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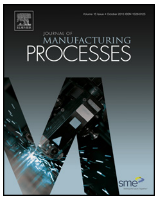

Technical Paper

Friction stir lap joining of 2198 aluminum–lithium alloy with weaving and pulsing variants

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ABSTRACT

Lap joints of 2198-T8 Al–Li alloy in 0.063 in. sheet thickness were friction stir welded to investigate the combination of this material and assembly method for the manufacturing of aerospace structures. Along with conventional friction stir welding (FSW), weaved FSW and pulsed FSW (PFSW) were evaluated to determine the potential impact of these variant technologies on weld strength. Additionally, a more traditional flat shoulder tool geometry operated with a tilt angle was compared to a tapered shoulder tool geometry operated at a 0° tilt angle, which offers the possibility of simplifying robotic welding operations. Faying surface sealant, the use of which is critical in aerospace applications, was investigated as well, to determine its impact on weld strength and to characterize its interactions with welding parameters and process variants.

List of symbols

ANOVA	analysis of variance
FSW	friction stir welding
IPM	inches per minute
P	pause length
R	weave radius
rpm	revolutions per minute
T	torque
TMAZ	thermo-mechanically affected zone
UTS	ultimate tensile strength
σ_y	yield strength
Z	axial force

1. Introduction

As composite and metallic airframe construction methods compete for dominance in the aerospace marketplace, much attention has been paid to the support technologies that are key enablers of these methodologies. In the production of metallic fuselages, wings, and other aerostructures, friction stir welding (FSW) has rapidly gained acceptance as a rivet replacement technology [1] which, when paired with new alloys, has enabled metallic construction methodologies to remain relevant and maintain a semblance of 'leading-edge' technology. Specifically, FSW enables the joining of metallic structures at significantly higher rates than riveting, along with having the advantages of reduced weight, reduced part count, increased joint strength, and lower overall manufacturing costs. Major aircraft manufacturers including Airbus, Embraer, and Bombardier, along with Eclipse Aerospace, in particular, have all committed resources to evaluating existing and developing new FSW technologies and incorporating them into the production of metallic airframe structures [2–7].

The dominant materials utilized in these metallic structures have been 2xxx and 7xxx series aluminum alloys, forming the aircraft skin and high strength structural members, respectively. A significant amount of research has been focused on friction stir welding this particular dissimilar combination of materials in both butt and lap joint configurations [8–14]. Recently however, more modern alloys, including the third generation of aluminum–lithium (Al–Li) alloys, have emerged enabling metallic structures to keep pace with composites on the critical fronts of weight efficiency, cost, and safety. More specifically, the latest iteration of Al–Li alloys exhibits improved performance with respect to density, stiffness, isotropy, fatigue crack growth resistance, fracture toughness, and corrosion resistance [15,16]. These alloys have also paired well with FSW as a joining method to offer an intriguing combination for manufacturers to consider [17,18]. The research community has taken notice as well, with a perhaps telling amount of work being

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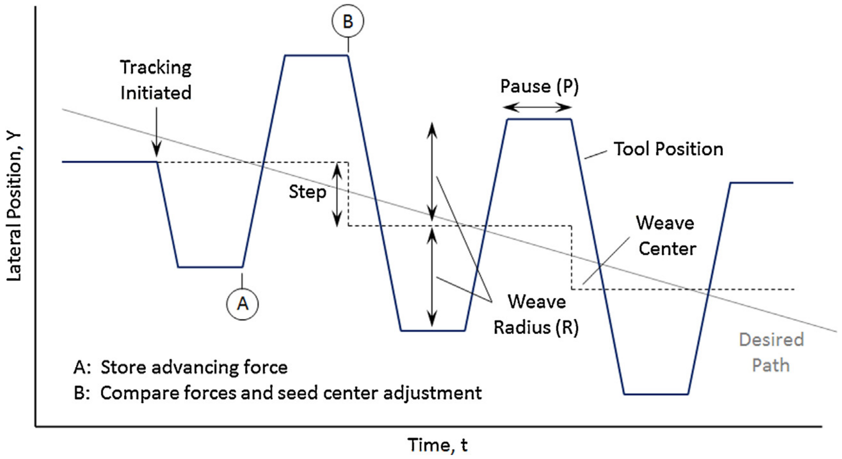

Fig. 1. Three cycles of WeaveTrack.

conducted on FSW of Al–Li alloys [19–31], with particular emphasis on 2198. Other Al–Li alloys receiving attention including 2199, viewed as a viable candidate for aircraft skin, and 2099 extrusions, which would be used to form internal structural members [32].

