THE ROLE OF SAMPLE GEOMETRY IN LASER PEENING-INDUCED COMPRESSIVE RESIDUAL STRESS FORMATION

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Abstract: This study investigates the effect of laser peening treatment on the residual stresses of friction stir-welded (FSW) aluminium alloy. X-ray diffraction (XRD) and contour methods were employed to measure the residual stress distribution in fatigue testing specimens. The results showed that laser peening is not effective in generating a compressive residual stress state near the free edges due to a lack of material that would constrain the plastically deformed region from the shock wave generated during the treatment. This increases the effective stress in these locations, leading to crack initiation. The fracture surfaces of peened samples exhibited similar characteristics, with cracks originating from one of the free edges, aligning with the residual stress results obtained from contour and XRD methods. The study suggests that laser peening treatment can significantly improve the fatigue life of FSW samples, but it might be difficult to quantify the life improvement in laser-peened fatigue testing specimens unless additional measures are taken to mitigate crack initiation near free edges. Optimizing laser peening parameters or machining the edges without disturbing the bulk residual stress state would be necessary to allow quantification of fatigue life improvement for a sample of this geometry. The findings highlight the importance of a comprehensive approach in designing and manufacturing fatigue test specimens for objectively characterising life improvement.

Keywords: Friction stir welding, Laser peening, Residual stresses, Crack initiation.

INTRODUCTION

Friction Stir Welding (FSW) has become increasingly popular in recent years as a potential solid-state joining process for aircraft fuselage structures. However, like any welding process, the high temperatures generated in FSW would result in tensile residual stress fields in and around the weld balanced by a compressive stress state further out in the parent metal. It would also result in microstructural gradations that can negatively impact joint performance during cyclic loading. Moreover, FSW may introduce defects that can serve as sites for fatigue crack initiation leading to a reduction in fatigue life.

Laser Peening (LP) could be a promising solution to recover fatigue life of FSW joints. LP induces surface compressive residual stresses, which would delay crack initiation and propagation. Extensive research has already demonstrated the effectiveness of LP in improving the fatigue life of aerospace components [1,2], with recent studies revealing that treatment can increase the life of as-welded FSW joints by up to a factor of 2 [3]. However, an analysis of the fracture surfaces in the latter study highlighted a consistent pattern where cracks repeatedly initiated near the free edge of the peened samples. This observation indicates that the treatment may have inadvertently made these areas more susceptible to initiation of fatigue cracking, potentially limiting the possibility to characterise the full life-extending benefits that LP can offer.

The main objective of the present research is to investigate the residual stress profile along the width and thickness of the weld after laser peening, in order to gain insight about the previously observed fatigue fracture behaviour. This article utilises X-Ray diffraction and the Contour method as the most viable options to obtain data near the free edges of the samples.

METHODS

Sample preparation

The present study is part of a larger investigation into the fatigue performance of FSW joints, where residual stresses before and after laser peening were measured on samples designed for fatigue testing [3]. Therefore, the design of the sample used in this study is similar to that of the previous studies, as well as the FSW and laser-peening parameters. This includes a 2.3 mm thick sheet of Aluminium 2024-T351, which was supplied by the project sponsor. The design of the fatigue specimens, as well as the dimensions of the FSW and laser-peened regions, are illustrated in Figure 1.

