Experimental report

22/10/2024

Proposal: **1-02-366**

Council: 4/2023

Title: Residual stress measurement in dissimilar titanium and aluminium spotweld joints produced by Friction melt bonding

Research area: Engineering

This proposal is a new proposal

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Samples: Titanium
Aluminium

Instrument	Requested days	Allocated days	From	To
SALSA	4	5	08/11/2023	13/11/2023

Abstract:

Titanium and aluminium assembly is of great interest in aerospace application due to its combination of high strength, light weight and good corrosion resistance. The large difference in their melting temperature, mechanical properties, corrosion potential and formation of brittle Ti/Al intermetallic compound (IMC) layer are major challenges and drawbacks to weld these two metals. Friction Melt Bonding (FMB) is a novel welding process patented at UCLouvain to join dissimilar metals with large differences in melting temperature. Our previous study at ILL (Proposal 1-02-212) helped to understand the residual stresses (RS) near the Al/steel interface produced by FMB. Original findings were disseminated in scientific communications. However, RS in Ti-Al weld joint is expected to be unique due to the large difference in CTE between Ti and Al and absence of phase transformation compared to that observed in steel. The spot weld geometry of the Ti-Al weld is also different to that of investigated Al/Steel like welds. Thus RS measurement remains crucial for these Ti-Al joints to develop fundamental understanding towards mitigation of mechanical and corrosion driven failure due to RS.

Proposal N°: 1-02-366

Title: Neutron diffraction residual stress measurement after solid state spot welding of Titanium and Aluminium alloy.

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1. Introduction

Titanium (Ti) and aluminium (Al) alloys are frequently used in the aerospace industry for their low density and excellent corrosion resistance. Given the difference in their mechanical properties, Ti/Al assemblies can offer a high strength-to-weight ratio in structures. However, joining Ti and Al without additional fasteners is challenging. Efficient (short joining cycles), reliable, and environmentally friendly welding processes are needed that do not significantly reduce the base metal's mechanical properties. Conventional fusion welding processes lead to the formation of excessive brittle intermetallic compounds (IMC) and high residual stresses due to large heat input, which are detrimental to static and fatigue loading in structures. By contrast, solid-state welding processes can present significant advantages in joining these two metals at a low heat input and the formation of fine microstructures. The low heat-input minimizes the negative effects related to different thermal expansion coefficients and fine microstructures enhance diffusion as grain boundaries act as diffusion paths.

However, understanding residual stress distribution in solid-state welds of Ti and Al is still limited. Therefore, for the current work, two different solid-state and semi-solid-state techniques were compared: Refill Friction Stir Spot Welding (refill FSSW) and spot Friction Melt Bonding (FMB) were chosen as the basis for understanding residual stress distribution in Ti-Al solid-state spot joints.

Both FMB, developed and patented at UCLouvain [1] [2], and refill FSSW, invented at Helmholtz-Zentrum Hereon [3], are innovative welding techniques with the potential to effectively join difficult-to-weld dissimilar alloys like Ti and Al. In FMB, a lap joint is formed by placing a Ti plate over an Al plate and the welding is carried out from the Ti side. In refill FSSW the reverse configuration is used, Al on top and welding is done from the Al side. Both methods offer unique advantages, producing robust, high-performing joints that meet the rigorous demands of industrial applications. By comparing these two processes, we aim to gain deeper insights into how they influence the performance and durability of Ti-Al solid-state weld joints. During the current beamtime, we specifically focused on evaluating the residual stress distribution in the weld and near the weld interface by neutron diffraction.

2. Materials and Methods (Experimental Procedure):

The spot FMB and refill FSSW welds were manufactured on 1.5 mm thick Grade 4 α-Ti and 3 mm thick 6061-T6 Al alloy plates of 80 x 40 mm length and width. The neutron diffraction measurements were performed with strain analyser for engineering applications (SALSA), neutron diffraction instrument at Institute Laue-Langevin (ILL).