An additional aspect of FSW utilization in the construction of metallic structures for aerospace applications that has been studied recently is the incorporation of corrosion prevention measures. Faying surfaces of joints are subject to in-service crevice or galvanic corrosion attack, and as such, technology has been developed that allows for sealants to be applied within the joints prior to welding [33]. Sealants migrate away from the joint line during welding, cure, and then protect against corrosion for the life of the joint. Specific research in this area has focused on sealant performance and impact on weld quality [34,35], extension to friction stir spot welding [36], in-process quality evaluation of sealant application [37], and the exploitation of sealant presence to enable automatic path tracking [38]; the latter papers, referenced throughout the present study, are indicative of the trend toward increased use of industrial robots in aerospace manufacturing for tasks other than part handling or conveyance, such as sealing and dispensing [39].

Given the aforementioned trends in aerospace manufacturing, involving advanced materials, joining methods, and corrosion prevention, the objectives of the present study are to build upon previous work in these areas and focus on some remaining unanswered questions. More specifically, these objectives focus on joining Al–Li with FSW, the exploration of FSW process variants, the impact of tool geometry, the incorporation of sealant within the joints, and the interactions of these items. The objectives are:

1. Determine optimal parameters for joining thin section 2198-T8 Al–Li sheet in a lap joint configuration. Incorporate FSW variants pulsing (cyclical variation in tool rotation rate) and weaving (cyclical variation in lateral tool position) and determine the resulting effects on weld shear strength.
2. Compare the traditional lap joining themes of flat shoulder geometry, high tilt angle, and high welding speed with a non-traditional combination of a tapered tool shoulder and welding at 0° tilt, which effectively eliminates a degree-of-freedom required of a welding robot.
3. Examine the interaction of welding parameters and tool geometry with the dynamics of sealant within the weld joint. Conclude how this interaction would affect in-process sealant quality evaluation and automatic sealant path tracking capabilities.

Weaving, or weaved FSW, is a process variant that arose from the development of a lateral position detection and control system for FSW [40]. This is a through-the-tool joint tracking technique that was inspired in part by successful through-the-arc sensing techniques in arc welding [41]. Fleming et al. first determined that blind FSW T-joints have a characteristic axial (Z) force signature as the position of the tool varies laterally relative to the location of the vertical member [42]. An extremum-seeking control technique known as WeaveTrack was then developed that weaves the tool side to side laterally while monitoring force values and makes periodic lateral position adjustments to seek a varying maximum force and thus track the workpiece [43]. A diagram of this cyclical process is displayed in Fig. 1.

Parameters affecting the performance of WeaveTrack include the weave radius (R), the lateral velocity, the pause length (P), the step size, the step threshold, and the welding speed. It has also been demonstrated that WeaveTrack is effective at tracking lap joints with an overlap width equal to the tool shoulder diameter with either axial force or torque (T) as the feedback signal [44] and at tracking blind paths outlined by between-sheet sealant in lap joints with the controller modified to track a varying minimum axial force [38]. The effect of weaving the tool side to side laterally on the mechanical properties of the joints has been examined as well, as it was suspected that weaving action would promote increases in the thermo-mechanically affected zone (TMAZ) width, which is critical for lap joint strength and has been the driver of other FSW tool designs and technologies [45,46]. Hendricks conducted the most comprehensive study, focused on lap joining Al 6061 in 0.125 in. thickness. It was found that weaving can indeed increase the strength of lap joints as compared to conventionally welded counterparts, with weave radius standing out as a critical parameter. Diminishing returns with increasing weave radii or even detrimental effects and a repeating surface defect were possible at the highest weave radii tested [47]. A characteristic, scalloped surface finish along which lap welds tended to fail in tension-shear testing has been documented for weaving as well [38]. An examination of these issues, both the advantages and disadvantages of weaving, has inspired aspects of the present study, especially with regard to flat versus tapered shoulder geometry and the resulting weld surface finish.

Pulsing, or Pulsed FSW (PFSW), is another technology that has grown from the exploration of potential extensions of arc welding techniques into FSW processes. The pulsation of welding current can be beneficial in the arc welding of aluminum alloys with regard to heat dissipation and the prevention of hot cracking [48]. It was believed that the pulsation of parameters, such as tool rotation rate or welding speed, in FSW could have benefits as well, ranging from improved process symmetry to increased heat dissipation