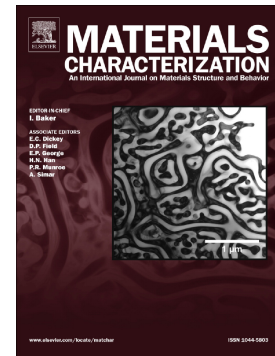


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Residual stress characterization of dissimilar Ti/Al spot welds: A comparative study using Synchrotron X-ray and Neutron Diffraction

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Abstract

Residual stress (RS) plays a critical role in the structural integrity of dissimilar titanium/aluminum (Ti/Al) spot welds, yet its reliable determination and interpretation remain challenging due to strong microstructural heterogeneity and steep stress gradients. In this study, RS distributions in Ti/Al spot welds produced by refill friction stir spot welding (refill FSSW) and spot friction melt bonding (FMB) are investigated using Neutron Diffraction (ND) and Energy-Dispersive Synchrotron X-Ray Diffraction (EDXRD). This work provides an original study on the quantification of RS using diffraction-based methods in dissimilar Ti/Al spot welds and presents a direct comparison between ND and EDXRD to assess their respective capabilities for RS determination. The results show that RS evolution is strongly dependent on the joining process. In spot FMB, RS is dominated by thermally induced stresses in the Ti, where constrained thermal contraction leads to high stress magnitudes and steep through-thickness gradients. In contrast, refill FSSW leads to a more uniform RS distribution owing to homogeneous deformation in the Al and limited influence of the process on the Ti. The comparison between ND and EDXRD reveals differences in the measured RS distributions, particularly in regions with steep gradients and pronounced microstructural heterogeneity, where spatial averaging effects influence ND measurements. In refill FSSW welds, where the microstructure is more homogeneous,

both techniques show comparable RS trends. These findings provide new insights into the relationship between welding process, microstructure, and RS evolution in dissimilar Ti/Al joints.

Keywords

Residual stress, Neutron diffraction, X-ray diffraction, Friction Melt Bonding, Refill Friction Stir Spot Welding, Ti/Al dissimilar welding

1. Introduction

Titanium (Ti) and aluminum (Al) alloys are increasingly employed in the transport industry due to their low density, high strength-to-weight ratio, and excellent corrosion resistance. The use of Ti/Al hybrid structures offers significant opportunities for weight reduction, improved structural strength, and cost-effective design in high demanding applications by combining low cost Al with high performance Ti [1]. Currently, dissimilar materials are predominantly joined using mechanical fasteners such as screws and rivets, which add weight, introduce stress concentrations, and limit fatigue performance [2]. Consequently, there is growing interest in replacing conventional fastening methods with spot welding for joining Ti and Al in order to further reduce the structural weight of aircraft components [3].

However, residual stress (RS) represents a critical challenge in welding Ti/Al dissimilar joints [4,5]. In dissimilar metal joints, RS primarily arises from phase transformations and the pronounced mismatch in thermal expansion, elastic properties, and plastic deformation between the two materials [6,7]. These locked-in stresses, introduced during thermal cycling and constrained plastic deformation, can be highly detrimental to the joint performance and structural integrity. Several studies have demonstrated that inadequately understood or uncontrolled RS has a significant influence on failure mechanisms, thereby promoting premature joint failure (when the part is subjected to fatigue), brittle fracture, or stress corrosion cracking [8–10]. This is particularly critical in highly loaded structural joints, where service-induced stresses may superimpose with welding-induced RS, leading to accelerated damage accumulation and reduced structural reliability.

Solid-state welding of Ti/Al dissimilar joints is gaining significant interest as an alternative to fusion welding, primarily due to reduced heat input, which enables improved control of intermetallic compound formation and reduces the magnitude and distribution of RS [11]. RS development in solid-state welding processes such as friction stir welding (FSW) has been extensively investigated, primarily for similar-metal joints. Campanella et al. [12] have reported that the RS profile in FSW Grade 2 Ti welds strongly depends on the joint configuration, transitioning from a V-shaped distribution in butt joints to an M-shaped profile in T-joints, which was attributed to differences in temperature distribution. Peel et al. [13] and Steuwer et al. [14] have demonstrated in their studies on FSW of

similar and dissimilar aluminum alloy butt welds that the weld zone is predominantly subjected to tensile RS in both longitudinal and transverse directions, which are balanced by compressive stresses in the surrounding material to satisfy the overall force equilibrium, resulting in an M shaped stress profile [15].

A recurring observation in solid-state welds is that the highest RS occurs in the longitudinal direction, reaching magnitudes two to three times higher than those in the transverse direction [14]. The magnitude and spatial distribution of these stresses are strongly governed by the process parameters and geometry, including the heat input and the process duration [13,16]. Reduced heat input has been associated with increased peak longitudinal stresses, which is attributed to steeper thermal gradients and insufficient time for stress relaxation during cooling. Furthermore, Deplus et al. [17] have shown that the extent of the tensile RS region correlates with the tool geometry during FSW of an Al alloy. According to their study, under low heat input conditions the tensile zone typically corresponds to the shoulder diameter, whereas higher heat input can extend this region to approximately 1.5 times the shoulder diameter. A promising approach to achieving a less intense residual stress field involves using rotationally symmetric spot-welding techniques to allow for stress compensation in the periphery of the spot welds. Therefore, the primary problem of high longitudinal RS, which build up along the weld length due to the differing thermal expansion properties of the two materials Ti and Al would thus be mitigated. Recent advances in understanding the RS distribution have extended to other innovative processes, such as refill Friction Stir Spot Welding (refill FSSW) [18] and spot Friction Melt Bonding (FMB) [6]. Spot FMB, developed and patented at UCLouvain, and refill FSSW, originally developed at Helmholtz-Zentrum Hereon, are innovative welding techniques with strong potential for joining dissimilar metals that are difficult to weld such as Ti and Al. Previous work by Bernardi et al. [18] have demonstrated that a plane-stress condition is generally not valid for thin refill FSSW lap welds in aluminum alloy 2219. Heterogeneously pronounced RS has been found across the weld thickness, depending on plastic deformation induced by the shoulder or thermal influence without mechanical influence. Becker et al. [19] have verified that the fatigue behavior in refill FSSW of Al alloys is mainly influenced by RS rather than by welding defects or microstructure. However, RS studies in solid-state dissimilar metal welds remain very limited and focus mostly on steel/Al joints. Scarcely any experimental study has reported spatially resolved RS analysis in solid state Ti/Al welds. Furthermore, a comparative analysis of RS evolution between different solid-state Ti/Al welding techniques remains largely unexplored.

Accurate RS characterization in dissimilar metal welds requires experimental techniques that provide both high spatial resolution and sufficient penetration depth. Synchrotron X-ray diffraction (SXRD) and neutron diffraction (ND) are the most established non-destructive methods reported in the literature,

each offering distinct advantages [18,20]. While SXRD enables high spatial resolution measurements with small gauge volumes [18,21], ND provides larger gauge volumes and deeper penetration, making it more suitable for thick sections and coarse-grained materials [6,22–24]. Despite their complementary capabilities, direct comparisons of these techniques for dissimilar metal welds are scarce. Furthermore, as highlighted by Withers et al. [25], a critical challenge in both methods is the accurate determination of the strain-free lattice parameter (d_0), particularly in welds exhibiting heterogeneous microstructures and chemical gradients caused by complex thermal and plastic deformation histories. A reliable d_0 determination often requires extraction of reference or comb samples, which adds substantial experimental complexity, particularly for ND measurements due to limited neutron flux and beamtime constraints, especially for Ti [26]. In addition, the lack of systematic comparisons between SXRD and ND techniques hinders the establishment of clear criteria for selecting appropriate measurement approaches based on exposure time, required spatial resolution, and penetration depth.

To address these gaps, this study presents a comparative RS analysis of dissimilar Ti/Al spot welds using SXRD and ND. Such a direct comparison provides critical insights on the role of microstructural heterogeneity and spatial averaging effects in the characterization and interpretation of complex RS fields in dissimilar joints. Two advanced joining processes were investigated: spot FMB [27], a semi-solid-state process, and refill FSSW [28], a solid-state process. In the spot FMB, the welding is performed from the Ti side, with the Al placed underneath [27], whereas refill FSSW employs the opposite configuration, with the Ti underneath and the welding conducted from the Al side [28]. By combining two complementary diffraction techniques with two distinct joining processes, this work provides new and systematic insights into the RS distribution within the weld region and near the Ti/Al interface for very different welding configurations, contributing to a deeper understanding of RS evolution in Ti/Al solid-state spot welds.

2. Experimental details

2.1 Materials and sample preparation

In this study, AA6061-T6 aluminum alloy sheets with a thickness of 3 mm and commercially pure titanium Grade 4 sheets with a thickness of 1.5 mm were used for welding. The sheets were welded in the as received state without previous annealing treatments. The sheets had dimensions of 80 mm × 40 mm. The chemical compositions of the Ti Grade 4 and AA6061-T6 Al alloy, determined by inductively coupled plasma optical emission spectroscopy (ICP-OES), are listed in Table 1. For clarity, X and Y correspond to the in-plane directions of the sheets, while the Z represents the thickness

direction (see Figure 1 and Figure 2). Prior to welding, oxide layers on both Al and Ti sheets were mechanically removed using P1200 SiC abrasive paper, followed by cleaning with acetone.

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Ni
AA6061-T6 wt%	0.62	0.36	0.24	0.09	0.92	0.13	0.05	0.02	97.4	0.01
Ti Grade 4 wt%	-	0.15	-	-	-	0.03	-	99.5	0.03	0.03

Table 1: Chemical composition of AA6061-T6 Al and Ti Grade-4 measured by ICP-OES.

The samples for microscopy were prepared using a standard grinding and polishing procedure, finishing with chemical-mechanical polishing using a mixture of colloidal silica (OP-S), hydrogen peroxide, and ammonia (100/20/5 mL). The hydrogen peroxide minimizes mechanical deformation of the Ti surface [29]. The cross-sections of the joints were subsequently examined using a FEI Quanta 650 scanning electron microscope equipped with an EDAX electron backscattered diffraction (EBSD) detector. EBSD was carried out using a step size of 0.05 μm and obtained data were analyzed using the TSL OIM 7.3 software. To reveal the grain structure, the Ti and Al surfaces on the weld samples were etched using Keller's reagent (95ml H_2O , 2.5mL HNO_3 , 1.5ml HCl , 1ml HF). TEM samples were prepared by extracting thin foils from the processed zone of the spot FMB Ti/Al weld cross-section using a focused ion beam (FIB) in an FEI Strata DB235TR system. The specimens were subsequently examined by high-resolution transmission electron microscopy (HRTEM) using a Thermo Fisher Titan Themis 300 microscope equipped with a probe aberration corrector and a monochromator, providing a spatial resolution of 70 pm and an energy resolution of 150 meV.

2.2 Spot FMB weld process

Spot FMB takes advantage of the difference in melting temperature between Ti and a lighter metal such as Al [27]. Figure 1 schematically illustrates the spot FMB process. In this technique, the upper Ti sheet is heated locally by friction using a rotating cylindrical tool. The heat generated is conducted to the underlying Al, leading to partial melting and interdiffusion at the interface, which results in the formation of a metallurgical bond, Figure 1 (a). Upon tool retraction, the molten pool solidifies, forming the weld, Figure 1 (b). The spot FMB process was carried out using a non-consumable cylindrical WC tool with a diameter of 16 mm at a rotational speed of 700 rpm and a plunge force of 5 kN, with a contact time of 85 s followed by a counter-pressure time of 30 s. The backing plate was made of stainless steel of thickness 5mm. The average maximum tensile lap-shear load for the spot FMB welds evaluated in this study was 10.6 ± 2.8 kN (see supplementary S1). Detailed processing parameters and the characterization for spot FMB Ti/Al joints are reported elsewhere [27].