The schematic of the spot weld measurement locations and the coordinate system used are shown in Figure 1, along with the diffraction scans across the weld cross section. The points measured refers to the center of the gauge volume. The smallest nominal gauge volume defined with SALSA, 0.6 × 0.6 mm in the X-Y plane and the depth of 2.0 mm in z direction, was used in this experiment to obtain high resolution data across the Ti/Al interface. The measurement points are mainly distributed from center of the weld along one side only. As the spot weld is rotationally symmetrical the assumption of symmetry was made along the X-Z plane at the center of the weld. Consequently, the 3 components of strain measurement were reduced to 2 components of radial (X = Y) and normal (Z). Hence, the assumption that the X component and Y component are identical is made for stress calculations (see eq 1 & 2). The reference measurements were carried out on the Ti and Al base material used for welding.

Neutron diffraction data was processed using the LAMP software to obtain the peak position (2θ). The calculation of individual strain components were done using Braggs law , stress computation for 2 components was done using the Hooke's law, where the assumption of $\epsilon_{yy} = \epsilon_{xx}$ (Radial component) was implemented for stress calculation [Eq (1) & (2)], where, λ^{hkl} & μ^{hkl} are the Lame's constant for crystallographic planes.

Generalized Hooke's law:

$$\sigma_{zz} = 2\mu^{hkl}\varepsilon_{zz} + \lambda^{hkl}(\varepsilon_{zz} + 2\varepsilon_{yy}) \quad \text{.......... (1)}$$

$$\sigma_{yy} = 2\mu^{hkl}\varepsilon_{yy} + \lambda^{hkl}(\varepsilon_{zz} + 2\varepsilon_{yy}) = \sigma_{xx} \quad \text{.......... (2)}$$

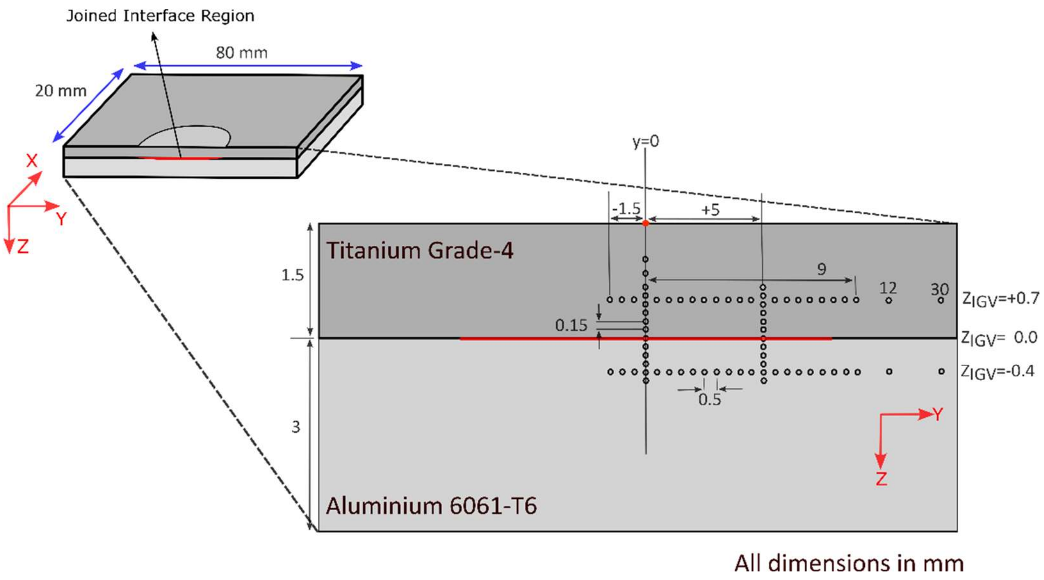

Figure 1: Schematic illustration of FMB & refill FSSW spot weld with the nomenclature of coordinates X, Y (Radial) and Z (Normal), along with dotted lines indicating the location of measurement scan (b) FMB spot weld cross section indicating the measured location and distribution of measurement points in 3 groups: horizontally in welded Ti (Z= +0.7 mm) and Al (Z= -0.4 mm), across the interface at the center of the weld (Y=0 mm) and across the interface at an offset of Y = 5 mm from the center of the weld.

3. Results and discussion

In the FMB spot weld of Ti-Al, Ti exhibits significant tensile residual stresses (RS) near the weld center (Fig. 2a), with maximum values observed at 2 mm from the weld center. This tensile stress is surrounded by transitions to compressive stress which show peaks at 0 mm (ca. -200 MPa) and 6 mm (ca. -130 MPa) at the mid-thickness of the Ti plate. The overall stress distribution in Ti forms a characteristic "reverse W" shape, indicating a self-balancing stress profile across the weld.

