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Technical Paper

Effect of tool geometry and welding speed on mechanical properties of dissimilar AA2198–AA2024 FSWed joint

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ABSTRACT

Different tool geometries were used to investigate the joining of aluminum alloys (AA2198 to AA2024) by friction stir welding (FSW). Three shoulder profiles (flat, raised spiral, and raised fan) and five different pin profiles (cone, half threaded cylindrical, straight cylindrical, tapered cylindrical and square) were selected. Preliminary investigations were conducted by moving the tool into a seamless sheet made of the AA2024-T3 in order to select the tools that produce defect-free joints. Preliminary investigations showed the raised fan shoulder profile helps the material flow from the edge of shoulder to the pin creating a smooth surface finish with no flash in comparison with flat and raised spiral shoulder profiles. Pins with a minimum diameter equal to half the plate thickness produced lack of penetration (LOP) defects, while increasing minimum pin diameter to the plate thickness eliminates the LOP defects. Half threaded cylindrical pin produced tunneling defect, whereas defect free joint made by straight cylindrical, tapered cylindrical and cubic pin profiles. So they were selected for joining AA2024 to AA2198. Fracture locations of different joint variants were observed the vicinity of the thermomechanical affected zone (TMAZ) of AA2198-T3 alloy, and in the nugget on the AA2198-T3 side which have the minimum hardness and highest strain localization as confirmed by hardness maps and digital image coronation (DIC). Higher measured temperature than dissolution temperature of AA2198 main strengthening precipitates could be the reason of low hardness and fracture in TMAZ and center of nugget. Furthermore a raised fan shoulder with a tapered cylindrical pin produced highest elongation and yield strength and it was selected as the best candidate for optimization of the welding parameters. It was found that higher rotational and traverse speeds enhance the formation of tunneling and kissing bond defects, suggesting that longer pins have to be used for higher traverse speeds. Welding speed 750 rpm with 450 mm min^{-1} could create joint with highest yield strength.

1. Introduction

Friction Stir Welding (FSW) is an emerging solid state joining technology that has been successfully used in the aerospace industry as an alternative to riveting for the assembly of airplane fuselage panels made of conventional AA2xxx and AA7xxx alloys [1–3]. The specific properties of structural materials, i.e. the ratio of the selected mechanical property to the material density, constitute one of the main drivers in material selection in the aerospace industry. The addition of one weight percent of lithium to aluminum alloys has been shown in the literature to decrease the density by about 3% and increase the Young's modulus by 6%, leading to a substantial increase of the specific Young modulus (E/ρ) [4]. These benefits after extensive researches led to the successful development and commercialization of the 3rd generation Al–Li alloys (e.g., AA2198), which have excellent combinations of specific properties, as compared to their conventional counterparts (e.g., AA2024) [5].

Aerospace industry is interested to replace conventional aluminum alloys with new generation of Al–Li alloys for mass gain purpose. Nevertheless, Al–Li alloys still remain relatively expensive. An economical weight reduction solution for structural components involves using hybrid designs with AA2198 alloys for critical regions, and keeping the remaining regions of the structure in AA2024. Thus, joining of aluminum alloys to Al–Li alloys appears as a necessity. However, there are relatively few papers on this specific joint, and particularly on optimum conditions for obtaining sound dissimilar FSW joints.

Tunneling defect, flash and kissing bond are common defects of FSWed joint. It is reported that kissing bond decreases the fatigue life

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time [6]. While, it does not affect significantly the tensile strength [7,8]. The key to producing reliable joints by the FSW process is to concurrently select the optimum welding tool and process parameters [9]. Shoulder profile affects the material flow [10], and its optimum design is critical for producing defect-free joints. Some studies have reported either shoulder profile [11–13] or pin design [14–20] effect on the mechanical properties of FSWed joints. Flat shoulder profile with conical pin is the simplest design and has been used successfully for joining aluminum alloys [21,22]. Also, adding a step to a conical pin [23] and half screwed pin (in comparison to full screwed) [24] was shown to increase the joint mechanical properties and to eliminate the cavity defect. The weld prepared by square pin profile results in smaller grain size and higher mechanical properties [18,25]. They were reported to produce defect free joints, irrespective of welding speeds [26]. As mentioned, appropriate process parameters have an important role to produce a sound weld. A low rotational speed or a higher traverse speed cause tunneling defect and kissing bond due to insufficient material mixing as the heat input is too low and the material is not soft enough [27]. On the other hand, a combination of high speeds and high traverse speeds causes cavities due to abnormal stirring [28]. In the range of optimized welding parameters, increasing the traverse speed in the presence of a constant rotational speed improves joint mechanical properties [29], while increasing the rotational speed results in higher heat input and lower mechanical properties [30]. It should be noted that close to the solidus temperature of the material, the rotational speed has negligible effect on mechanical properties due to self-stabilizing phenomenon [31,32].

