Through thickness non-destructive residual stress-mapping of friction stir welds in Aluminium using neutron diffraction

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1. Introduction and the SALSA instrument

The non-destructive determination of residual stresses within engineering components using laboratory equipment is limited to the surface (X-ray) or near surface regions (Barkhausen-noise) and with limited spatial resolution. Bulk stress investigations are often carried out using destructive methods. Examples are deep-hole drilling, slicing or the contour method. The destructive methods are based on the relaxation of stresses and therefore limit further materials investigations and include the destruction of an expensive, highly elaborated part.

Neutron stress determination conquers these shortcomings. It is a **non-destructive** technique, applicable to mock-ups as well as realistic sized engineering components. It allows mapping of stress fields from the bulk of the work piece to its surface with adjustable lateral resolution, providing the full stress tensor for each measuring point. The technique is based on diffraction at (poly-) crystalline material, comparable to x-ray diffraction, but permits much higher penetration. Neutron techniques are well suited for in-situ or in operando investigations, using even complex sample environment. Examples are heat treatment, tensile testing, fracture dynamics or casting. The non-destructive character allows the investigation of complete development cycles since the same sample can be measured repetitively, after it has received further treatment or aging tests.

SALSA, which stands for "Stress Analyzer for Large Scaled engineering Applications", is a stress diffractometer dedicated to engineering sciences and industrial R&D [1]. It is part of the instrument suite of the Institut Laue-Langevin (ILL) in Grenoble, France, which operates one of the most intense neutron sources in the world.

SALSA provides a maximum of flexibility in terms of sample size and shape, allowing laterally resolved stress- and texture determination. The resolution is variable between 0.6 and 4 mm and allows stress mapping with penetration depths of 60 mm in steel, 70 mm in Titanium alloys, 40 mm in Nickel and 300 mm in Aluminium, to give some examples. The minimum sample thickness for stress determination is 0.5 mm.

A special technique allows the determination of stress profiles from the surface into the bulk with the first measuring point at 40 microns below the surface. This technique is applied to surface treatment investigations, comprising Laser shock peening, induction hardening, spray coating etc. SALSA can host samples of up to 1.5 m length and a weight of 700 kg. The sample table is a hexapod, allowing tilt and translation in order to position the sample in the right orientation to the beam with a precision of 5 micrometres.

2. Investigation of Friction Stir Welds

As an example we present a partial result of a test series with OHB-System regarding friction-stir welding (FSW) of aluminium. OHB System[1] is one of the leading space companies in Europe, delivering satellites and high-tech components for the space sector.

The focus of the following paragraph will lie on the neutron technique. Friction stir welded (FSW) Aluminium plates (2XXX series) of 250 x 700 mm^2 and 6 mm in thickness were investigated using the set-up shown in figure 1. Special interest lied on the stress field across thickness within nugget and heat affected zone (HAZ).

The gauge volume was defined by three focussing collimators to a dimension of 0.6x0.6x2mm^3. The sample is then position and scanned through the gauge volume with the help of the hexapod stage. For each position, the Bragg-diffraction peak Al(311) is recorded. The angular position θ of the peak is a precise measure of the lattice spacing of the crystallites within the material. Since this lattice spacing changes with the surrounding stress field, stresses can be determined from the peak shift relative to the unstrained condition θ_0. Strain can be calculated directly from the peak shift:

$$\varepsilon = \frac{d - d_0}{d_0} = \frac{\sin(\theta_0)}{\sin(\theta)} - 1$$

d and d_0 are lattice spacings of the strained and unstrained crystal lattice respectively. The measurements are performed in the three principle axis directions of the sample by orienting it accordingly relative to the scattering vector (fig. 1). This allows the direct determination of the stress tensor. If the principal axis directions are not known, measurements in six independent orientations are performed.

Figure 2 shows 2D maps of the three principal stress components: longitudinal (in welding direction), transversal (to the weld nugget) and normal (to the plate). The section covers 16 mm width from the centre of the weld into the HAZ and 3 mm in depth to the middle of the weld thickness. Origin is the surface central point of the weld. The normalized[2] 2D stress distribution indicates the gradient between tensile (+) and compressive (-) regions and their evolution in depth of the weld. As expected, maximum tensile stresses appear near the HAZ, with a more compressive state within the weld nugget. Note that all stress levels are normalized by the longitudinal component.

