Optimisation of Friction Stir Welding Parameters Using the Taguchi Technique for Dissimilar Joining of AA5083 to Copper

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Abstract

This work reports on the impact of process parameters on the intermetallic compound formation and the resultant mechanical properties of aluminium grade AA5083 to copper joints created by friction stir welding. The effect of welding speed (hence cooling rate), tool rotational speed, material placement, and tool design are considered in this analysis. The Taguchi design of experiments (DoE) was applied to identify the significant parameters that affect FSW joints' mechanical strength and to reduce the number of experiments required to optimise joint efficiency. The aluminium to copper FSW joints exhibited diverse intermetallic compounds, such as Al_2Cu, AlCu, and Al_4Cu_9, and their evolution was found to be controlled by the tool rotational and welding speed. The highest ultimate tensile strength of 194.5 MPa was achieved at 1500 rpm tool rotational speed, 100 mm/min traverse speed, and zero tool offset.

Keywords friction stir welding, dissimilar joining, joint integrity, metallurgy, intermetallic compounds

1. Introduction

Dissimilar welded joints between copper and aluminium offer an attractive solution in engineering systems, where the partial replacement of copper with aluminium maintains the electrical properties of the former in parallel with the lower cost and lightweighting benefits of the latter. Such applications include, but are not limited to, shell and tube heat exchangers, electrical connections such as capacitor windings, and transformer conductors. Despite the above-mentioned merits of this partial replacement approach, a range of challenges exist due to the mismatch in the thermal, physical, and metallurgical properties of each metal. The solid-state friction stir welding (FSW) process has the potential to replace conventional fusion joining methods due to its ability to produce defect-free dissimilar metal and alloy joints of high quality.

2. Taguchi approach and orthogonal array selection

This work aims to optimise the dissimilar AA5083 to copper FSW process parameters by applying the robust elimination process of the Taguchi method. The obtained process parameters are then less sensitive to changes in any remaining, uncontrolled parameters, e.g., environmental conditions, user input, and other factors. This elimination process using the Taguchi method requires a specific orthogonal array (OA) design to identify the overall process parameters and the least number of experiments. Herein, the tool rotational speed, tool welding speed, and tool design were found to have a major impact on the joint quality. Consequently, the OA was designed to involve these three process parameters, each on a three-level range; this resulted in an L9 (3^3) OA. The joint ultimate tensile strength (UTS) was considered as a characteristic property, allowing for the statistical analysis of variance (ANOVA) method to be applied to specify the significant effect of each parameter. Ultimately, FSW joints were repeated to confirm the predicted optimal levels that resulted from the ANOVA method.

3. Experimental methodology

3.1. Experimental setup: Dissimilar friction stir butt welds of AA5083 to commercial pure copper were produced using a fully instrumented HT-JM16X8/2 static gantry FSW machine. The plates of AA5083 and copper had dimensions of 150 x 50 x 3 mm^3, resulting in an overall welded plate width of 100 mm, hence allowing for sub-sized tensile specimens to be manufactured. The influence of three different FSW tool designs was considered together with two more process parameters (tool rotational and welding speed). A simple tool design (S) and tapered tool pin design (T), which were both equipped with a shoulder of 18 mm in diameter and 2.7 mm pin length, and a relatively larger tool design (L) with a shoulder of 22 mm in diameter and similar simple tool pin design of 4.5 mm in diameter, were the three tool designs to be investigated.

3.2. Materials and FSW process details: The chemical composition and mechanical properties of the AA5083 and commercially pure copper parent materials were established prior to welding. Defect-free welds were consistently achieved by placing the softer material (AA5083) on the advancing side (AS), whilst the FSW tool was always centred on the seam line, i.e., no tool offset. Hence, the Taguchi OA was designed to compute the influence of tool rotational speed, tool welding speed (ω/v ratio), and tool design on the dissimilar joints' mechanical integrity. This study assessed process parameters in the range of 1000-1500 rpm tool rotational speeds and 80-120 mm/min welding speeds.

3.3. Microstructural characterisation and mechanical testing: Metallographic samples of the produced welds were prepared using standard metallographic techniques in accordance with ASTM E407-09. A two-stage etching process was implemented to allow high resolution optical and scanning electron microscopy (SEM) to be undertaken. Energy dispersive spectroscopy (EDS) was used to analyse the different weldment zone compositions and X-ray diffraction (XRD) analysis was carried out to confirm the presence of intermetallic compounds (IMCs). Subsequently, Vickers microhardness measurements were recorded to further evaluate the dissimilar FSW butt joints. Tensile testing of the sub-sized specimens extracted transversely to the weld direction was performed in accordance with ASTM-E8.

4. Results and discussion

4.1. Signal to noise ratio selection: In this work, the joint UTS was considered as the quality characteristic factor of response, allowing for the impact of tool rotational speed, tool welding speed, and tool design to be independently evaluated using the Taguchi optimisation technique. Larger-the-better signal to noise (S/N) ratio method was considered to identify the significant order of effect and percentage contribution of each factor on the joint UTS. As a result, 9 means of UTS and 9 S/N ratios were generated, allowing for a statistical analysis to be conducted to achieve the maximum response value (UTS). Consequently, the optimum level of each process parameter (ω, v, and tool design) was considered at the highest S/N ratio. A 1500 rpm rotational speed, 100 mm/min welding speed, and the relatively larger shoulder design (L) were the optimal levels that resulted in the highest joint UTS. Additionally, the ANOVA method was applied to verify that the chosen process parameters are significantly affecting the dissimilar joint UTS. It was found that the tool rotational speed, tool design and tool welding speed are the significant order of effect, from high to low, on the joint UTS.

4.2. Prediction of joint UTS: the objective of the herein proposed optimisation process is to accurately predict the joint mechanical performance as a function of the most significant process parameters. It was established that the joint UTS in dissimilar FSW of AA5083 to commercially pure copper can be predicted as: $\text{UTS (predicted)} = \omega^{(3)} + v^{(2)} + L^{(3)} - 2\text{T}$, where:

$\omega^{(3)}, v^{(2)},$ and $L^{(3)}$ represent the average UTS at 1500 rpm (level 3), 100 mm/ min (level 2), and the L type tool design (level3), respectively. T reprsents the overall mean of UTS in MPa.

5. Conclusions

- Successful weld joints between AA5083 and commercially pure copper were achieved by placing the softer material (AA5083) on the AS at different levels of FSW tool rotational speed, tool welding speed, and tool design.
- The significant order of effect on the joint UTS, from high to low, was found to be ranked as: tool rotational speed, tool design, and tool welding speed. The tool rotational speed was found to have a principal effect on the joint mechanical integrity.
- A good agreement between predicted and actual values of UTS was achieved.