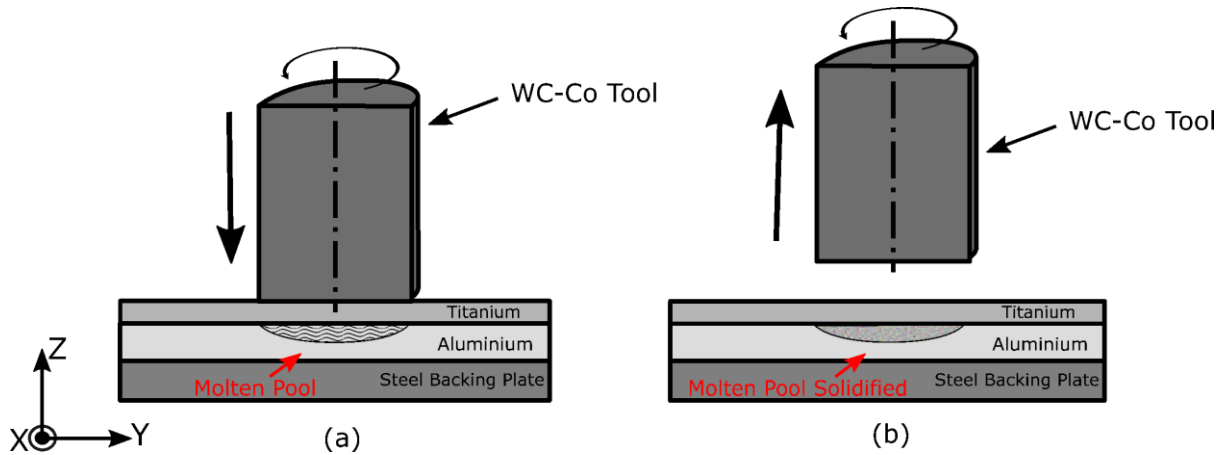


Figure 1: Schematic of the spot FMB Ti/Al welding process showing (a) local aluminum melting driven by frictional heat generation from rotating tool contact on the titanium surface, and (b) tool retraction resulting in melt pool solidification.

2.3 Refill FSSW Weld Process

Refill FSSW is a solid-state welding technique that is based on heat generated by friction to plasticize the workpiece material. The sheets are typically clamped in overlap configuration and welded without a resulting exit hole. A tool consisting of three components is used: the clamping ring, the shoulder, and the probe. The outer stationary clamping ring is used to apply the clamping force for locking the sheets in position. The inner probe and the shoulder between the probe and the clamping ring rotate typically at the same speed and direction. The process is schematically presented in Figure 2. In the first stage, the shoulder is moved downwards and plunges into the workpiece. The material is softened by the frictional heat and begins to deform plastically. At the same time the probe retracts upwards, generating a cavity. This volume is filled with the material displaced by the shoulder, without any void generation, as the volumes generated and displaced are identical, i.e. ensuring plastic incompressibility. As soon as the desired plunge depth is reached, the axial tool motion stops, and a dwell period starts during which shoulder and probe still rotate. When the dwell time is reached, probe and shoulder retract to the original positions, finishing the weld. In case of dissimilar Ti/Al, the shoulder only plunges into the upper Al sheet and is not intended to get in contact with the Ti surface, only generating the bonding by diffusion and, in part, through micro mechanical interlocking. The joints were created using a rotational speed of 2200 rpm, plunge time of 2 s, plunge depth of 2.8 mm, dwell time of 10 s, clamping force of 5 kN, and the tool dimensions were 20/12/8 mm in diameter for the clamping ring, shoulder, and probe. The resulting weld achieved a maximum lap-shear load of 14.5 ± 1.6 kN (see Supplementary S1).

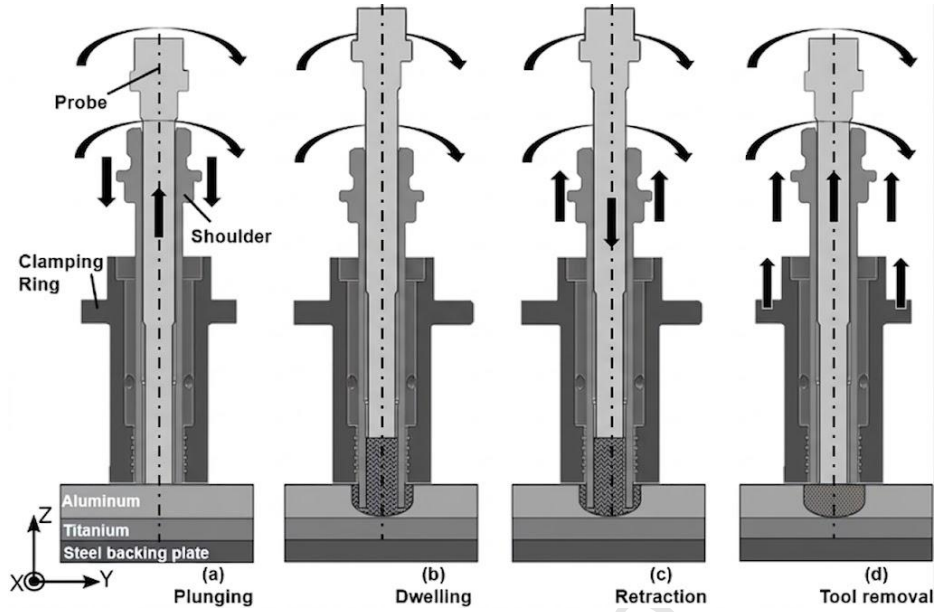


Figure 2: Schematic of refill FSSW Ti/Al weld process showing the four sequential stages: (a) plunging, (b) dwelling, (c) retraction, and (d) tool removal.

2.4 Spot weld process comparison

A comparison of the spot FMB and refill FSSW processes highlights three key differences: (i) the stacking configuration of the Ti and Al sheets, (ii) the location of plastic deformation during welding, and (iii) the occurrence of localized melting in spot FMB. The Ti sheet is stacked above the Al in spot FMB, whereas in refill FSSW the Al sheet is placed on top of the Ti. Consequently, the tool interacts with different materials in each process: in spot FMB, the tool directly contacts the Ti, generating frictional heat that results in localized melting of Al at the interface, while in refill FSSW, the frictional contact occurs between the tool and the Al sheet. The resulting plastic deformation induced during processing is illustrated schematically in Figure 3. In spot FMB, the Ti in contact with the tool experiences heterogeneous plastic deformation, Figure 3 (a), whereas in refill FSSW, the Al undergoes significant plastic deformation up to the weld interface, Figure 3 (b). As the Ti sheet is not in contact with the tool, only very slight deformation near the surface of Ti might occur due to the material flow of the plasticized Al. Owing to these differences in the processing approaches, each method offers distinct advantages for the joint configuration and final application depending on which material is intended to accommodate the majority of plastic deformation.

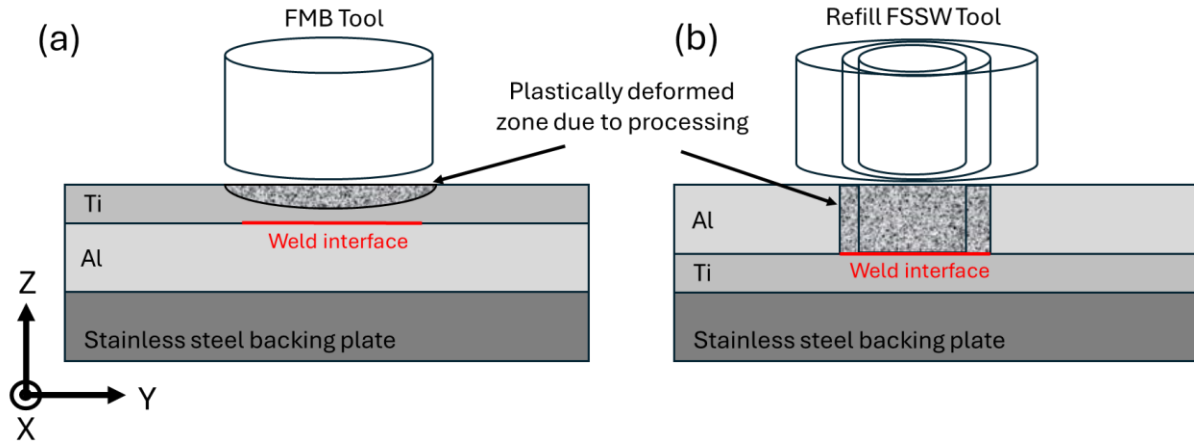


Figure 3: Schematic comparison of (a) Spot FMB and (b) refill FSSW processes for Ti/Al joining, illustrating the different Ti/Al stacking configurations for sheets and the resulting plastic deformation zones in the Al and Ti sheets.

2.5 Neutron diffraction

The ND measurements were performed at the Institut Laue–Langevin (ILL) using the SALSA (Strain Analyzer for Large and Small Scale Engineering Applications) instrument in Grenoble, France [30]. Detailed descriptions of the instrument and measurement principles are available elsewhere [22,23]. To maximize spatial resolution across the Ti/Al interface, the smallest nominal gauge volume available in SALSA, $0.6 \times 0.6 \text{ mm}^2$ in plane with a depth of 2.0 mm, was employed. The neutron wavelength was set to $1.9 \text{ \AA}$ for the Ti $\{10\bar{1}3\}$ reflection and $1.73 \text{ \AA}$ for the Al $\{311\}$ reflection, corresponding to diffraction peaks at $2\theta \approx 90.8^\circ$ for Ti and $\approx 89.9^\circ$ for Al, respectively. The diffraction data were processed using LAMP software and a Gaussian function was used to determine the peak positions 2θ , as illustrated in Figure 4 (a), (b). The welded specimens were mounted on the SALSA hexapod for precise positioning during measurement, Figure 4 (c). The acquisition time was approximately 10 minutes for Al and 20 minutes for Ti at each point and direction.

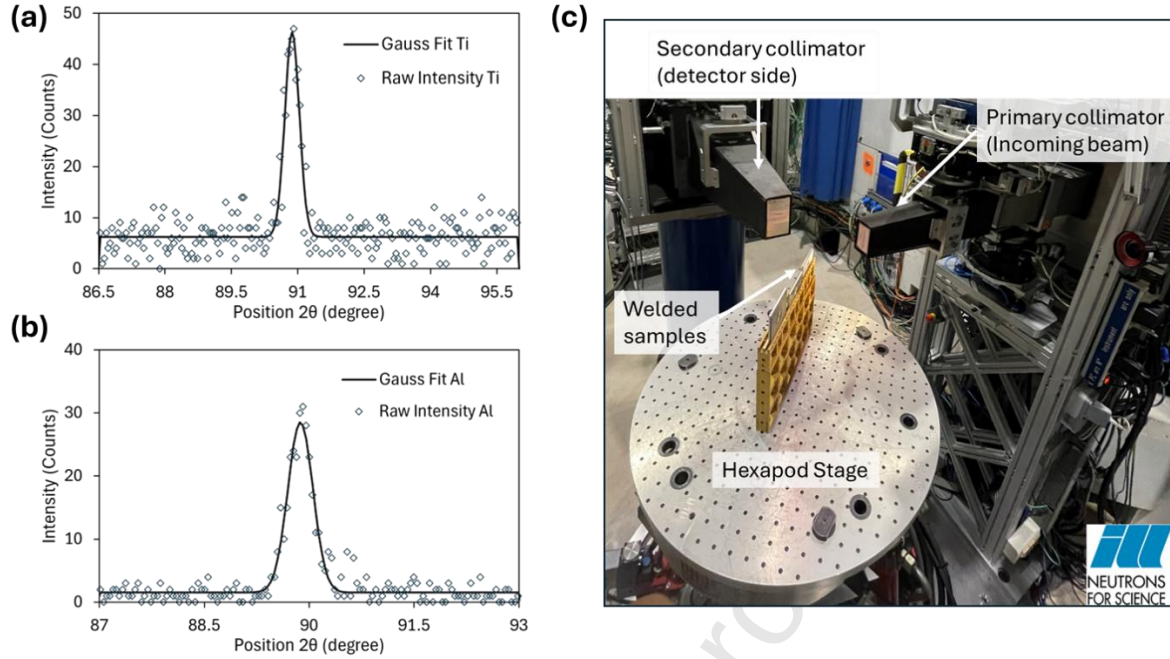


Figure 4: Example of ND data fitting performed during the post processing in case of (a) Ti {1013} peak fitting and (b) Al {311} peak fitting. (c) Welded specimens mounted on the hexapod at SALSA instrument during ND experiment at ILL.

