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Weld zone and residual stress development in AA7050 stationary shoulder friction stir T-joint weld

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ABSTRACT

This paper shows the potential of stationary shoulder friction stir welding (SSFSW) for producing higher quality T- section joints relative to a conventional friction stir welding (FSW) approach. The residual stress distributions and their relationship to the weld zone microstructure and hardness distributions in SSFSW T-joints were investigated, as a function of welding travel speed. The final longitudinal residual stress fields were asymmetric, although individual weld zones showed similarities to those for conventional butt SSFSWs. The thermal excursion and plastic strain arising from the second pass lowered the residual stresses seen from the first pass, so that the largest tensile stresses (~160 MPa) were found close to the nugget from the second weld pass. The asymmetry in hardness distribution was caused by the thermal field of the second pass which thermally treated material in the first pass and resulted in areas of age hardening and increased over ageing, depending on the position of overlap of the thermal fields. The effects of the second weld pass on the first pass were more apparent when a lower travel speed was used owing to the increase in heat input and duration of the thermal cycle.

1. Introduction

In transport applications, such as aircraft fuselages and railway rolling stock, where high stiffness and low weight are required, stiffened panels are widely fabricated from aluminum alloys by attaching extruded 'stiffeners' to a skin sheet. This requires the production of mechanically efficient T-joints between the skin and stiffeners. For high strength aluminum alloys, which are considered to be 'un-weldable' by fusion processes, joining stiffened panels is usually achieved by riveting the extruded stiffener to the skin, which requires a substantial overlap reducing the joint efficiency. Recently, a series of studies by Fratini et al. (2006), 2009; Donati et al. (2009) and Buffa et al. (2009) have shown that friction stir welding (FSW) has potential as an alternative approach for performing T-joints in high strength aluminum alloys, thereby avoiding the additional overlap weight, as well as the opportunity for fatigue initiation associated with fasteners. These authors investigated a FSW T-joint configuration where the welding tool pin penetrated through the skin into a heavily constrained stiffener, to form a joint; as shown in Fig. 1(a). However, geometrical issues associated with a conventional FSW tool meant that in all cases only non-ideal weld geometries could be considered. Despite heavy clamping either side of the stiffener, to constrain the material, Cui et al. (2013) reported that weld defects such as lack of full bonding and 'tunnels' were difficult to eliminate with the tool through-skin configuration. This was attributed to the difficulty in ensuring sufficient material flow across the full stiffener width near the tip of the pin. Particular additional issues reported with this set-up included: thinning of the skin sheet, the high precision required for the clamping and tool geometries to avoid defects, and the limited fillet radius achievable. Thin-gauge sheet has also proven to be very difficult to join with this weld configuration.

More recently, it has been demonstrated by Russell (2008) that it is possible to produce FSWs with a non-rotating stationary shoulder. For conventional butt welds, stationary shoulder FSW (SSFSW) has been found by Avettand-Fènoël and Taillard (2016); Wu et al. (2015); Sun et al. (2018a), 2017 and Sun et al. (2018b) to have a number of advantages including: a lower heat input, much higher surface quality, a narrower and more uniform through thickness weld zone and reduced residual stresses. A further advantage of a non-rotating shoulder is that it can be modified to produce a range of weld bead profiles and fillet welds. Martin and Way (2011) were the first researchers to realize the potential for producing fillet welded T-joints using SSFSW by adopting a 90° profiled tool shoulder (Fig. 1(b)). Subsequently, Maltin et al. (2014), Martin (2014) and Li et al. (2015) have confirmed that superior defect-free T-joints can be made by SSFSW, compared to the earlier

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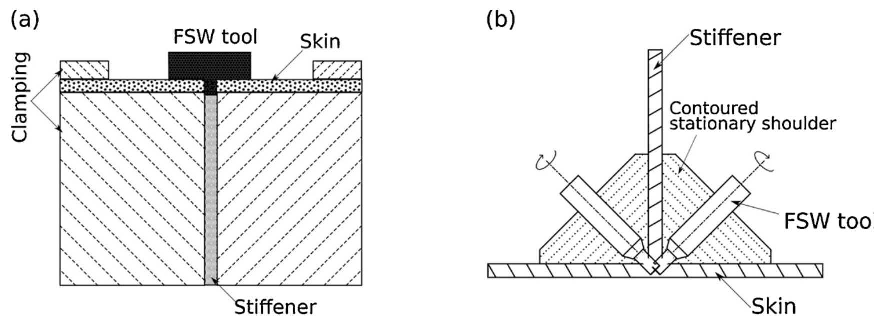

Fig. 1. Schematic diagrams of T-joints produced by (a) conventional FSW with the tool penetrating the skin configuration (Buffa et al., 2009; Donati et al., 2009; Fratini et al., 2006, 2009) and (b) SSFSW fillet welding approach proposed by Martin and Way, (2011).

attempts based on a conventional FSW tool, with improved fatigue resistance and mechanical performance. However, very little research has yet been published on the effect of the process parameters on the microstructure development in SSFSW T-joints. Furthermore, there have been no reports on the associated residual stresses, without which it is not possible to assess the joint's structural integrity, nor optimize the weld process parameters.

