Non-destructive testing of specimens obtained by friction stir welding for aeronautical applications

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Keywords

Non-destructive testing, aluminium alloys, aircraft construction, friction stir welding, residual stress, Bragg Edge Mapping, X-ray micro computed tomography, porosity texture.

Introduction

The history of world aviation is closely related to aluminium and the history of creating aluminium alloys, and the more durable and reliable aluminium became, the higher, farther and safer airplanes flew.

The first person who managed to understand the potential of aluminium in the aerospace industry was the writer Jules Verne, who provided a detailed description of an aluminium rocket in his fantastic novel 'Journey to the Moon' in 1865. In 1903, the Wright brothers got the first airplane off the ground, in which parts of the engine were made of aluminium.

At present, aluminium is used in the aviation industry everywhere in the world. From two thirds to three quarters of a passenger plane's dry weight, and from one twentieth to half of a rocket's dry weight accounts for the share of aluminium in airborne craft.

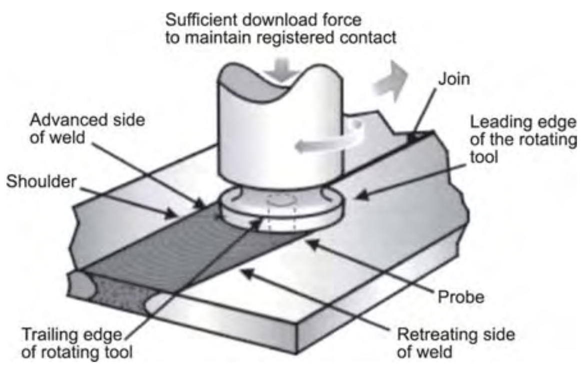

Figure 1. Scheme of the FSW process

Aluminium is used for manufacturing various components of spaceship equipment: fuselages, panels, frames, brackets, etc. Certain parts of the aircraft, like the fuselage, need to be welded. Welding aluminium has never been an easy task, but a new technique called 'friction stir welding' has made it much easier.

Friction-stir welding (FSW) is a solid-state joining process [1] in which a cylindrical-shouldered tool is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces of sheet or plate material, which are butted together (Figure 1).

Like virtually all manufacturing techniques, welding induces residual stresses in the obtained component. Residual stresses are those stresses present in a material or structure when no external loads are applied. Residual stresses may reduce the performance or cause failure of manufactured products. They may increase the rate of damage by fatigue, creep or environmental degradation. This is why it is important to evaluate the residual stress level in a component. For investigating the residual stress level in different Al plates obtained by FSW, we used neutron diffraction.

The advance of the rotating tool in the material introduces texture phenomena that can generate effects of anisotropy on the mechanical properties of the material. We investigated the presence of texture using Bragg Edge Mapping by neutron scattering.

The presence of cavities in weldings can lead to failure of the component during the fatigue cycles, as a consequence of crack growth and propagation. FSW is known to induce very low level of porosity. We verified it using X-rays micro-CT and compared it with a laser-beam welding.

Materials and methods

1) Residual stress investigation

Three AA2024 T-joint FSW specimens obtained using different rotating tool speeds: 340 rpm (2 samples) and 500 rpm

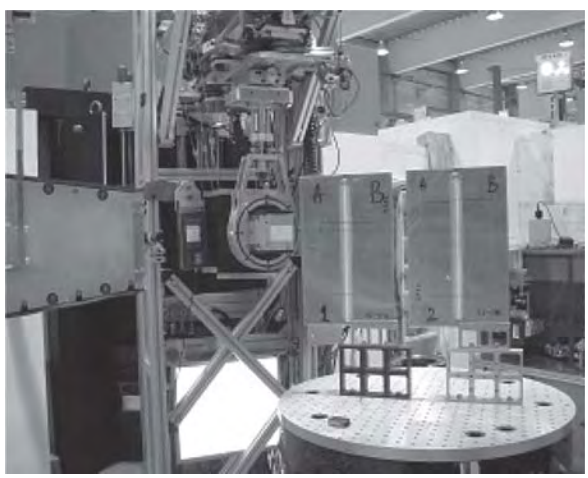

Figure 2. Experimental setup, SALSA diffractometer at ILL Grenoble

(1 sample) were analysed. The dimensions of the welded plates were: 300 mm × 200 mm × 3.5 mm. The measurements were performed on the SALSA strain/stress diffractometer (Figure 2) at Institute Laue Langevin (ILL), Grenoble (F).

