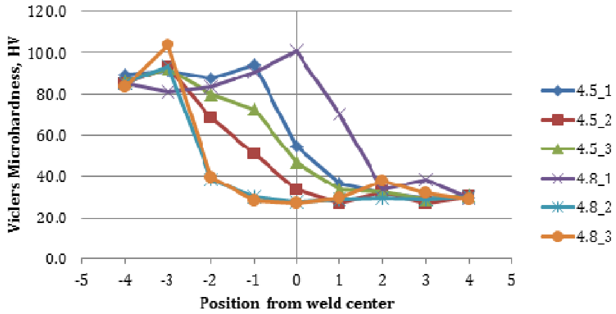

Fig 5: Microhardness profiles of the welds

For all the welds, it was observed that the microhardness values obtained were close to the microhardness values of the parent materials both at the aluminium and copper sides of the welds. This indicated that the heat input into the welds had little effect on the microhardness properties of the metals. This also suggested the absence of the formation of intermetallic compounds within the grains of the welds. The minor increase in HV of the copper side compared to the parent copper at HV 91.8 is due to the grain refinement according to Hall-Petch relations as observed by Morris [17].

IV. CONCLUSIONS

The Friction Stir lap welds of aluminium and copper sheets have been produced at 900 rpm and 4.5 and 4.8 mm plunge depths. The results obtained have been presented and discussed. The areas of the defects observed have been correlated to the processing parameters employed. The total surface areas of the voids were seen to decrease with an increase in the plunge depth.

Microstructural analysis revealed grain refinement at the HAZ, TMAZ and WZ of the copper while the aluminium grains showed little signs of grain refinements. However, the equiaxed grain structure was maintained for the copper grains in all the microstructural zones. Microhardness profiling suggested the absence of the formation of significant amounts of intermetallic compounds. The range of the processing parameters and the plunge depths considered in this research study need to be optimized to produce lap welds with sound integrity.

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