With the SSFSW process, it is currently not possible to simultaneously weld from both sides of a T-joint, as some degree of pin overlap is required to avoid defects associated with undispersed segments of the original join line between the flange and plate (see Martin and Way (2011)). Thus, SSFSW fillet welding is an asymmetric sequential welding process. In FSW, it has been noted by Barnes et al. (2008) that sequential weld passes can influence the microstructure, hardness distribution and residual stress introduced by the previous pass. Furthermore, the effect of a subsequent weld pass on the first pass is position-dependent due to the spatial variation in the local thermal field and plastic deformation. For example, Brown et al. (2009) have investigated repeating fully overlaid multi-pass AA7050 FSW butt welds, in the context of a weld repair scenario, and found that the nugget grain size and hardness were insensitive to the number of passes, while the hardness and tensile strength in the heat affected zone (HAZ) cumulatively diminished. Subsequent modelling by Robson et al. (2010) has demonstrated that the near constant properties of the WN can be explained by the re-deformation reaching steady state at the high strains experienced in each pass and full solutionisation occurring during each repeated pass, whereas the reduction in strength in the HAZ strength was caused by the accumulative effect of the repeated thermal excursion on coarsening of the strengthening precipitates. Other researchers, such as Simoncini et al. (2016) and Cabibbo et al. (2014) have investigated double sided FSW and shown that where the thermal field from the second pass overlaps the first, the second pass effectively reheat treats the first pass, leading to an asymmetric hardness distribution, with both zones of re-solution treatment and additional overaging seen in the previous welding pass.

As well as affecting the final microstructural condition, the dual-pass FSWs required by a T-joint configuration would be expected to impact on the final residual stress state, but no data is currently available in the literature. As described by Withers (2007a), residual stresses are an important factor in determining the service life of welded structural components. In single SSFSW butt welds, Sun et al. (2017) have demonstrated that the residual stresses introduced can be lower than in the conventional FSW, because the stationary shoulder results in a more uniform and lower heat input. However, for a T-joint welding configuration, the residual stress distribution will be more complicated and also affected by the welding sequence, which involves a second welding pass from the opposite side of the stiffener. For example, Fu et al. (2014) have investigated the longitudinal residual stress distribution in dual pass metal inert gas (MIG) steel T-joints and determined a higher residual stress in the second weld pass, even though the input power was kept the same. A similar residual stress distribution has been reported by Ahn et al. (2018) in AA2024 laser welded T-joints, where the lower level of residual stress seen in the workpiece side with first weld was attributed to partial relief and redistribution of the residual stresses during the subsequent weld pass.

To fill the current knowledge gap reviewed above, we have investigated the residual stresses formed in a typical aerospace alloy AA7050 T-joint by neutron diffraction and the associated weld zone microstructure as a function of tool travel speed, which is known to be the most important process variable (see Sun et al., 2018a). To understand the accumulative effect of the second weld on the microstructure and hardness distribution in the first pass, the behavior of the individual welds was also investigated sequentially. However, due to limited access to the neutron source, it was only possible to map the residual stresses in completed T-joints and discuss the results with the information concluded from the sequential microstructure and hardness evolution.

2. Experimental details

2.1. Welding procedure

6 mm gauge hot rolled AA7050-T7651 plates (nominal composition 5.7–6.7%Zn, 1.9–2.6%Mg, 2.0–2.6%Cu, ~0.11%Zr, < 0.15% Fe, < 0.12%Si, balance Al) were used for this study. Plates were machined into 126 mm × 300 mm sample workpieces for the 'skin' and 60 mm × 300 mm for the stiffener. Prior to welding, material was skim machined (0.15 mm) from all edges to provide surfaces free from

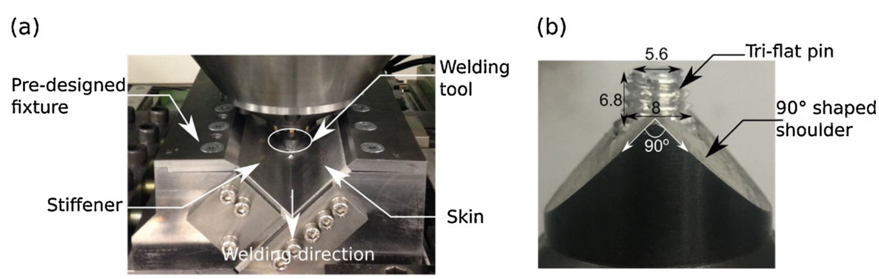

Fig. 2. Schematic diagram showing (a) the welding fixture employed for producing the T-joint fillet welds and (b) the SSFSW tool.