A monochromatic neutron beam with a wavelength of 1.69Å and the Al (311) reflection with a corresponding 2θ angle of 88.5° were considered for determining the interplanar distance using Bragg's law.

25 points on a line perpendicular to the welding direction were investigated for each of the two analysed samples, using a gauge volume of 1.5 × 1.5 × 1.5 mm^3 and the measurements were performed in three orthogonal directions: longitudinal (X), transversal (Y) and normal (Z) - see Figure 3.

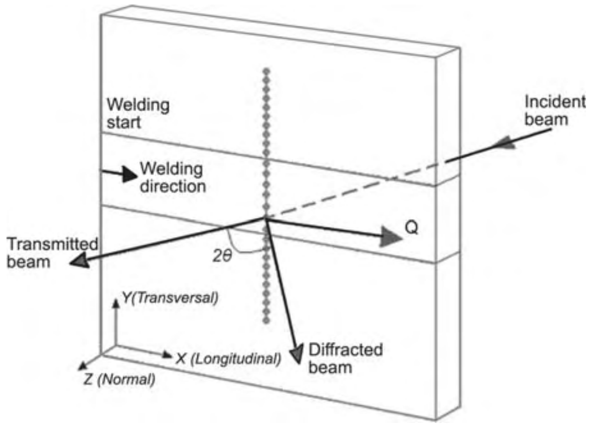

Figure 3. Measuring points and directions

The neutron diffraction technique for the residual stress analysis is based on the Bragg's law (1):

$$\lambda = 2d_{hkl}\sin(\theta_{hkl}) \tag{1}$$

where d_{hkl} represents the interplanar distance for the (hkl) atomic plane, λ is the neutron beam wavelength and θ is the half of the diffraction angle 2θ.

The strains in the three orthogonal direction can be obtained using equation (2):

$$\varepsilon_{i\,hkl} = \frac{d_{i\,hkl} - d_0}{d_0} \tag{2}$$

where i = X, Y, Z and d_0 is the unstrained interplanar distance for the considered (hkl) plane and can be determined for each investigated point from the assumption that for each point the normal stresses (Z direction) were negligible due to the geometry of the specimen (3) [2], [3].

$$d_0 = \frac{(1-\nu)d_Z + \nu(d_X + d_Y)}{1+\nu} \tag{3}$$

where ν is the Poisson ratio.

Finally, the residual stresses in the case of an isotropic elastic material (characterised by a macroscopic Young's modulus E and Poisson ratio ν) along the principal axis - longitudinal (X) and transversal (Y), as we assumed stresses in the normal (Z) - can be determined using the relations reported in equation (4) [4]:

$$\begin{cases} \sigma_X = \dfrac{E}{(1-2\nu)(1+\nu)}\left[(1-\nu)\varepsilon_X + \nu(\varepsilon_Y + \varepsilon_Z)\right] \\ \sigma_Y = \dfrac{E}{(1-2\nu)(1+\nu)}\left[(1-\nu)\varepsilon_Y + \nu(\varepsilon_X + \varepsilon_Z)\right] \end{cases} \tag{4}$$

2) Texture investigation using Bragg Edge Mapping

The Bragg Edge Radiography measurements were performed on the same specimens described before, both in the welding area and in the rest of the plates in order to analyse the texture change in the welding. The investigations were performed on the V7 Cold Neutron Radiography and Tomography (CONRAD) instrument at Berlin Neutron Scattering Facility, Helmholtz Zentrum Berlin. In Figure 5 is presented a description of the experimental setup, where the white neutron beam is transformed in a monochromatic beam by using a double-crystal monochromator and then passes through that sample positioned on a table situated in front of a CCD detector.