Schematic illustrations of the spot FMB and refill FSSW spot welds, together with the coordinate system used in this work, are shown in Figure 5 and Figure 6, respectively. The ND scan paths across both the welds are indicated in Figure 5 (a) and Figure 6 (a), and the corresponding cross-section is magnified to facilitate identification of the measurement lines. All reported measurement positions refer to the center of the gauge volume, also referred to as instrumental gauge volume (IGV). For both spot FMB and refill FSSW, a radial symmetry of the weld was assumed. This geometric symmetry allowed measurements to be performed along a single radial direction (Y) across the weld center, effectively reducing beamtime. Consequently, the in-plane strain components were assumed equal ($\epsilon_{xx} = \epsilon_{yy}$) for stress calculations. This assumption follows from the rotational symmetry of the spot weld around the Z -axis (see also Figure 1 and Figure 2). As a result, the three independent strain components (ϵ_{xx} , ϵ_{yy} , and ϵ_{zz}) were reduced to two independent components: the radial component ($X=Y$) and the normal component (Z). The methodology, including the governing equations for determining lattice strains and RS, is described in detail in the Supplementary Section S2. Reference lattice spacings (d_0) were obtained from the Ti and Al base materials with the same dimensions as the welded specimens. The lattice spacing was measured separately in the radial and normal directions to account for the directional dependence of the diffraction measurement. Initial RS resulting from rolling might initially affect the base material (outside the weld and heat-affected zones), but given that the original sheets were subsequently cut, its effect should be very small due to redistribution of stresses. Furthermore, such initially generated RS and heterogeneous microstructure/texture prior to welding is assumed to

be fully eliminated within the weld zone due to the severe plastic deformation, partially local melting and high thermal exposure.

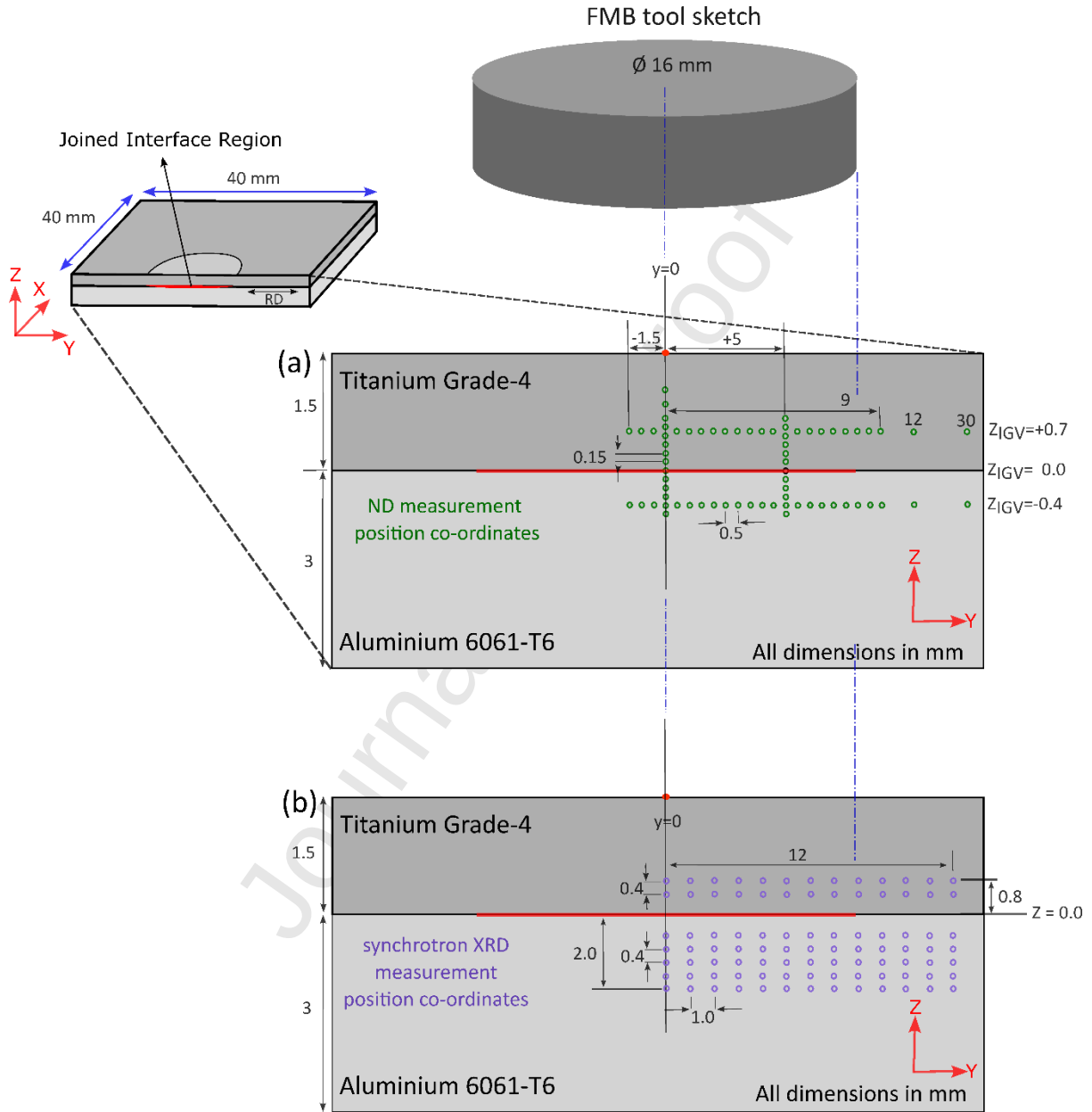


Figure 5: Schematic illustration of spot FMB weld, showing the tool geometry (dashed lines) and the corresponding scanned paths. (a) ND consisting of 3 groups: horizontal scan in welded Ti (at $Z = +0.7$ mm) and Al (at $Z = -0.4$ mm) from weld center ($Y = 0$ mm), vertical scan across the interface at the center of the weld ($Y = 0$ mm), and at an offset of $Y = +5$ mm from the center of the weld (IGV corresponds to the centroid position of the instrumental gauge volume), (b) EDXRD consisting of two horizontal line scans in the Ti sheet at $Z = +0.4$ and $+0.8$ mm, and five horizontal line scans in the Al sheet at $Z = -0.4$, -0.8 , -1.2 , -1.6 , and -2.0 mm. All EDXRD measurements were performed radially from the weld center ($Y = 0$ mm) to $Y = 12$ mm, with a step size of 1 mm between adjacent measurement points.

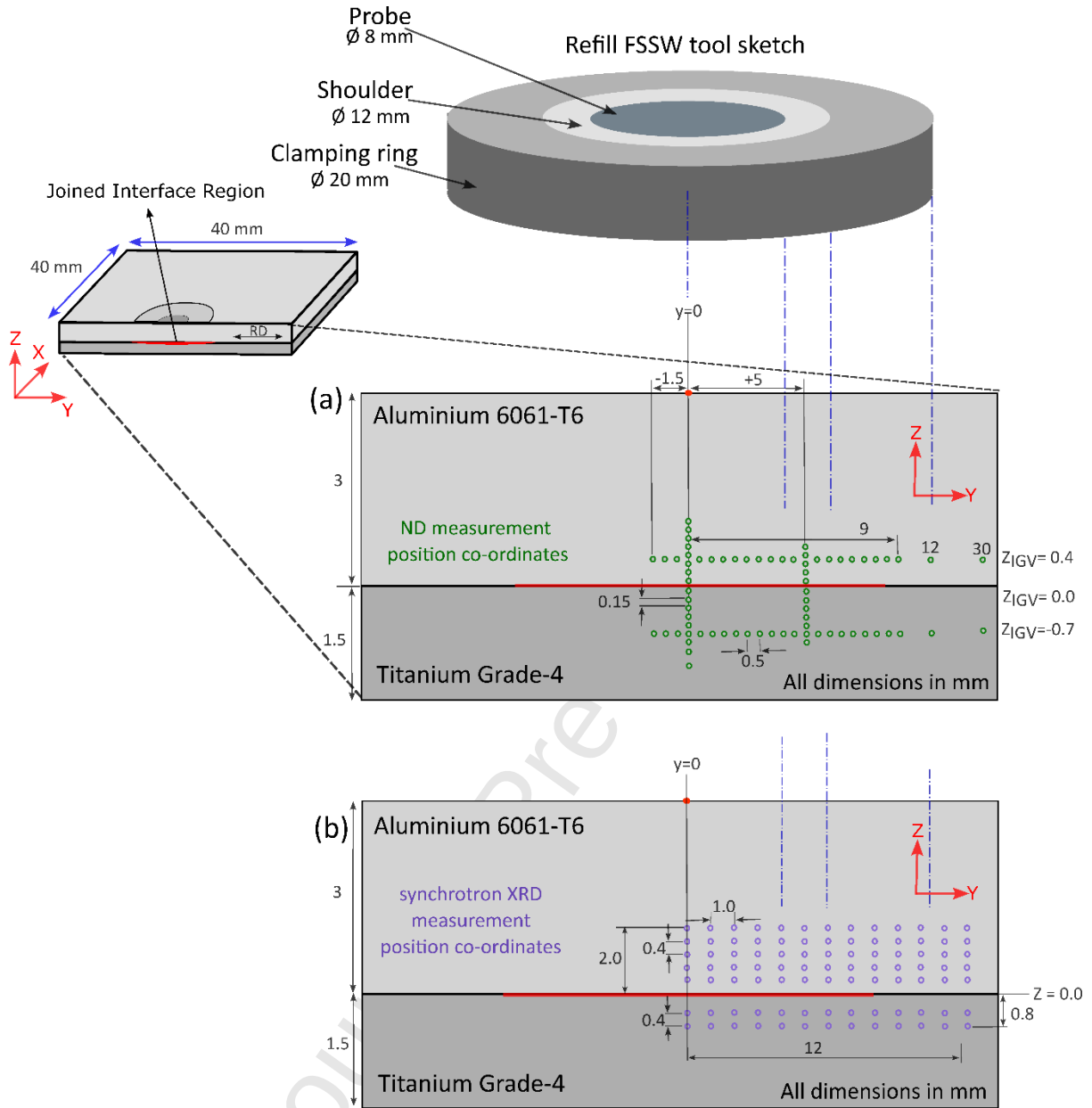


Figure 6: Schematic illustration of refill FSSW weld, showing the tool geometry (dashed lines) and the corresponding scanned paths. (a) ND consisting of 3 groups: horizontal scan in welded Ti (at $Z = -0.7$ mm) and Al (at $Z = +0.4$ mm) from weld center ($Y = 0$ mm), vertical scan across the interface at the center of the weld ($Y = 0$ mm) and at an offset of $Y = +5$ mm from the center of the weld (IGV corresponds to the centroid position of the instrumental gauge volume) (b) EDXRD consisting of two horizontal line scans in the Ti sheet at $Z = -0.4$ and -0.8 mm, and five horizontal line scans in the Al sheet at $Z = +0.4, +0.8, +1.2, +1.6$, and $+2.0$ mm. All EDXRD measurements were performed radially from the weld center ($Y = 0$ mm) to $Y = 12$ mm, with a step size of 1 mm between adjacent measurement points.