The line profiles in figure 2 show the stress evolution parallel to the surface at different depths. The maxima follow the weld seam inside the material and a clear trend to tensile stresses from the surface to the middle thickness of the plate is detected.

[1] https://www.ohb-system.de/

[2] for confidential reasons

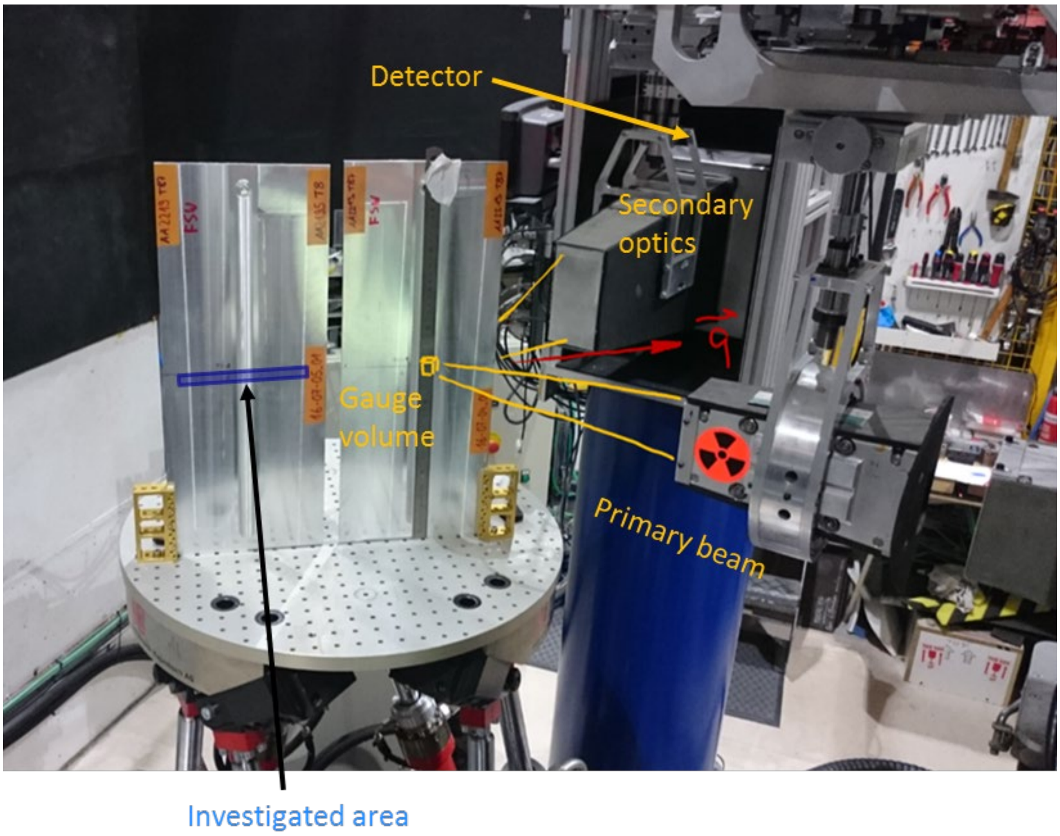

Figure 1 Set-up for measurements in two test welds at the same time. The primary beam is shaped by two radial focussing collimators. A third collimator (secondary optics) in front of the detector defines the third dimension of the gauge volume. The scattering vector q indicates the investigated strain component. In this specific geometry it is the transversal one. The distance between beam optics and samples is about 400 mm, leaving room for sample movements.