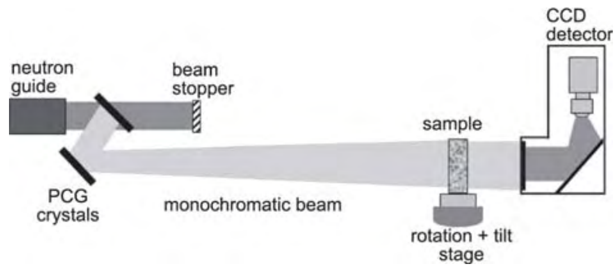

Figure 4. Experimental sketch, Bragg Edge Mapping experiment

The neutron attenuation coefficient for polycrystalline materials decreases suddenly for well-defined neutron wavelengths - the so-called Bragg edges [5]. The position of these edges is defined by the symmetry and the parameters of the crystal lattice. At wavelengths greater than this critical value no scattering by particular (hkl) lattice planes can occur because the corresponding Bragg reflection angle reaches its maximum of $2\theta = 180°$. Therefore a sharp increase in the transmitted intensity occurs, and the strong-contrast variations near the Bragg edges become available [6]. Therefore, by performing a wavelength scan around the Bragg edge, it is possible to the visualize texture features caused by local changes in the crystal structure. In other words, this method allows a direct visualization of the texture mapping, at least from a qualitative point. Some attempts are being carried out in the literature in order to get also quantitative information by this method [7].

In our experiment we increased the wavelength from 4Å to 5Å with a step of 0.025Å, with a spatial resolution of about 100 µm.

3) X-ray Micro-CT for porosity observations

Micro-CT is known to be a unique technique for the non invasive, non-destructive 3-D characterization of materials in medicine, material science and biology. It is a 3-D radiographic imaging technique, similar to the conventional computed tomography systems used in medical and industrial applications. Unlike such systems, which typically have a maximum spatial resolution of about 1 mm^3, micro CT is capable of achieving a spatial resolution of the order of 1μm^3. In particular, synchrotron radiation offers the possibility of selecting X-rays with a small energy bandwidth from the wide and continuous energy spectrum whilst, at the same time, guaranteeing a high enough photon flux for efficient imaging.

If a specimen is imaged several times in different orientations (radiographies), three-dimensional (volume) information on the sample structure can be obtained using computer algorithms (Figure 5). This is called a tomographic reconstruction or computed tomography. As the resolution is in the range of few microns, it is also called micro-CT. It enables us to look at slices of the investigated object without physically cutting it.

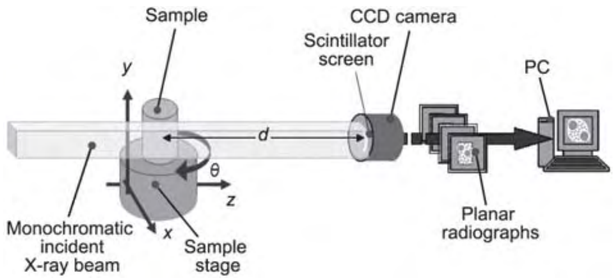

Figure 5. Setup of a micro-CT experiment

As we previously performed a micro-CT experiment on a laser-beam welding and it proved to be a powerful technique to non-destructively observe the presence of porosity in the welding, we performed the same experiment on a specimen cut out from the middle of the welding - see Figure 6. Our aim was to verify that the FSW induces a negligible level of porosity in the welding.