The ND scans across the weld interface at the weld center ($Y = 0$ mm) and at a 5 mm offset from the weld center ($Y = 5$ mm) involved partial immersion of the IGV (referred to as sampled gauge volume - SGV-) in order to determine the RS distribution close to the weld interface. Such partial gauge-volume immersion induces pseudo-strain effects, which can be corrected by shifting the gauge-volume

centroid. This pseudo-strain correction was applied in the present work and is described in detail elsewhere [6,22,23].

2.6 Energy-Dispersive Synchrotron X-Ray Diffraction

Energy-Dispersive Synchrotron X-Ray Diffraction (EDXRD) measurements in transmission geometry were performed at the beamline P61A, operated by Helmholtz-Zentrum Hereon, at PETRA III at Deutsches Elektronen-Synchrotron (DESY, Germany). The diffraction patterns were recorded in a High-Purity Germanium (HPGe) point detector [31] and the incident beam was shaped to a cross-section of $100 \times 100 \mu\text{m}^2$. The 2θ angle was calibrated using a standard Si powder (NIST 640f), and the tail-to-tail gauge volume resulted in an elongated diamond shape with a length of $\sim 1.5 \text{ mm}$ in the direction of the beam due to the diffraction angle of 7.6241° . The EDXRD scans were conducted on the exact same samples, for both FMB and refill FSSW, that were investigated by ND.

Measurements were performed with the gauge volume positioned fully inside the Al or the Ti sheets to avoid spurious strains, with spacings of 0.4 mm in the thickness direction (Z) and 1 mm in radial direction (Y), see Figure 5 (b) and Figure 6 (b). Due to the relatively large grain size in some regions, induced by high heat-input in terms of long processing durations, the $\sin^2\psi$ method was applied [32,33]. The $\sin^2\psi$ method relies on changing the angle between the scattering vector and the sample by some angle ψ through the sample rotation. The method is particularly relevant for large grains populations (compared to the gauge volume dimensions) to increase the robustness of the calculations [32,33]. For the $\sin^2\psi$ scans, the samples were mounted on an Eulerian cradle, see Figure 7 (a) and each measurement position, shown in Figure 5 (b) and Figure 6 (b), was rotated in ψ from $\sim 0^\circ$ to $\sim 90^\circ$ (in a continuous scan) using 16 individual measurements with exposure times of 2 s for Al and 15 s for Ti to find the associated strain components in Z and Y . Subsequently, the samples were rotated 90° around their vertical axis to determine the strains in X direction. All peaks were fitted with pseudo-Voigt functions using the open-source P61A Toolkit software [34]. As strain-free references (d_0), comb-shaped samples were machined out using electrical discharge machining (EDM), see schematic in Figure 7 (b). The teeth were produced by generating 3.75 mm deep slits and d_0 measurements were performed in the same positions as in the actual samples. The gauge volume was placed fully inside the teeth to avoid the presence of pseudo-strains.

The analyzed crystallographic planes were the Al $\{311\}$, $\{331\}$, and $\{420\}$ and the α -Ti $\{21\bar{3}1\}$, $\{20\bar{2}3\}$ and $\{21\bar{3}3\}$ as they are weakly affected by intergranular strains, have similar elastic constants, and exhibited the smallest errors. The determined stresses presented in this work are a simple average of individual stresses of the previous crystallographic planes. The corresponding elastic constants are

presented in Supplementary S2. For the stress-difference analysis (between ND and EDXRD) presented later, the Ti stress values at $Z=0.7$ mm determined by EDXRD were interpolated to allow direct comparison at the same measurement position.

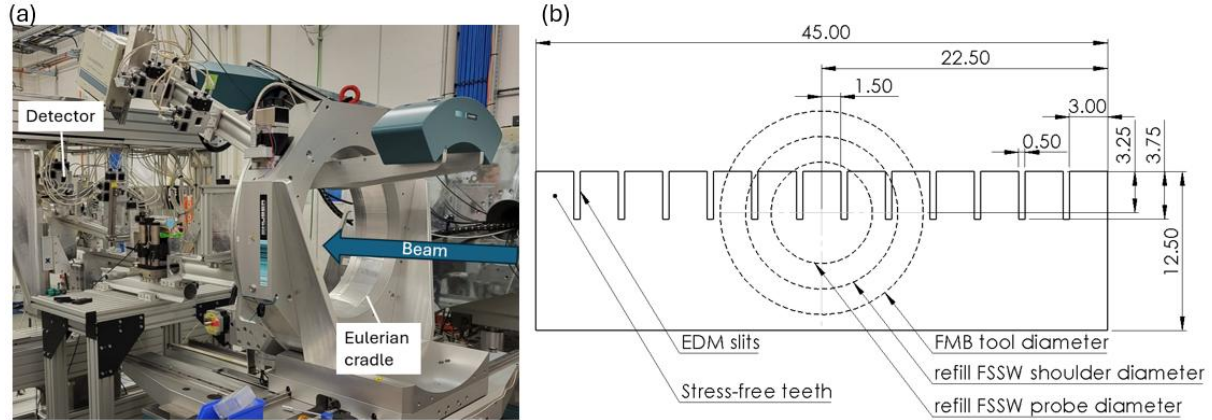


Figure 7: a) Setup for the EDXRD measurements at P61A, operated by Helmholtz-Zentrum Hereon, at Petra III (DESY, Germany), showing the beam direction, the eulerian cradle on which the samples were mounted, and the detector position. (b) Schematic representation of the strain-free samples (combs) dimensions used in the current study. All dimensions are in mm.

3. Results

This section presents the RS for the dissimilar Ti/Al joints produced by spot FMB and refill FSSW. The results are structured by characterization technique and joining process. Sections 4.1 and 4.2 present the ND and EDXRD results for the spot FMB weld, respectively, while Sections 4.3 and 4.4 report the corresponding ND and EDXRD results for the refill FSSW weld.

3.1 ND measurements in spot FMB weld

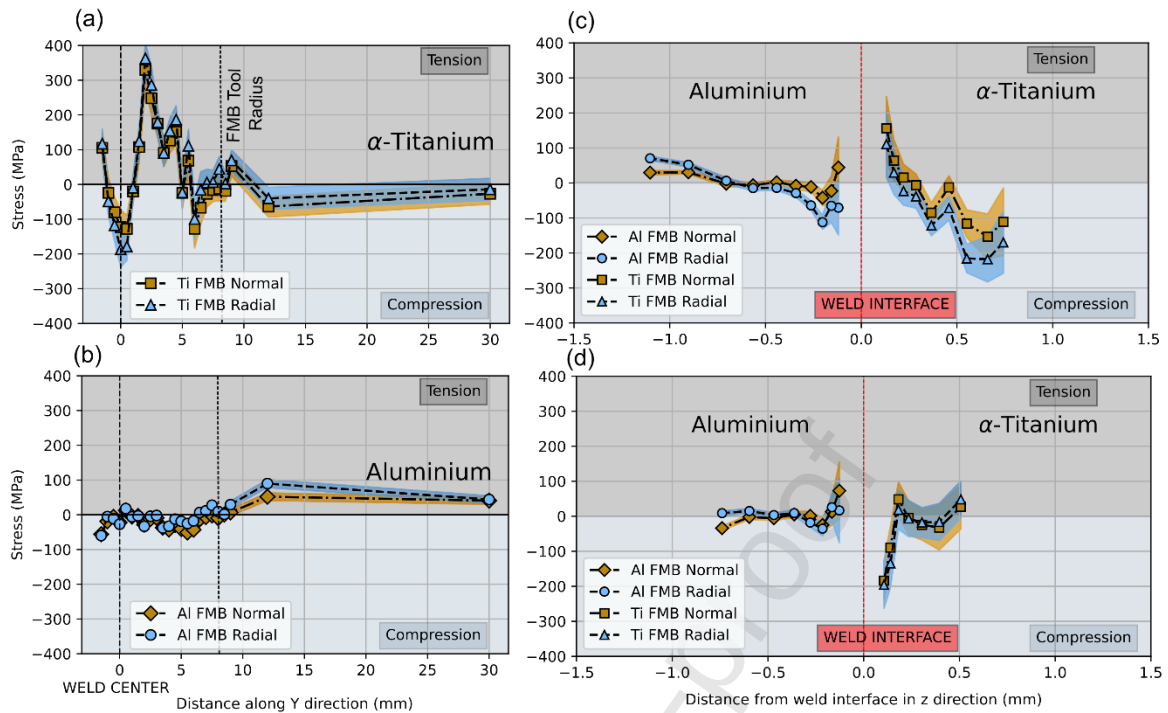


Figure 8: Normal and radial RS components determined for the spot FMB welded sheets along the sheets (a) at $Z + 0.7$ mm in Ti and (b) at -0.4 mm in Al from the weld interface. (c) RS determined along the weld interface through thickness at weld center and (d) at 5 mm offset distance from weld center. The reader is referred to Figure 5 (a) for coordinates and for point positioning. The shaded regions along the data indicate the error bars.

In the spot FMB weld of Ti/Al, the Ti sheet exhibits significant tensile RS slightly outside of the weld center, Figure 8 (a), with maximum values occurring at approximately 2 mm from the weld center. These tensile stresses are surrounded by transitions to compressive stresses, with peaks of about -200 MPa at the weld center ($Y = 0$ mm) and -130 MPa at $Y \approx 6$ mm. The resulting RS distribution forms a characteristic “reverse W” shape, indicating a self-balancing stress state across the weld. Furthermore, the stress differences between the two directions are small, suggesting a hydrostatic nature of RS.

In the Al sheet, Figure 8 (b), the RS shows less variability compared to Ti. Near the weld center, the stresses are low but predominantly compressive, transitioning to tensile stresses further away from the weld center. This gradual transition from compressive to tensile stresses occurs primarily beyond the spot 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. Similarly to the Ti, little stress differences are observed between normal and radial components. Stresses along the spot FMB weld interface reveal distinct behaviors in Ti and Al.

At the weld center on the Ti side, Figure 8 (c), the highest tensile stresses are observed near the interface, transitioning to compressive stresses with increasing distance from the interface, and showing roughly similar values in radial and normal directions. This stress distribution indicates a balance through-thickness within the Ti sheet. In contrast, the Al side exhibits an opposite trend, with compressive stresses dominating near the interface and transitioning to tensile stresses further away, where the radial and normal components clearly differ. The elemental segregation due to local melt pool and nano scale Ti-Al intermetallics (~ 5 nm) formed at weld interface, as reported by Krishnamurthy et al. [27] is expected to play a negligible role as the gauge volume is much larger than the nano scale segregation around the intermetallics. At a radial distance of 5 mm from the center of the weld Figure 8 (d), tensile RS is detected in the Al close to the interface, while stress decreases rapidly to near-zero values beyond ~ 0.3 mm from the interface. On the Ti side, compressive radial and normal stresses of approximately -100 MPa are observed adjacent to the interface, followed by a sharp transition to tensile stresses reaching approximately 80 MPa.

3.2 EDXRD measurements in spot FMB weld

EDXRD measurements (Figure 9) revealed pronounced RS gradients on both sides of the joint. On the Ti side, great tensile stresses (around $+210 \pm 50$ MPa) are observed in the region of severe plastic deformation and high heat input, extending up to 3 mm in radius from the weld center at a height of 0.8 mm (Z) from the interface. These tensile stresses are balanced by compressive RS (-265 ± 53 MPa) beyond a radial distance of approximately 4 mm (also at $Z = 0.8$ mm). In contrast, strong compressive RS (around -350 ± 60 MPa) are observed at the weld center close to the interface ($Z = 0.4$ mm). These observations show some inconsistency with the ND residual stress measurements, which is discussed in detail in Section 4.1. Additionally, stresses in X and Y directions (in-plane) exhibit similar behavior and magnitude, supporting the assumption used in ND residual stress computation that the in-plane stresses are equal. Furthermore, stresses in Z direction also show a similar trend to that of the other two components, with slightly lower values (in magnitude), which again indicates the presence of stresses with hydrostatic nature. Overall, the RS distribution in Ti exhibits a localized peak, with the maximum stress concentrated at the tool-workpiece interaction zone and near the weld interface.