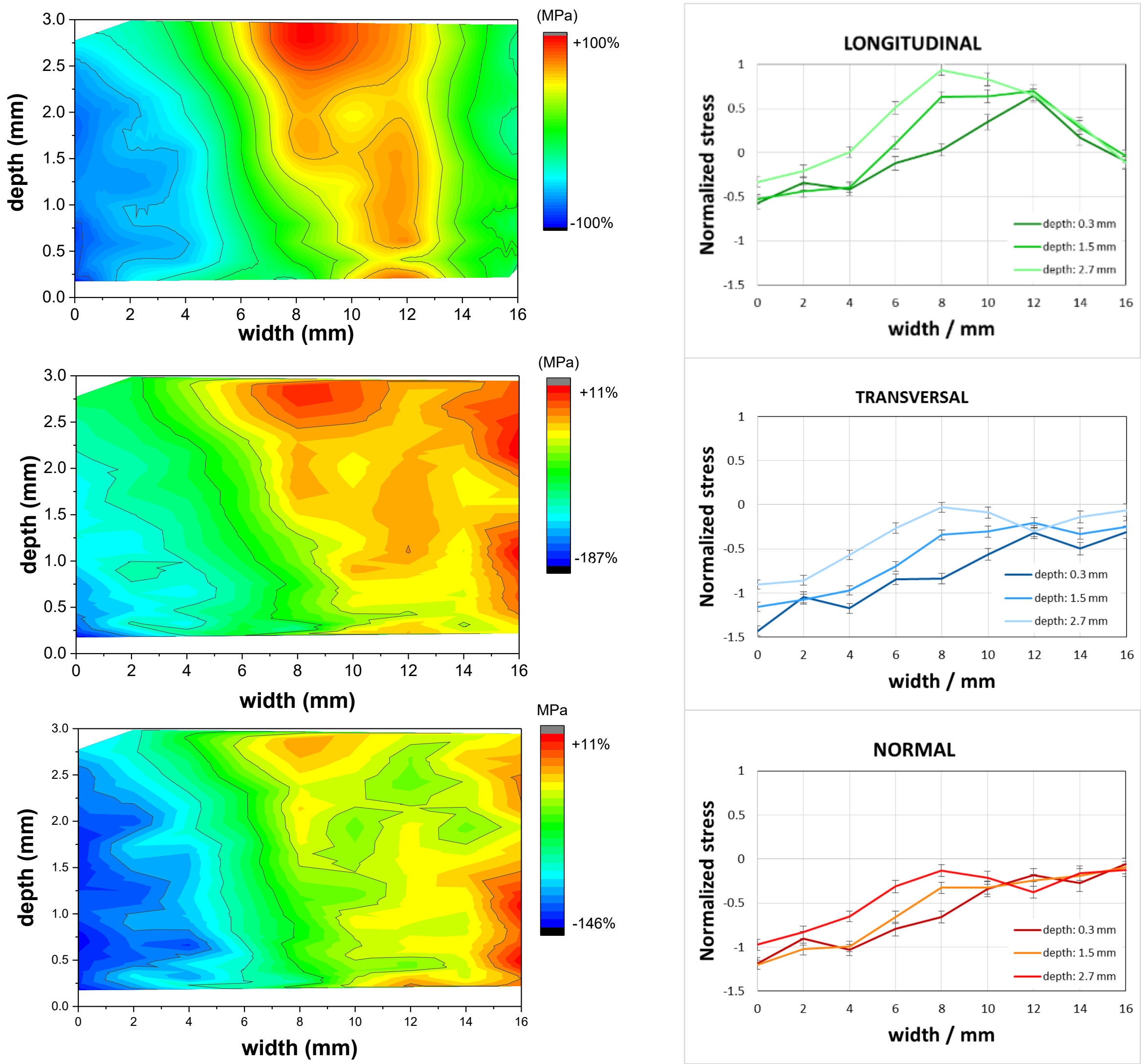

Figure 2 left: Residual stress 2D mapping of longitudinal, transversal and normal components. Right: corresponding profiles at depths of 0.3, 1.5 and 2.7 mm. The weld seam is at 9 mm.

3. Perspectives

There is a growing interest from various industrial sectors in neutron stress mapping because of its unique ability to provide full tensor measurements non-destructively. For instance in the space sector, NASA is investigating welds and additive manufactured parts using several techniques including neutron stress scanning [2, 3].

4. References and Acknowledgment

[1] T. Pirling, et al., "SALSA—A new instrument for strain imaging in engineering materials and components", Materials Science and Engineering: A, vol. 437, no. 1, pp. 139–144, 2006.

[2] T. Watkins, et al., "Neutron Characterization for Additive Manufacturing", Advanced Materials & Processes, March 2013

[3] S. Bagg, et al., "The effect of laser scan strategy on distortion and residual stresses of arches made with selective laser melting", NASA technical Reports Server, 2016, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160008858.pdf

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