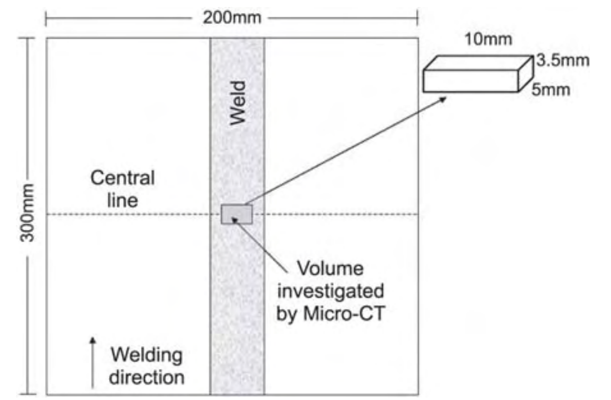

Figure 6. Micro-CT investigated area of the welding

The measurements for the laser-beam welding specimen were performed on the SYRMEP beamline [8] at ELETTRA synchrotron radiation facility using an energy of the X-ray beam of 30keV, while the investigation of the FSW specimen was done on the BAM line [9] at the BESSY-II synchrotron radiation facility in Berlin, using the same beam energy. In both cases the spatial resolution was about 10μm.

The visualization of the reconstructed volume of the analysed welding area was done by using a commercial software, VG Studio Max.

Results and discussion

1) Residual stress

As expected, low levels of residual stresses were observed in all three specimens that we analysed, with a maximum tensile stress of 100 MPa in the longitudinal direction. The stresses are tensile in the welding area, while they go compressive in the parent plates.

We first compared the residual stresses obtained for the two specimens in which the welding was performed using different speeds of the rotating tool (Figure 7).

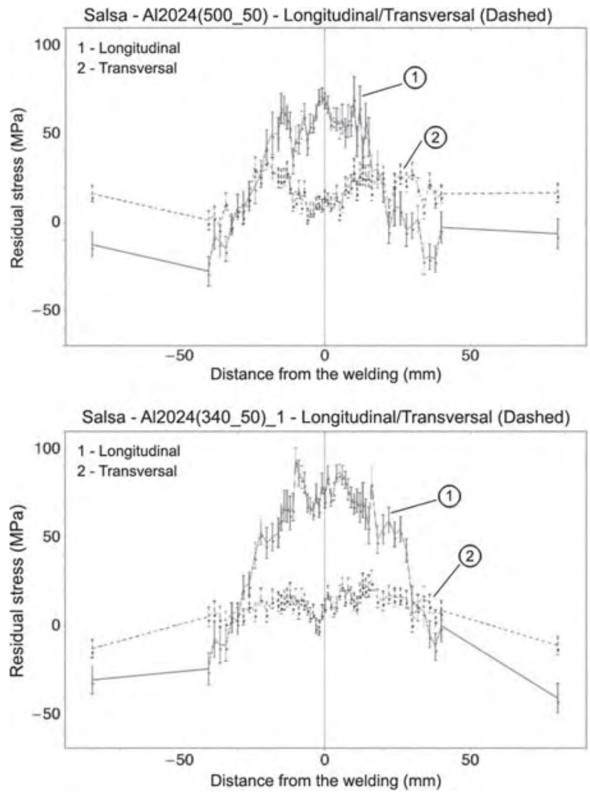

Figure 7. Comparison between residual stresses for two different rotating tool speeds (500rpm and 340rpm).

It seems that for a higher rotating tool speed (500 rpm) the stresses in the longitudinal direction are about 20 MPa lower than those obtained for a lower rotating tool speed (340 rpm) in the same direction, while for the transversal direction, the opposite effect of the same magnitude was observed.

The second task of our analysis was to verify the reproducibility of the welding in terms of residual stresses. We investigated another specimen, welded using the same rotating tool speed of 340 rpm. As it is reported in Figure 8, we obtained similar stresses for the two specimens.

2) Texture investigation

Figure 9 shows the three curves of the transmission in function of the wavelength for three considered areas in the welding region, each region having a largeness of about 5 mm. The black pins indicate the limits of the welding area.