The FSW parameters were optimized for several dissimilar joints between AA2024 to 5xxx series [33], 6xxx series [34,35] and 7xxx series [36]. Dissimilar friction stir welding of AA2024-T3 and AA2198-T3 in butt-joint configuration has been already investigated in terms of microstructural and specific mechanical characterizations for a particular configuration [37,38], but no research on optimization of friction stir welding tool geometry and parameters for joining dissimilar AA2024 and AA2198 joints has been reported in the open literature. Optimized welding parameters for producing similar butt joints for each alloy, AA2024-T3 and AA2198-T3, have been proposed in the literature [2,39–42]. The optimized rotational speeds are actually close for both alloys in the thickness less than 10 mm, while the optimized traverse speed for AA2024 is yet lower (73 mm min^{-1} vs. 300 mm min^{-1}). Therefore, a trade-off in terms of welding parameters must be found for the welding of AA2024 to AA2198.

In this study, the effect of the shoulder geometry and pin profile on the microstructure and mechanical properties of FSWed AA2024-T3/AA2198-T3 joints is documented. To that end, three different shoulder and five pin geometries were used to produce a FSW pass in an AA2024 plate for a given set of welding parameters. Macrograph observations were done to evaluate the occurrence of defects such as tunneling, kissing bond, and flash. Tensile properties (yield strength, ultimate tensile strength, and ductility) of the different welds were investigated to understand the effect of tool geometry and select an optimal tool design. To assess the influence of FSW welding speed on the mechanical properties of the joints, different traverse speeds in the range of 50–450 mm min^{-1} with two different rotational speeds, 750 and 1000 rpm, were investigated with the optimal tool. Fractographic analyses in combination with microhardness maps and Digital Image Correlation (DIC) technique were used to investigate microstructural features responsible for the fracture.

2. Experimental procedures, materials and methods

2.1. Base materials

Base materials consisting of AA2024-T3 and AA2198-T3 rolled sheets with a thickness of 3.2 mm were used. The nominal chemical compositions of these base materials are reported in Table 1.

2.2. Tools and fixture designs

A specific fixture was designed to increase the repeatability rate of the friction stir welding process, as shown in Fig. 1. The welding direction, the cross-weld direction and the normal direction are denoted WD, CWD and ND, respectively. Stoppers, supporters, and clamps were used to fix the plates in these directions, respectively. Clamps and supporters are equipped with screws, and so they apply opposite forces to the ND and CWD directions, while there is no need to apply any force in the welding direction due to the application of the welding force. The supporters and clamps were fixed with a torque wrench to ensure that reproducible forces were applied during the different welding tests.

Seven tool designs, denoted from A to G in Fig. 2, were designed and manufactured based on literature recommendation. The formulas for calculating the specific tool dimensions are shown in Table 2. AISI 4340 steel hardened up to 49 HRC by quenching and tempering before machining was selected for the tool material, as recommended by Ref. [45].

2.3. Welding process

The first step in the present study was to find the appropriate tool geometry for friction stir welding of AA2024-T3 and AA2198-T3. Two series of welds were produced and investigated. The first of these series were made by moving the tool into a seamless one piece of the AA2024-T3 sheet (i.e., bead-on-plate weld) in order to select the tools that produce defect-free joints on the basis of metallography and visual examinations. The second series was produced using dissimilar welding of AA2024-T3 and AA2198-T3 plates. Then, the tool that could produce a joint between AA2024 and AA2198 with the highest yield strength was selected as the best candidate for further optimization. To optimize the welding for the selected tool, combinations of traverse (ν) and rotational speeds (ω) used in the present study and their related sample codes are presented in Table 3 with heat input index [47,48] which is a candidate for the representation of the average thermal profile during welding. The rotation speed, the welding traverse speed, the plunge depth and the tilt angle were 750 rpm, 50 mm min^{-1}, 0.2 mm, and 0°, respectively. Sodium hydroxide solution (20 g NaOH + 100 mL H_2O) was used in order to remove the material stuck to the tools between experiments. For the dissimilar configuration, AA2024 plates were placed on the retreating side (RS), with the weld direction perpendicular to the transverse direction (TD), and on the advancing side (AS), AA2198 plates were placed with their rolling direction (RD) perpendicular to the welding direction. This configuration was chosen because the tensile properties of AA2024-T3 in transverse direction are comparable with those of AA2198-T3 in the rolling direction [38]. Consequently, this configuration could maximize the joint efficiency in the tension condition.

2.4. Sample preparation and mechanical tests

The FSWed samples were prepared for metallographic observations using standard polishing procedures down to 1 μm diamond paste followed by BUEHLER Vibromet polishing for 48 h, with a 0.05 μm colloidal silica solution. A Keller etchant was employed for 15 s to reveal the microstructure. Optical micrographs were obtained with an OLYMPUS Lext OLS4100 laser scanning confocal microscope. Tensile test samples for base metals were done on TD and RD directions for AA2024 and AA2198, respectively. Tensile specimens were machined from the welded plates such that the loading direction was parallel to the cross-welding direction of the joined plates. Specimens were extracted from both base materials to provide a reference, and from the joints, as specified in Fig. 3a (the joint being centered in the specimen gage). Tensile tests were performed on dog-bone tensile specimens with the geometry displayed in Fig. 3b. As the tool plunging into the material surface produces sharp edges which are stress concentration sites, the