In Al (Fig. 2b), the RS measurements show less variability compared to Ti. Near the weld center, the stresses are predominantly compressive, transitioning to tensile stresses further away from the weld center. This gradual shift from compressive to tensile stresses occurs primarily beyond the FMB tool radius, around 8 mm from the weld center. Despite these fluctuations, the maximum RS in Al is notably lower than in Ti, with both tensile and compressive stresses remaining below 100 MPa.

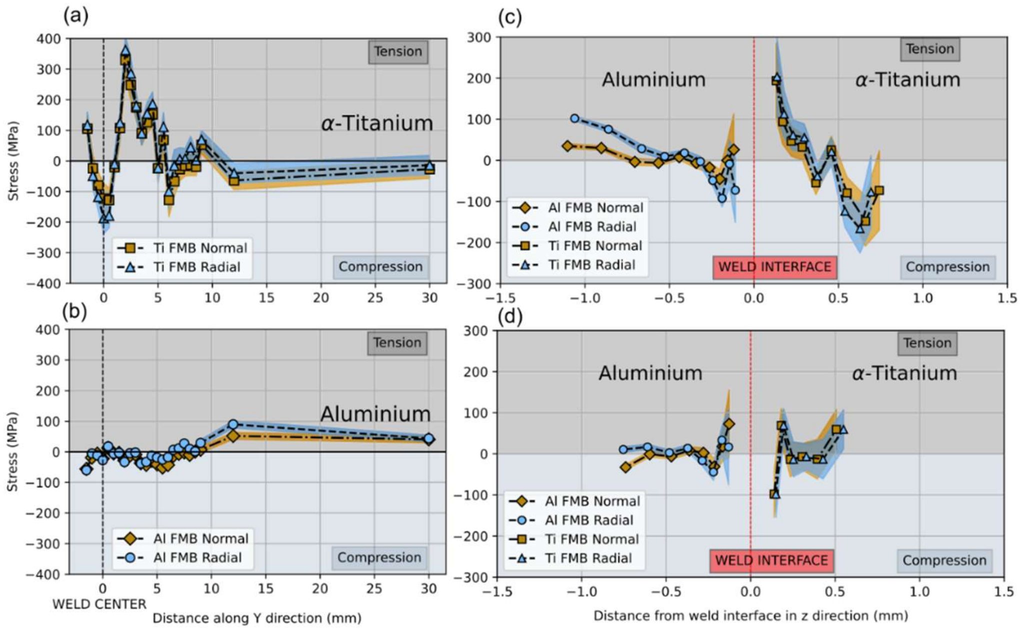

Figure 2: Normal and radial stress component of residual stress obtained for the FMB spot welded plate along the thickness of the plate (a) at Z +0.7 mm in Ti and, (b) at -0.4 mm in Al from the weld interface. (c) Residual stresses obtained along the weld interface through thickness of Ti-Al weld interface at weld center and, (d) at 5mm offset distance from weld center. [readers are ref to Figure 1 for coordinates] The shaded region along the data point indicates the error bar.

Stress measurements along the FMB weld interface (Fig. 2c,d) show distinct behaviors between the two materials. In the center of the weld on the Ti side (Fig. 2c), the highest tensile stresses are observed near the weld interface, while compressive stresses dominate further away from the interface. This balance of stresses indicates a well-distributed RS profile in the Ti plate through the weld thickness. In contrast, the Al side shows an opposite pattern, where compressive stresses are predominant near the interface, transitioning to tensile stresses further away. This fluctuation in Al is likely due to localized melting and strain accumulation at the interface, compounded by the partial immersion of the gauge volume in Al during measurement. Outside of the center at a radius of 5 mm (Fig.2d) there are tensile RS in the Al close to the interface and almost no RS in the Al after 0.3 mm or more to the interface. On the Ti side compressive stresses were detected (ca. -100 MPa) close to the interface with a sharp transition to tensile stresses (ca. 80 MPa).