It can be observed the increase of the transmitted intensity at 4.6Å for all three curves, due to the fact that less neutrons are diffracted because the Bragg reflection angle corresponding to the (111) lattice planes of Al reaches its maximum of $2\theta = 180°$.

The curve corresponding to the centre of the welding region has a lower transmission around 4.6Å than the other two curves corresponding to the lateral areas of the welding region. This is due to the fact that more (111) planes are satisfying the Bragg law in that region, so more neutrons are diffracted, resulting in a weaker transmitted beam in that area. It means that the rotating tool induces a certain level of texture in the centre of the welding, that is visualized in the corresponding radiographic image.

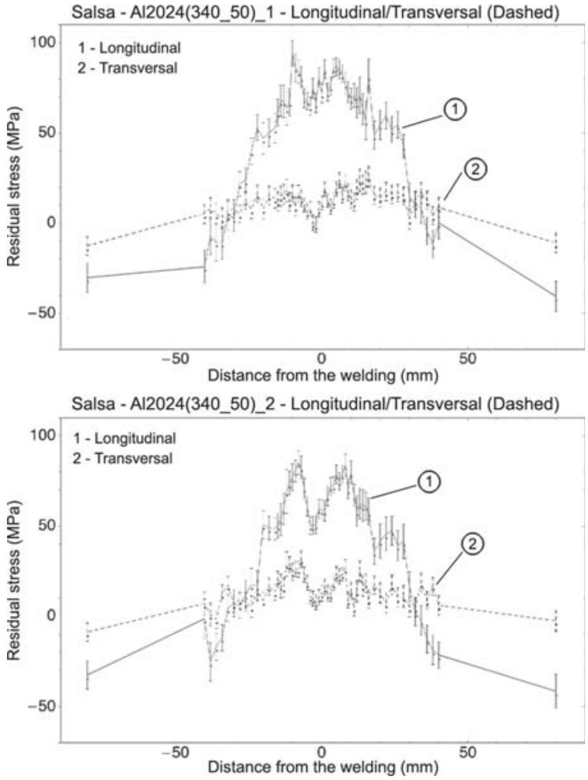

Figure 8. Comparison between residual stresses for two different specimens, same rotating tool speed (340rpm)

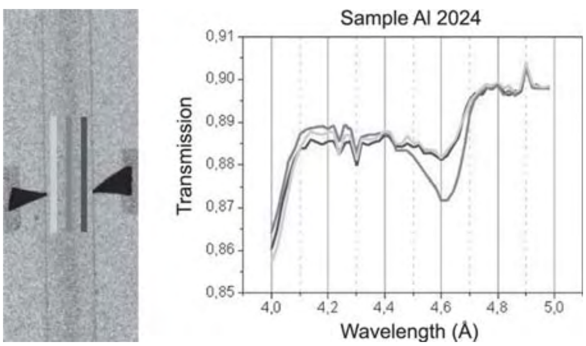

Figure 9. Transmission vs. wavelength at different positions in the welding

We also analysed a three regions outside the welding. In this case, similar levels of the transmitted beam intensity were observed (Figure 10).

3) Micro-CT observations

First we present the results of the micro-CT analysis in a Al 2024 C-geometry specimen submitted to a laser welding (Figure 11). As shown, synchrotron radiation based micro-CT allows the identification of porosity inside the specimen, with a good resolution. In particular, in this case, the evidence of the presence of porosity inside the investigated sample allowed us to explain the non symmetric behaviour of the residual stresses measured in this sample.