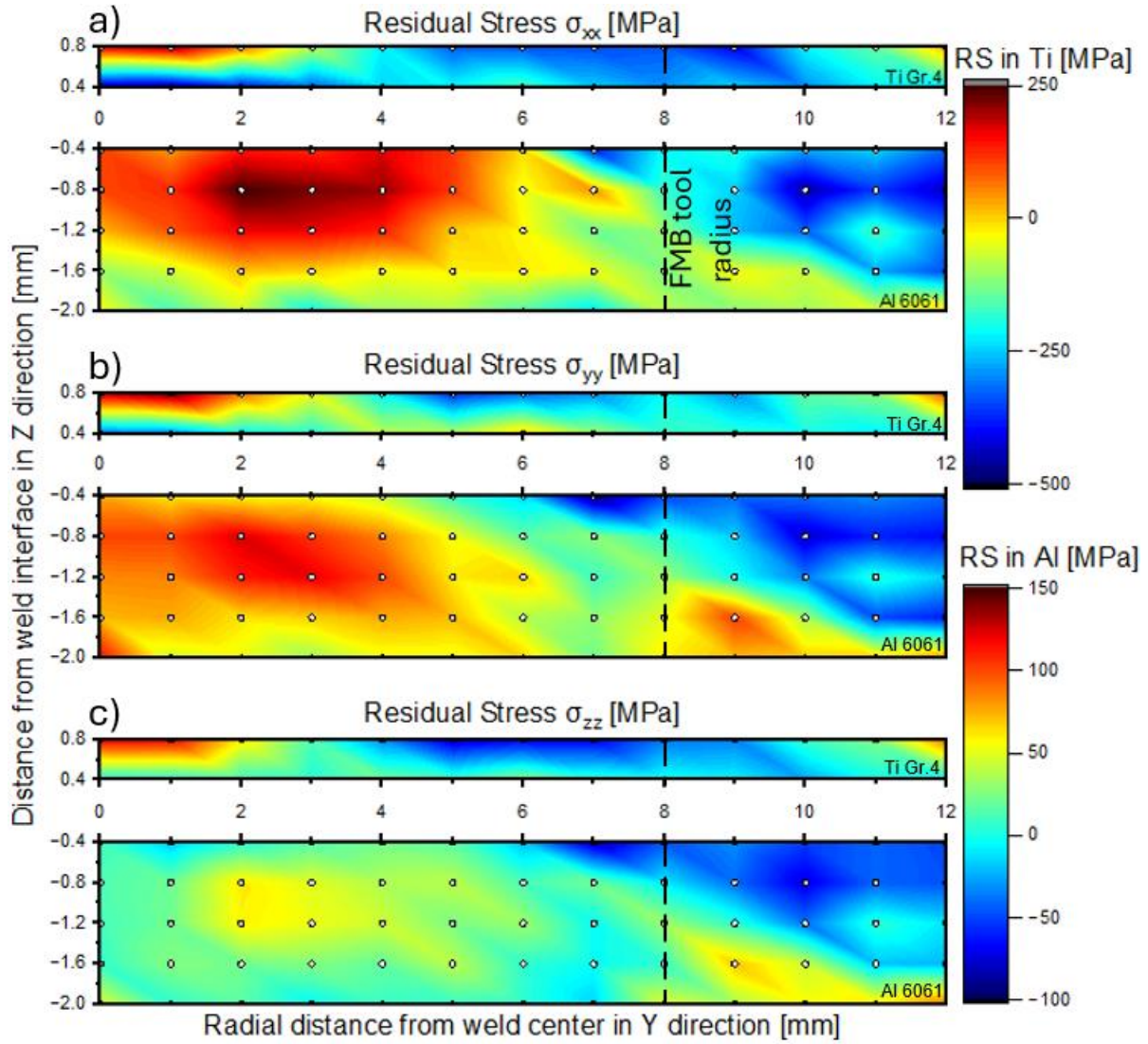


Figure 9: Determined triaxial RS a) σ_{xx} , b) σ_{yy} , and c) σ_{zz} within the dissimilar Ti/Al spot FMB welded sheets using EDXRD. The top map refers to Ti and the bottom to Al 6061-T6. The reader is referred to Figure 5 (b) for coordinates and for point positioning.

On the Al side, the RS distribution is strongly influenced by the spot FMB process, which involves partial and localized Al melting and a heat-affected zone around it. Near the weld center and close to the interface, high tensile stresses are observed, reaching approximately $+150 \pm 25$ MPa in the in-plane directions (X and Y) and $+50 \pm 27$ MPa in the normal direction (Z). These stresses are balanced by compressive RS of about -50 ± 20 MPa in the surrounding region. The lower magnitude of the normal stress component compared to the in-plane components (a significant difference to the Ti region) is consistent with trends reported in the literature [35,36]. Accordingly, the assumption made for ND measurements that the in-plane radial components (X and Y) are equivalent appears to be reasonable.

The observed differences between ND and EDXRD experiments can be primarily attributed to:

- 1) the distinct gauge volumes (and consequently spatial resolutions) of the two techniques, with ND averaging stresses over a larger volume than EDXRD.
- 2) the different strain-free references used. In the ND and EDXRD experiments, a constant and a variable d_0 were used, respectively.

This aspect is considered throughout the discussion and is addressed in detail in Section 4.1.

3.3 ND measurements in refill FSSW weld

The refill FSSW weld in the Al sheet, at $Z = +0.4$ mm and parallel to the interface, is characterized by a homogeneous tensile RS distribution in the weld center, reaching approximately +150 MPa in the radial direction and +75 MPa in the normal direction up to a radius of $Y \approx 4$ mm (probe region, Figure 10 (b)). Homogeneous tensile residual stresses in this large region are likely based on low thermal gradients. The friction-based temperature is generated in the surrounding tool and workpiece contact zones leading to temperature dissipation limitations towards the top and weld periphery [28]. Additionally, in through thickness direction, the interface isolates the temperature dissipation due to the low thermal diffusivity of the Ti. This center region is then surrounded by the shoulder area ($4 \text{ mm} < Y < 6 \text{ mm}$), where a sharp decrease in tensile RS is observed. At the outer radius of $Y \approx 6$ mm, RS approaches near zero values in both normal and radial directions. Beyond the clamping ring, in the range of $6 \text{ mm} < Y < 9 \text{ mm}$, a parabolic regime is present indicating slight compressive RS, particularly in radial direction with a peak value of - 50 MPa. Outside of the weld region, at $Y > 12$ mm, compressive RS in both normal and radial direction of - 100 MPa are found.

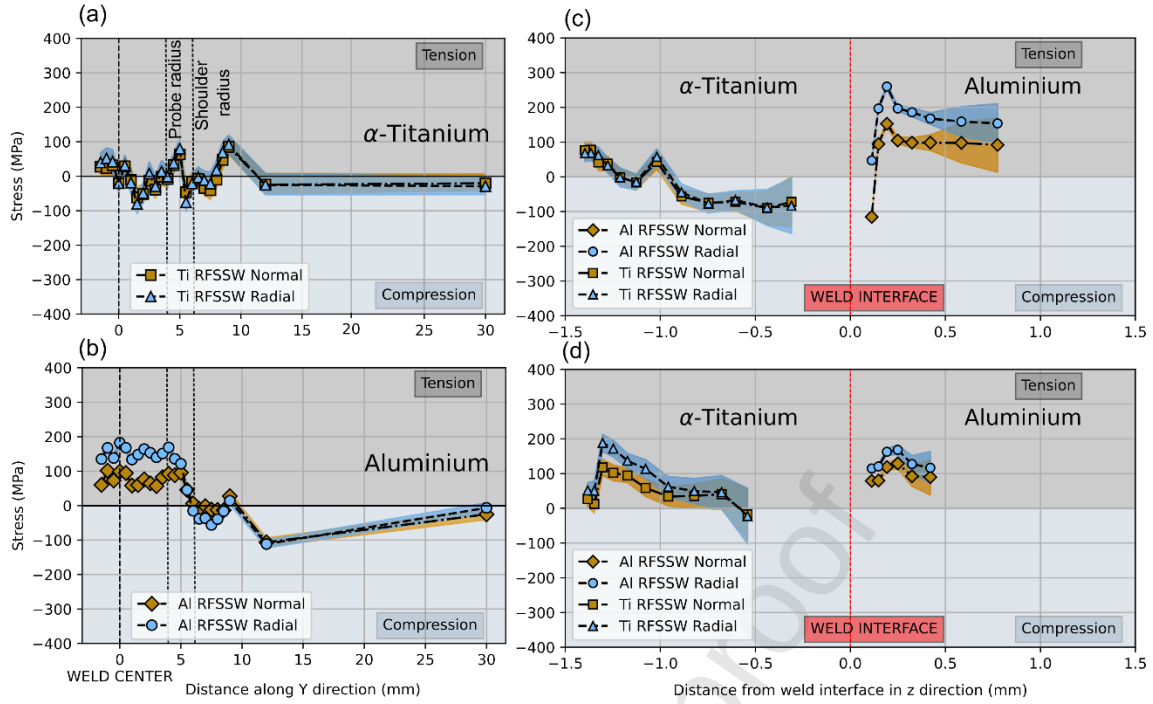


Figure 10: Normal and radial RS components determined for the refill FSSW spot welded sheet along the sheet (a) at Z - 0.7 mm in Ti and, (b) at +0.4 mm in Al from the weld interface. (c) RS determined along the weld interface through thickness at weld center. The reader is referred to Figure 6 (a) for coordinates and for point positioning. The shaded regions along the data indicate the error bars.

On the Ti side, the RS is relatively low at the mid-length region of the Ti sheet, showing alternating peaks up to -100 and $+100$ MPa (Figure 10 (a)). Normal and radial RS show a highly similar regime, demonstrating the presence of hydrostatic stresses. Beyond the clamping ring, an additional peak of $+100$ MPa was observed at $Y \approx 9$ mm.

Figure 10 (c) shows the RS distribution along the through thickness direction Z in the center of the weld. On the Al side, peaks at $Z \approx +0.2$ mm of $+150$ MPa and $+260$ MPa were determined for normal and radial direction, respectively. Near the interface, at $Z \approx +0.1$ mm, the RS regime is characterized by strong compression of -100 MPa in normal direction and 50 MPa in radial direction.

RS in the Ti was determined in the range of $Z \approx -0.3$ mm and $Z \approx -1.4$ mm, with values ranging between $+90$ MPa at large distance to the interface and -100 MPa close to the interface. Except for a slight peak at $Z \approx -1$ mm, the values follow a clear pattern.

Further outside of the weld, at $Y \approx 5$ mm, similar but less pronounced RS distributions are indicated, see Figure 10 (d). Due to limited measurement values in the region near the interface, it is unclear if the significant RS gradient in Al close to the interface is also present at $Y \approx 5$ mm. Potentially, the intense RS gradient is limited to a smaller area around the interface due to the reduced temperature regime.

A sharp decrease of tensile RS was determined at a significant distance from the interface, starting at $Z \approx -1.3$ mm.

3.4 EDXRD measurements in Refill FSSW weld

The EDXRD measurements of the refill FSSW weld showed pronounced RS gradients on the Al side (Figure 11). In accordance with the ND results, the central area, up to a radius of $r \approx 4$ mm, revealed the highest tensile RS close to the interface (at $Z \approx 0.4$ mm) due to thermo-mechanical processing. Tensile stresses of up to 150 ± 20 MPa are found in X and Y directions, transitioning to low tensile ($+35 \pm 20$ MPa) in X and low compressive (-28 ± 20 MPa) RS in Y in the outer weld area and periphery. Identical to the ND results, a sharp gradient separating the center area from the surrounding was found in the shoulder area. The discrepancies in the in-plane directions X and Y were predominantly found outside of the plastically deformed zone, widely homogeneous up to the maximum radius of 12 mm. This behavior had already been observed by Bernardi et al. [18]. In the weld center, the influence of the severe plastic deformation leads to a highly similar RS distribution for the in-plane X and Y directions through the sheet thickness direction. Starting at the high tensile RS near the interface, a clear gradient towards the top surface shows lower tensile RS in Z direction and slight compressive in X and Y directions at 2 mm from the weld interface.