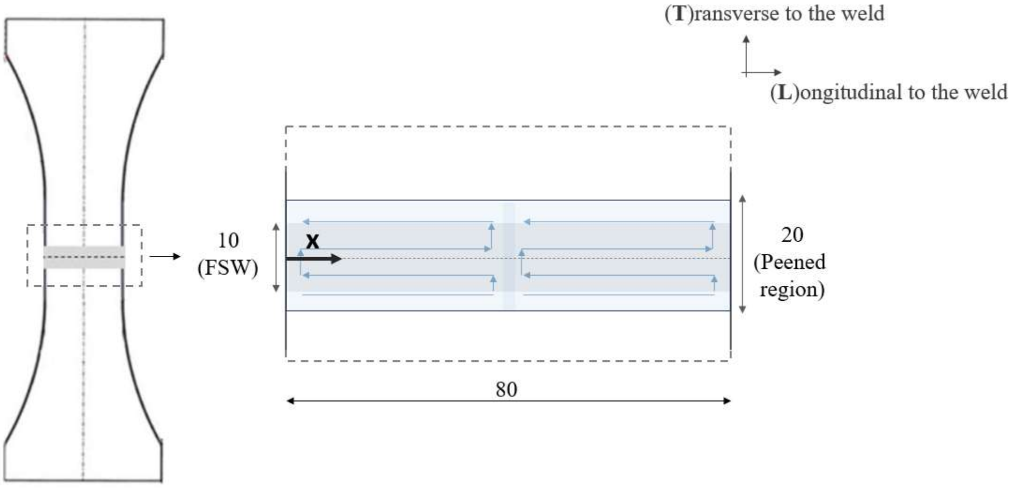


Figure 1: Fatigue test sample design and schematic of FSW and LSP regions.

As can be observed, laser peening has been applied to the entire length of the FSW region which coincides along the width direction of the specimen. Moreover, the peening process was carried out with precision to ensure that there was no gap left between the peened area and the free edges of the sample. The treatment was carried out on both faces of the sample to ensure compressive residual stresses were introduced both on the shoulder and root sides of the FSW.

X-Ray diffraction

XRD is a non-destructive technique used to measure residual stresses up to a depth of a few micrometers below the surface of the material. In this study, two FSW samples were measured after LSP treatment.

The surface stress of the samples was measured in both the in-plane principal directions using two different X-ray strain scanners. Initially, the specimens were measured by a Stresstech diffractometer, and then the analysed stresses were verified by Pulstec.

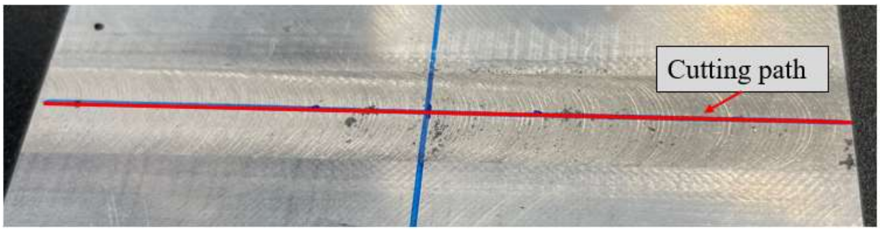
For the StressTech measurements, a 2 mm diameter collimator was used. The d-$\sin^2\Psi$ technique was used, where the d-spacing was measured in 11 different inclinations spanning ± 45°. The exposure time given was 8 seconds per measurement, and no tilt oscillation was given to avoid any texture or related microstructural influence. A modified χ measuring mode was used, which is more suitable for thin-walled tubes.

For the Pulstec system, an aperture size of 2 mm was used, and the exposure time was optimized to achieve a specific peak intensity and found to be approximately 7 seconds. A 2D area detector was used to capture the diffraction pattern. The measuring mode used was cosα, which involves tilting the tube at a fixed angle (α) with respect to the specimen. This measurement was carried out to validate the Stresstech results.

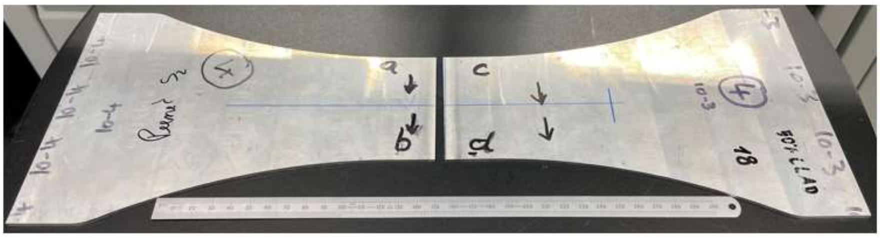
The contour method

The contour method is a destructive residual stress measurement method that obtains a 2D residual stress map with a single measurement process in one principal strain direction. The method was very useful for measuring the residual stress state along the transverse direction to the weld (the longitudinal axis of the sample and was selected due to its capability to measure stresses through the entire thickness and width of the sample in one experimentation.