Using the VG Studio Max software, we could analyse any part of our specimen. One can look at different slices (Figure 12) in order to visualise the porosity in 2D or the whole investigated volume can be observed in 3D as in

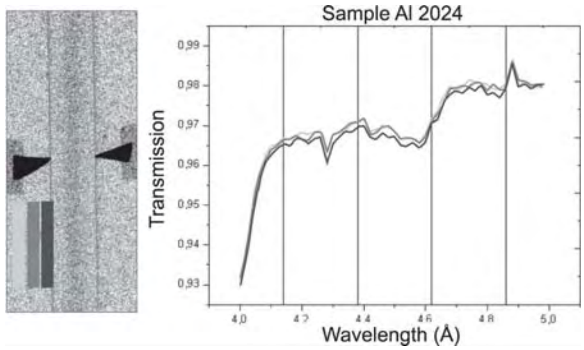

Figure 10. Transmission vs. wavelength at different positions outside the welding

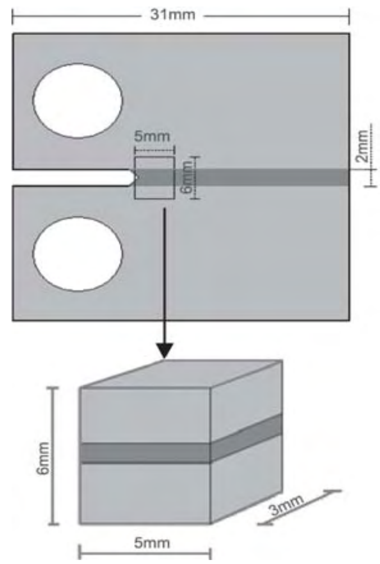

Figure 11. Geometry of the laser-beam welding and investigated area in a compact tension specimen

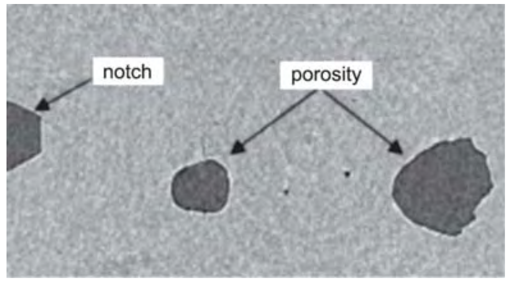

Figure 12. Slice of the reconstructed volume

Figure 13, where the material was rendered invisible and the air regions (porosity inside the analysed volume of the specimen and air at its margins) appear in a light colour.

In order to verify the absence of porosity reported in the literature in the case of FSW, we performed the same micro-CT experiment on a sample cut across the welding.

As shown in Figure 13, the material looks compact. As expected, no porosity is visualized, at least at the spatial resolution achievable in this experiment (about 10μm).

Conclusions

Different non destructive techniques were used for investigating FSW specimens: neutron diffraction for residual stress analysis, Bragg Edge Mapping for texture analysis

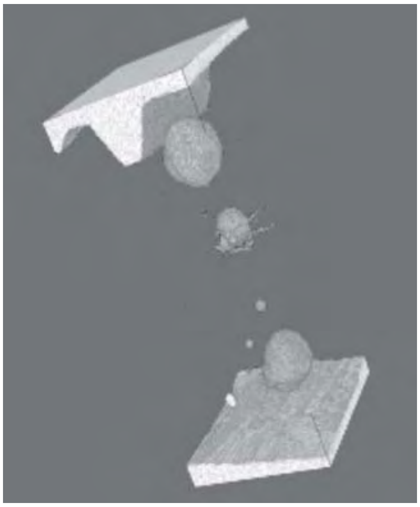

Figure 13. Porosity visualisation by micro-CT in the laser-beam welded specimen

Figure 14. Absence of porosity in the FSW specimen

and X-ray micro-CT for microstructural observations. The obtained residual stresses are in good agreement with other results on similar Al alloys found in the literature. We confirmed the low stress level in FSWs, checked the influence of the rotating tool speed on the level of stresses and we also verified the reproducibility in terms of stress values and trend for two different Al 2024 specimens obtained by using the same welding parameters. The Bragg Edge Mapping technique allowed us a qualitative visualization of the texture in a FSW specimen, mapping the local texture induced by the rotating tool in the welded region. Finally, synchrotron radiation micro-CT demonstrated that there is no porosity present in the FSW Al alloy.

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