On the Ti side, only minor RS fluctuations were observed over the entire mapping, and the values were generally close to those of a stress-free condition, concluding that the Ti sheet is mostly unaffected by the process. The uncertainty on the Ti side was in the range of +60 to +110 MPa.

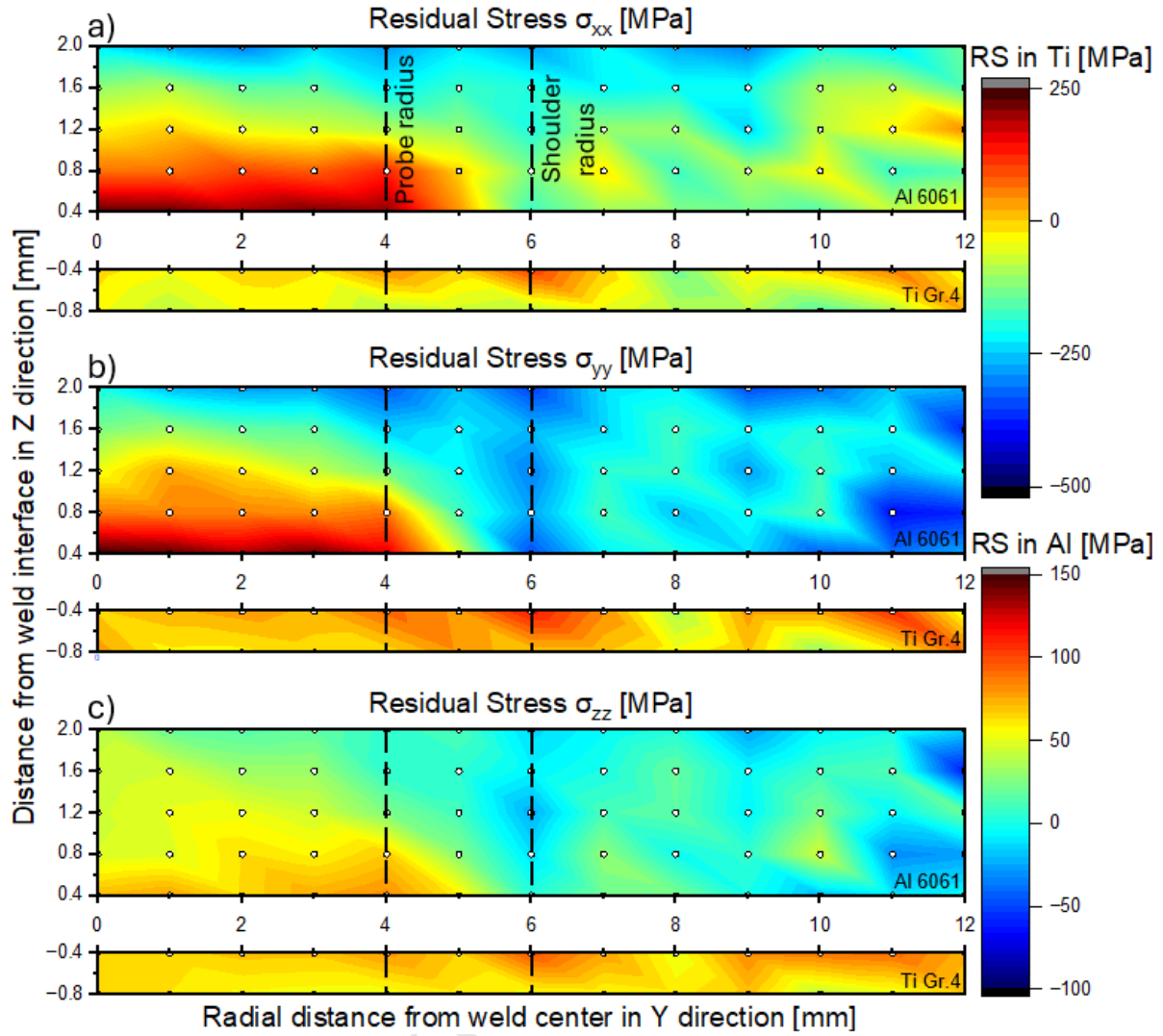


Figure 11: Determined triaxial RS a) σ_{xx} , b) σ_{yy} , and c) σ_{zz} within the dissimilar Ti/Al refill FSSW using EDXRD. The top map refers to Ti and the bottom to Al 6061-T6. The reader is referred to Figure 6 (b) for coordinates and for data point positioning.

4. Discussion

4.1 RS differences between ND and EDXRD in spot FMB Ti/Al welds

These differences are attributed primarily, on the one hand, to the pronounced microstructural heterogeneity in the spot FMB Ti region, combined with the different gauge volume sizes of the two techniques, and, on the other hand, to the use of a spatially invariant strain-free reference in the ND analysis for both Ti and Al phases. As shown in Figure 12, the Ti sheet at the spot FMB weld center contains markedly different microstructural regions, including severely deformed fine-grained zones, elongated grains, and partially unaffected base material. Hardness mapping across these distinct microstructural regions are provided in Supplementary Figure S3.

Diffraction measurements are bulk-averaged techniques, and the larger ND gauge volume samples multiple regions simultaneously. Consequently, the ND-derived RS represents an averaged response over material volumes that may have different deformation histories, textures, and defect densities. In contrast, EDXRD probes a smaller, more localized volume. Therefore, EDXRD is initially better suited for resolving local RS gradients in the highly heterogeneous spot FMB Ti region.

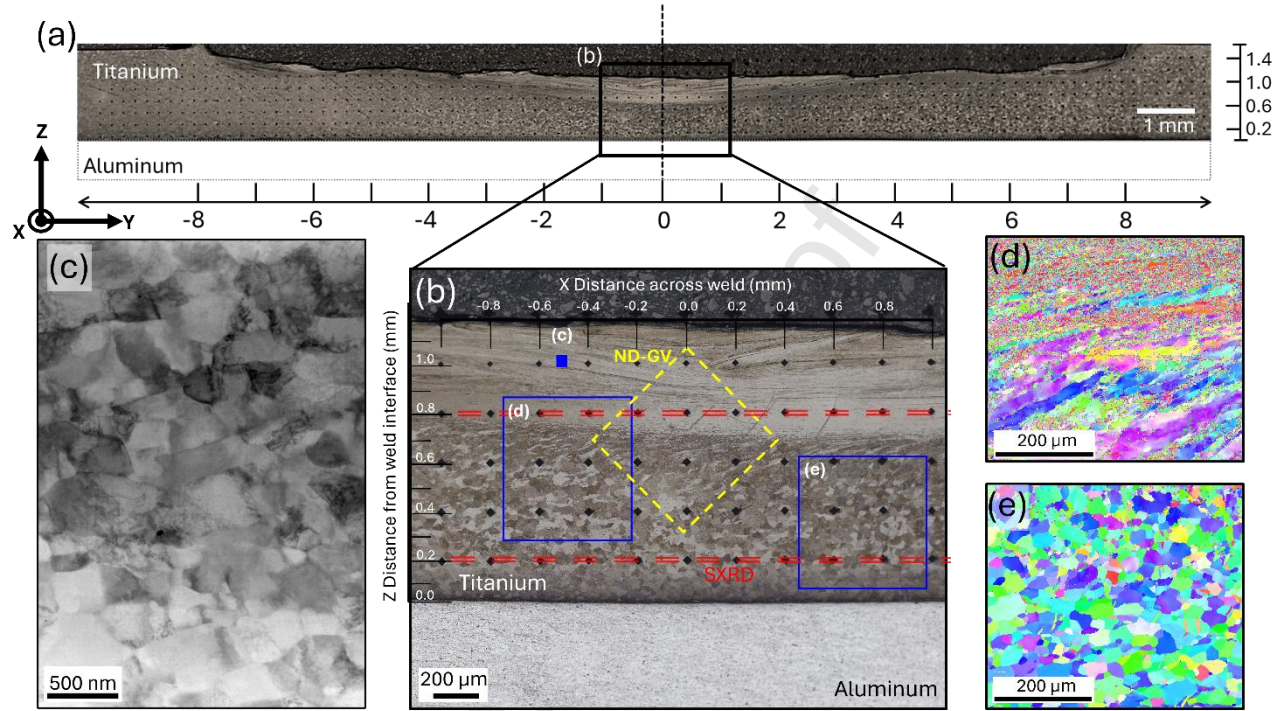


Figure 12: (a) Light optical micrograph (LOM) of the titanium cross-section at the spot FMB weld center, showing the microstructural gradient across the process zone along the weld; (b) higher-magnification view highlighting the Al region and the heterogeneous microstructure through the titanium sheet thickness, where the yellow dotted rhombus denotes the ND gauge volume encompassing three distinct microstructural zones, and the parallel red dashed lines indicate the location of the EDXRD measurements; (c) transmission electron microscopy (TEM) image revealing refined grains formed due to severe plastic deformation (SPD); (d) EBSD map showing elongated grains at the boundary between the SPD region and the adjacent zone; and (e) EBSD image of the non-affected base titanium, characterized by undeformed equiaxed grains.

To avoid the influence of different strain-free lattice parameters used in ND and EDXRD measurements, and to analyze solely the effect of the gauge volumes, the stress differences between two orthogonal directions at the same point for a given technique (which are unaffected by the d_o parameter) provide a more robust basis for comparing both techniques [37,38]. The difference between the radial and normal stress components (calculated as $\sigma_{yy} - \sigma_{zz}$) is proportional to the deviatoric stress, while uncertainties in d_o influence the hydrostatic stress component [39]. The measurement positions and stress differences ($\sigma_{yy} - \sigma_{zz}$) for spot FMB are shown in Figure 13 (a), (c) and Figure 14 (a), (c) for Ti and Al phases, respectively, revealing clear discrepancies between the two techniques. This simple comparison demonstrates that the larger gauge volume employed in ND spatially averages the residual

stresses across the heterogeneous stir zone of the Ti (Figure 13 (c)), which exhibits steep microstructural variations (Figure 12), whereas the smaller gauge volume of EDXRD resolves these local variations much better. Moreover, in the Al sheet (Figure 14 (c)), differences are observed up to $Y < 5$ mm from the weld center. This effect is mainly attributed to sharp thermal gradients in radial direction during cooling of the molten pool, and to the presence of Ti, which, also upon cooling, generates high tensile stresses in the Al sheet near the interface (due to the lower coefficient of thermal expansion of Ti). As in the Ti region, the larger gauge volume of ND tends to smooth the stresses (mainly the in-plane components) compared to EDXRD. This fact is supported by the work of Jimenez-Mena et al. [5], in which, in a steel/aluminium system processed by FMB, stresses in Al, in both longitudinal and transverse directions, tended to increase as the distance to the interface decreased within the first 1.5 mm (in Z direction). These findings also show that, although the stresses determined via ND are primarily hydrostatic in nature (as previously indicated), the stress differences between the two radial and normal directions can reach up to 100 MPa in Ti and up to 80 MPa in Al, highlighting the differences between both diffraction techniques.