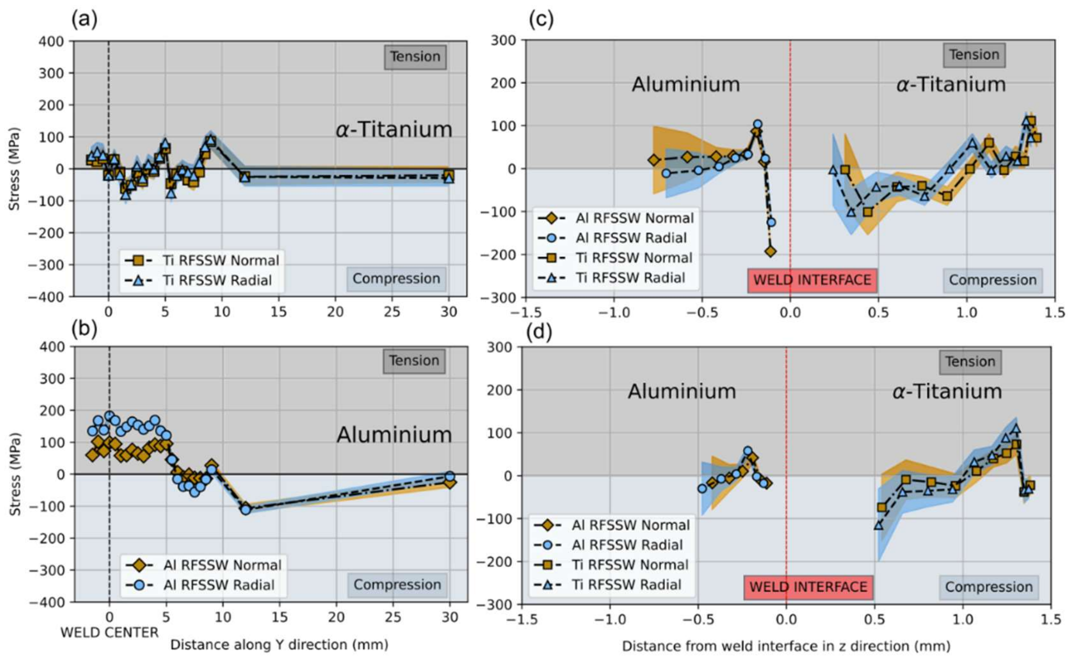

Figure 3: Normal and radial stress component of residual stress obtained for the refill FSSW spot welded plate along the thickness of the plate (a) at Z +0.7 mm in Ti and, (b) at -0.4 mm in Al from the weld interface. (c) Residual stresses obtained along the weld interface through thickness of Ti-Al weld interface at weld center and, (d) at 5mm offset distance from weld center. [readers are ref to Figure 1 for co-ordinates] The shaded region along the data point indicates the error bar.

In the refill FSSW spot weld of Ti-Al, RS in Ti (Fig. 3a) are comparatively lower in magnitude than those observed in FMB welds. However, a clear transition from compressive to tensile stress can still be seen as we move away from the weld center. The peaks in compressive and tensile stresses align with the radii of the refill FSSW tool components (shoulder and probe). These regions around the tool radii are characterized by particularly high deformation rates which could contribute to the explanation of these transitions.

In contrast, the RS in Al (Fig. 3b) are significantly higher than in Ti within the refill FSSW weld. Uniform tensile stress magnitudes are measured up to 5 mm away from the weld center, corresponding to the volume that is pressed into the cavity left by the retracting probe. The material here experiences substantial plastic deformation and the highest process temperature. Along the weld thickness (Fig. 3c & d), the RS are mainly in the range of -100 MPa to 100 MPa with one exception in the center of the weld on the Al side, where large compressive stresses around -200 MPa were found. These compressive stresses may be beneficial, as they reduce the likelihood of premature weld failure which are mostly due to tensile RS at the weld interface.

Overall, the RS distribution in both Ti and Al shows distinct characteristics in FMB and refill FSSW spot welds of Ti-Al. The stirred material, Ti in case of FMB and Al in case of refill FSSW, accommodates higher stresses than the material without tool contact, with the weld interface being critical in determining how stresses evolve in both materials. While the typical W distribution was clearly recognizable in the FMB, the refill FSSW revealed a stress distribution that was directly related to the tool components. Notably, this study marks the first time that RS in Ti-Al solid-state welds have been quantified. **These findings were presented at the "13th International Symposium on Friction Stir Welding and the 3rd International Joint Symposium on Joining and Welding" in Kyoto, Japan (May 2024) [4]. An extended scientific article detailing these original findings on RS in FMB and RFSSW Ti-Al spot welds is under writing.**

4. Acknowledgement

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5. References

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