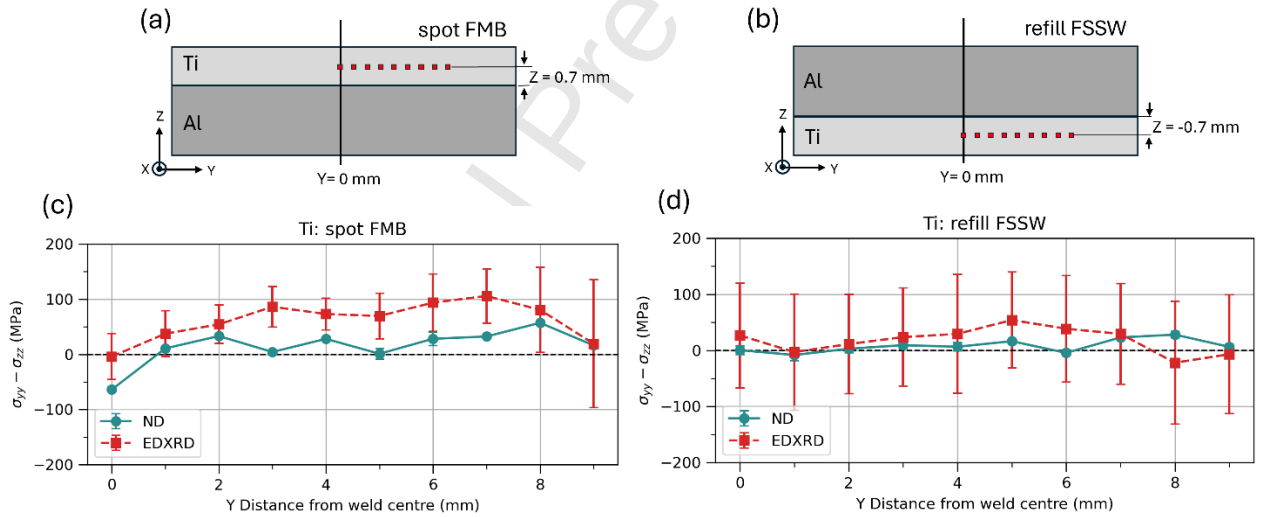


Figure 13: Schematic showing the positions used to calculate the stress differences relative to the weld center in (a) spot FMB and (b) refill FSSW. Stress difference evolution in the Ti sheet as a function of radial distance from the weld center for (c) spot FMB weld and (d) refill FSSW weld. The reader is referred to Figure 5 and 6 for coordinate definition.

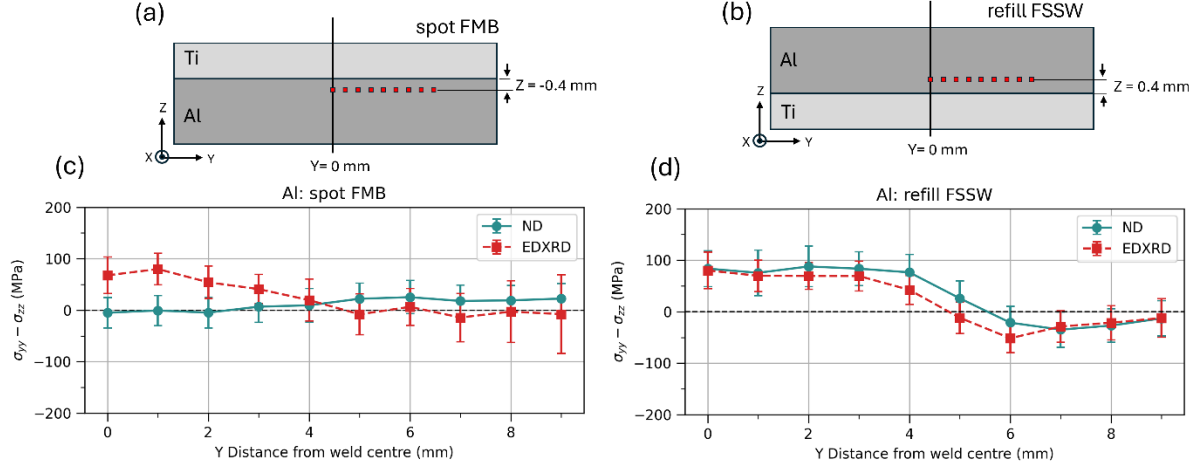


Figure 14: Schematic showing the positions used to calculate the stress differences relative to the weld center in (a) spot FMB and (b) refill FSSW. Stress difference evolution in the Al sheet as a function of radial distance from the weld center for (c) spot FMB weld and (d) refill FSSW weld. The reader is referred to Figure 5 and 6 for coordinate definition.

Having analyzed the effect of the gauge volume, it is interesting to compare and quantify the differences and trends when using the comb or the base material as strain-free reference. These stress differences, calculated as $\Delta\sigma_{yy(ND-EDXRD)}$ and $\Delta\sigma_{zz(ND-EDXRD)}$, are presented in Figure 15 and Figure 16 for Ti and Al phases, respectively, and are calculated by subtracting the stress values obtained via ND and EDXRD techniques for the same stress direction. The curves illustrate how ND measurements underestimate stress in the first millimeter (the transition occurs at $Y \sim 1.5$ mm), whereas from $Y > 1.5$ mm, the behavior reverses and stresses are overestimated. This explains why the stresses determined via ND in the first ~ 1.5 mm of Figure 8 (a), in the absence of a suitable d_0 , exhibit a sharp transition from compression into tension. Moreover, beyond $Y \geq 2$ mm, all differences become approximately constant and the stresses determined by ND provide a basis solely for trend analysis.

In the Al sheet (Figure 16), the differences $\Delta\sigma_{yy(ND-EDXRD)}$ and $\Delta\sigma_{zz(ND-EDXRD)}$ are less pronounced than in the Ti sheet, although, broadly speaking, greater for $\Delta\sigma_{yy}$, than for $\Delta\sigma_{zz}$ (the discrepancy is primarily associated with the in-plane stress component). The initial differences are negative (as in the case for Ti) and the trend shifts to positive at $Y \sim 6$ mm (coinciding with the point where the in-plane stresses shift from tension to compression in Figure 9); in other words, there is an initial underestimation followed by a final overestimation. This again reflects the influence of the base material as d_0 on the ND measurements and how the stresses shift toward compression near the weld in Figure 8 (b) (whereas the expected behavior is tensile as shown in Figure 9) and toward tension further away (when compressive stresses are observed via EDXRD).

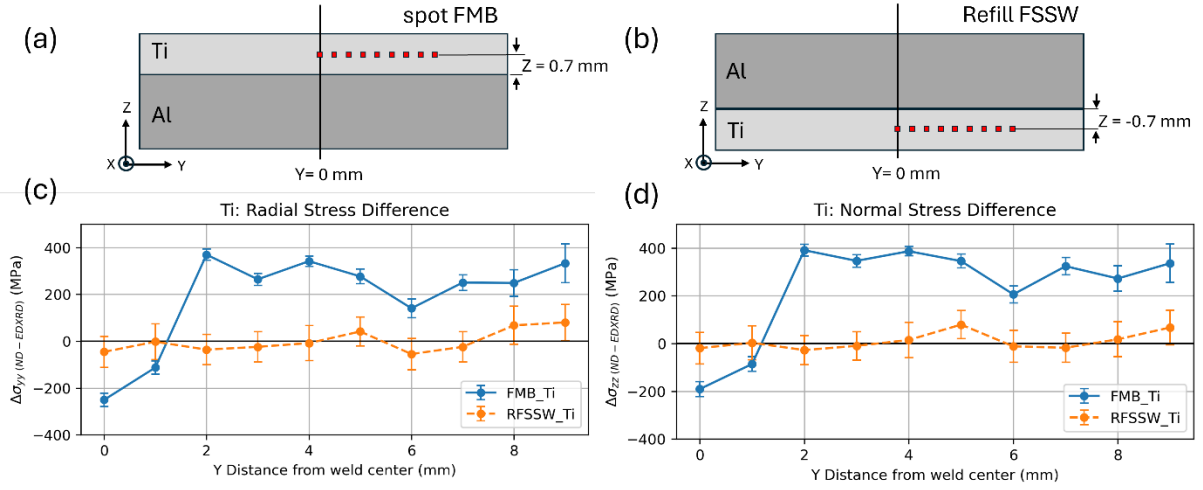


Figure 15: Schematic showing the measurement positions relative to the weld interface in (a) spot FMB and (b) refill FSSW. (c) Differences in radial RS ($\Delta\sigma_{yy} = \sigma_{yy-ND} - \sigma_{yy-EDXRD}$) for spot FMB and refill FSSW welds as a function of radial distance. (d) Differences in normal RS ($\Delta\sigma_{zz} = \sigma_{zz-ND} - \sigma_{zz-EDXRD}$) for spot FMB and refill FSSW welds as a function of radial distance. The reader is referred to Figure 5 and 6 for coordinate definition.

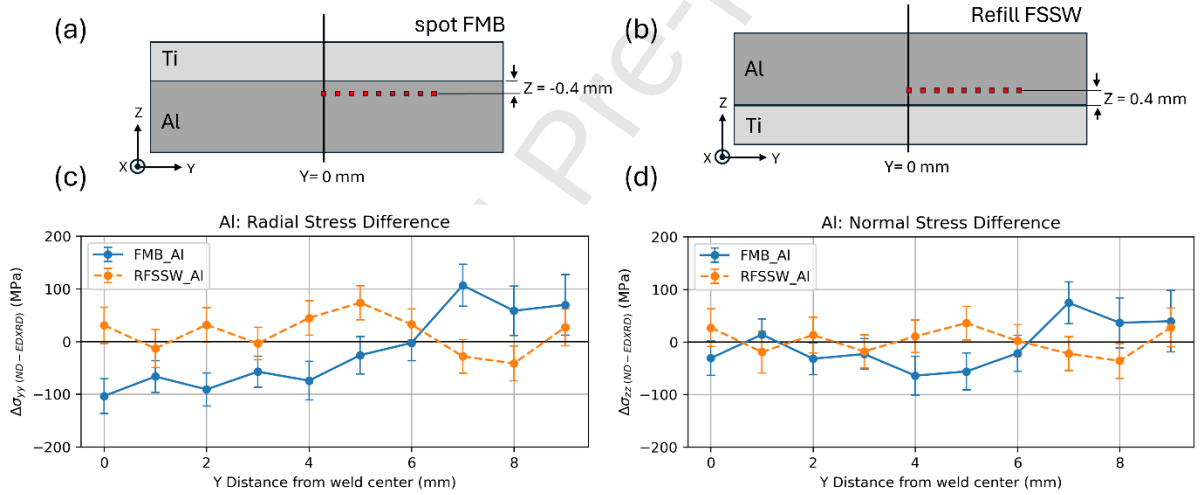


Figure 16: Schematic showing the measurement positions relative to the weld interface in (a) spot FMB and (b) refill FSSW. (c) Differences in radial RS ($\Delta\sigma_{yy} = \sigma_{yy-ND} - \sigma_{yy-EDXRD}$) for spot FMB and refill FSSW welds as a function of radial distance. (d) Differences in normal RS ($\Delta\sigma_{zz} = \sigma_{zz-ND} - \sigma_{zz-EDXRD}$) for spot FMB and refill FSSW welds as a function of radial distance. The reader is referred to Figure 5 for coordinate definition.

4.2 RS comparison between ND and EDXRD in refill FSSW Ti/Al welds

In refill FSSW, by once again eliminating the influence of the strain-free reference, the differences ($\sigma_{yy} - \sigma_{zz}$) caused by the variations in the size of the gauge volume between ND and EDXRD are much smaller than in spot FMB, becoming almost negligible in some positions, as can be observed (together with the measurement positions) in Figure 13 (b), (d) and Figure 14 (b), (d) for Ti and Al phases, respectively. Unlike spot FMB, the Ti sheet is not directly affected by tool-induced deformation and both stress differences (Figure 13 (d)) indicate that ND and EDXRD sample more comparable RS states.

Similarly, the Al stir zone exhibits a more homogeneous recrystallized microstructure and the absence of a solidified zone, as shown in Figure 17, resulting in smaller spatial variations in the residual stresses (Figure 14 (d)).

Once the influence of the different gauge volumes has been ruled out, it is possible to compare the total stresses at $Z=0.4$ mm (in Al) and $Z=-0.7$ (in Ti) with the stress differences $\Delta\sigma_{yy(ND-EDXRD)}$ and $\Delta\sigma_{zz(ND-EDXRD)}$ between the two diffraction techniques for identical directional components (as shown in Figure 15 and Figure 16 for Ti and Al, respectively). Since the rotating tool interacts only with the Al sheet, the plastic deformation is concentrated within the Al stir zone, while the Ti sheet undergoes comparatively limited deformation. Therefore, little stress variation is to be expected in Ti (as observed in Figure 11); thus, a constant d_0 (from the base material) serves as a simple and reliable reference at the analysed Z position. Regarding the Al sheet, the microstructure developed beneath the probe and near the interface ($Z=0.4$ mm) appears to exhibit slight differences, at least in terms of interplanar spacings compared to the base material, as seen in Figure 16 (which shows slightly greater sensitivity in the radial direction than in the normal direction). The direct consequence is that, even when using the base material as strain-free reference, the determined stresses will not only show same trends as those obtained with a comb-shaped sample, but their magnitude will also be relatively close to those determined by EDXRD (primarily in normal direction); this allows for the use of a simpler, less time-consuming methodology for ND experiments when analyzing near the interface (with certain limitations).

The broad tensile RS plateau observed in refill FSSW Al (Figure 10 and Figure 11) is likely attributed to the relatively high thermal exposure due to the long dwell time of 10 s, which promoted softening throughout the plastically deformed zone, see Supplementary material Figure S4. Therefore, the typical RS reduction in the center of the plateau leading to the typical M-shaped stress distribution, often reported for age-hardenable 6xxx Al alloys [14], was suppressed.

The difference between the two in-plane stress components (σ_{xx} and σ_{yy}) observed outside the processed zone in EDXRD measurements (Figure 11 (a), (b)) indicates a deviation from the radial symmetry assumption in ND. This may be related to the rectangular plate geometry and asymmetric heat dissipation conditions during welding. The use of different crystallographic constants for each direction due to the initial rolling texture may have merit although in a secondary role.

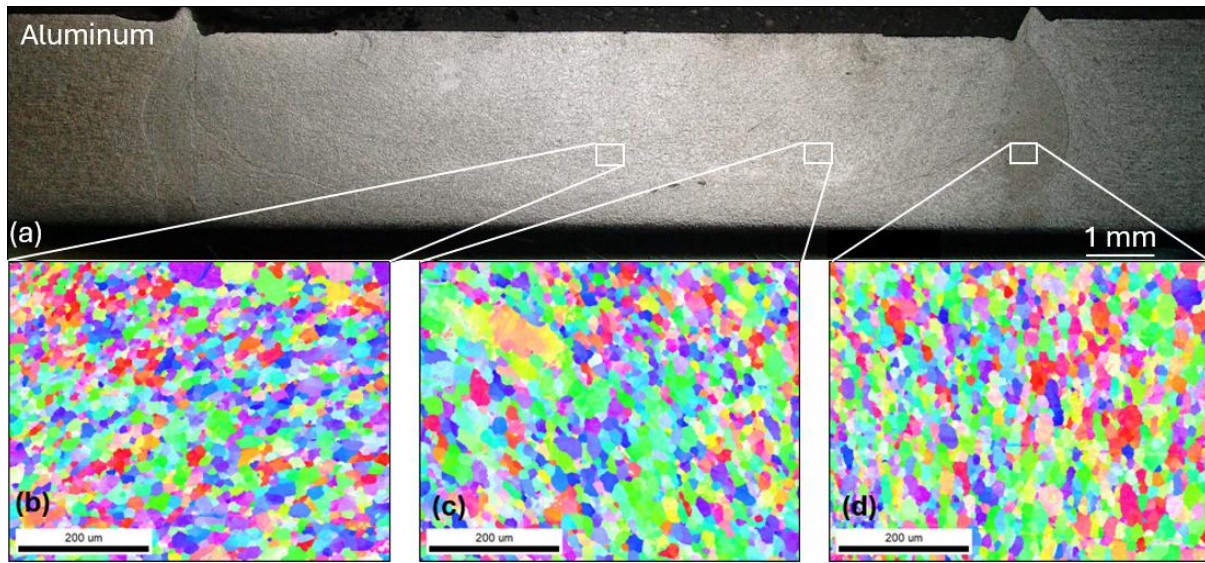


Figure 17: (a) Light optical micrograph of the Al side cross-section at the refill FSSW weld center showing the microstructure of the weld; EBSD maps show (b) the recrystallized microstructure at the center of the weld at a distance of 1 mm from the interface, (c) the microstructure at a radius of 3 mm and an interface distance of 1 mm, and (d) the microstructure at a radius of 6 mm and an interface distance of 1 mm.

4.3 RS comparison between Refill FSSW and spot FMB Ti/Al welds

The different RS distributions in spot FMB and refill FSSW arise from their different heat-generation (see Figure 18) and deformation mechanisms (Figure 3). In spot FMB, heat is generated mainly at the Ti surface by frictional contact between the rotating tool and the Ti sheet. This produces localized heating, severe plastic deformation, and strong microstructural gradients in Ti. As a result, high tensile RS values are concentrated in the Ti near the tool-workpiece interaction zone, surrounded by high compressive RS adjacent to the center zone.

In refill FSSW, the tool only interacts with the Al sheet. Heat generation and plastic deformation are therefore concentrated in the Al near the interaction zones between the Al sheet, the shoulder, and the probe. Consequently, the RS distribution in the Al sheet after refill FSSW is governed mainly by plastic deformation and thermal softening. Thus, despite their different joining process characteristics, both spot FMB and refill FSSW exhibit the highest residual stresses in the sheet that is in direct contact with the tool.

The through-thickness RS gradients are steeper in spot FMB, especially in Ti, because of localized heating and constrained cooling. In refill FSSW, the stress gradients in Al are smoother due to the increased thermal diffusivity, the more homogeneous deformation, and recrystallization of the Al stir zone. In both weld types, the normal stress component, σ_{zz} , remains lower than the in-plane

components, which is consistent with the reduced through-thickness constraint in thin-sheet welding [35,36].

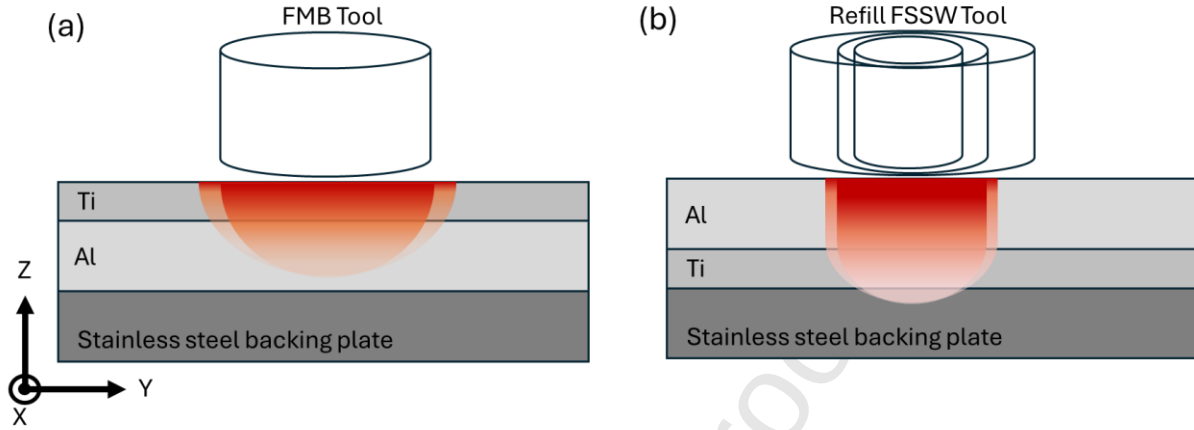


Figure 18: Schematic contour map of the thermal heat generation across the weld cross-section in (a) spot FMB and (b) refill FSSW dissimilar Ti/Al welds [40,41].

4.4 Methodological implications of ND and EDXRD for RS determination in Ti/Al welds

ND and EDXRD provide complementary information rather than directly interchangeable RS values. In highly heterogeneous weld regions such as FMB Ti, the larger ND gauge volume increased the uncertainty in local stress evaluation. When combined with its smaller gauge volume, EDXRD enables improved resolution of local RS gradients and microstructure-related stress variations.

In more homogeneous weld regions, such as refill FSSW, the smaller $\Delta\sigma_{yy}$ and $\Delta\sigma_{zz}$ values (Figure 15 and Figure 16) indicate that ND and EDXRD provide more comparable RS trends. Therefore, the choice of measurement technique should be guided by the characteristic length scale of the microstructural heterogeneity, the expected RS gradients, and sample thickness. ND remains valuable for RS evaluation when greater penetration depth is needed or smooth stress gradients are expected (refill FSSW), whereas EDXRD is advantageous for localized RS analysis in regions with steep and/or smooth gradients, i.e. spot FMB or refill FSSW.

5. Conclusions

This paper presents a novel comparison of RS in dissimilar Ti/Al spot welds using ND and EDXRD, together with a direct comparison between two welding techniques: spot FMB and refill FSSW. These processes differ in their material-side processing approach, with spot FMB involving primary tool

interaction with the Ti sheet and refill FSSW with the Al sheet, resulting in fundamentally different thermo-mechanical conditions and RS evolution.

The results show that RS evolution in dissimilar Ti/Al spot welds is strongly dependent on the joining process, with fundamentally different mechanisms governing spot FMB and refill FSSW. In spot FMB, RS are dominated by thermally induced stresses in the Ti, where thermal contraction during cooling is constrained by the surrounding material and the Ti/Al interface, resulting in high stress magnitudes and steep through-thickness gradients. In contrast, refill FSSW is characterized by a more uniform stress distribution due to the higher thermal diffusivity of Al and homogeneous recrystallization over a wide area. Without direct tool interaction, the Ti side is mostly unaffected in terms of RS.

The comparison between ND and EDXRD highlights that the suitability of each technique depends on the weld microstructure and the characteristic length scales of RS gradients. In spot FMB welds, where pronounced microstructural heterogeneity and steep RS gradients are present, EDXRD provides higher spatial resolution of local stress variations owing to its smaller gauge volume. In contrast, ND measurements are affected by larger gauge-volume averaging across heterogeneous regions and sharp RS gradients that provide much less resolution. In refill FSSW welds, where the microstructure is more homogeneous and RS gradients are less severe, both techniques show comparable residual stress trends.

Accurate RS determination in dissimilar Ti/Al spot welds therefore requires careful consideration of microstructural heterogeneity and gauge-volume effects. While EDXRD is particularly effective for resolving localized RS variations, ND remains valuable for bulk RS evaluation due to its larger sampling gauge volume and greater penetration depth. The combined use of both techniques provides a comprehensive framework for RS determination.

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CRediT authorship contribution statement

Sanjay C. Krishnamurthy: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Data curation, Writing – Original Draft. **Lasse Malaske:** Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Data curation, Writing – Original Draft. **David Canelo-Yubero:** Methodology, Formal analysis, Investigation, Validation, Data curation, Writing – Review & Editing. **Marc-André Nielsen:** Investigation, Resources, Writing – Review & Editing. **Thilo Pirling:** Investigation, Resources. **Marie-Noëlle Avettand-Fènoël:** Investigation, Resources, Validation, Writing – Review & Editing. **Aude Simar:** Conceptualization, Methodology, Validation, Writing – Review & Editing, Funding acquisition, Supervision. **Benjamin Klusemann:** Conceptualization, Methodology, Validation, Writing – Review & Editing, Funding acquisition, Supervision.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT-5.3 for language editing and improvement of clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data availability

Data will be made available upon request.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Novel residual stress characterization in dissimilar Ti/Al spot welds using ND and EDXRD
- Spot FMB and refill FSSW show distinct residual stress evolutions
- High residual stress in Ti for spot FMB, more uniform residual stress in Al for refill FSSW
- EDXRD resolves steep residual stress gradients; ND probes larger gauge volumes