One peened FSW sample was sectioned on a Fanuc Robocut α-C600i wire electro-discharge machine using a brass wire of 0.25 mm diameter. Symmetric and rigid clamps were used during the cutting operation. The samples were cut from one end to the other and through the thickness, as can be observed in Figure 2. The cutting speed for the sample was 0.5 mm/min.



(FSW shoulder side)



(Contour cut)

Figure 2: The contour method - sample and contour cut.

The surface displacement profile of both cut surfaces of the sample was measured with a Zeiss Contura g2 coordinate measuring machine (CMM) using 1 mm diameter scanning probe. The distance from the perimeter and between the individual measurement points of the sample cut surface was set as 0.05 mm.

The displacement data of the cut surfaces of each sample was post-processed using the Matlab analysis routines for data aligning, cleaning, flattening and smoothing. The data smoothing of all samples was performed using a cubic spline with knot spacing of 0.5 mm along the thickness (X-axis) and 3.5 mm along the width (Y-axis).

The final step is to introduce a finite element model where the measured surface contours are introduced as displacement boundary conditions, and the original stresses to be determined are back-calculated [4]. To do this, an FE model of one half of the sample was built with 8-node brick element (C3D8R) on the Abaqus software. A mesh size of 0.05 mm along the thickness (X-axis) and 0.5 mm along the width (Y-axis) was used. The reverse of the measured & smoothed contour was applied as the displacement boundary condition. Constraints were applied to the model to avoid rigid body motion. Finally, linear elastic FE analysis with the following material properties was performed to get the residual stresses locked inside the samples before cutting. A modulus of elasticity [E] = 73 Gpa and Poisson's ratio [υ] = 0.33 were considered to analyse the stress from the measured strain.

RESULTS

The X-Ray diffraction surface residual stress results for the root side of a FSW sample are presented in Figure 3. Only the transverse direction of stress is shown since it coincides with the loading direction during fatigue testing.

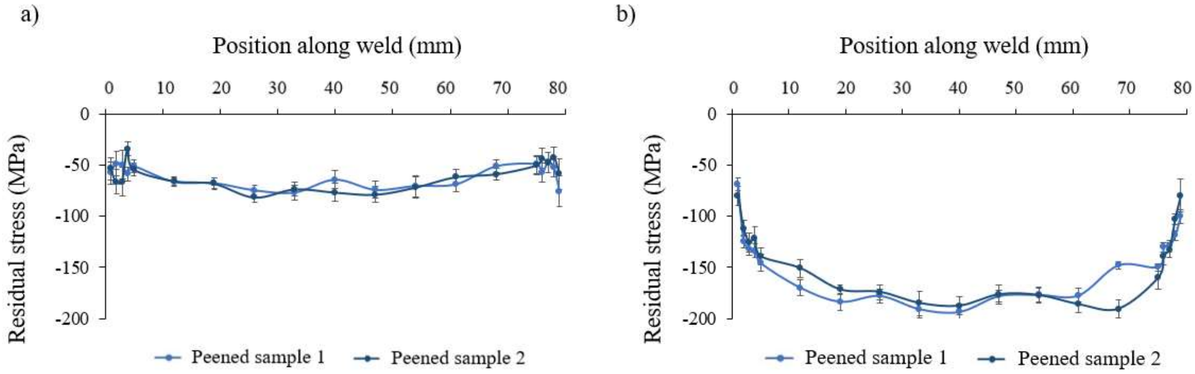


Figure 3: X-Ray diffraction results in the direction transverse to the weld line, parallel with the loading direction. a- root side, b-shoulder side.

As evident from the results, the surface residual stresses in the transverse direction on the shoulder side (Fig 3-a) are compressive and approximately uniform on average. On the root side (Fig 3-b), compressive transverse stresses are considerably higher in the middle region of the sample width, while experiencing a significant decrease towards the ends of the sample. Specifically, the average stress decreases from 180 MPa to 65 MPa. This trend was consistently observed in both analysed peened samples.

To obtain a more comprehensive characterization of the residual stresses through the thickness of the sample, the results obtained from the contour method are presented in Figure 4. These are represented through the thickness of the sample (2.3 mm) for three sections along the width: a middle section (x = 40) and two sections immediately next to the free edge (x=0 and x=80).

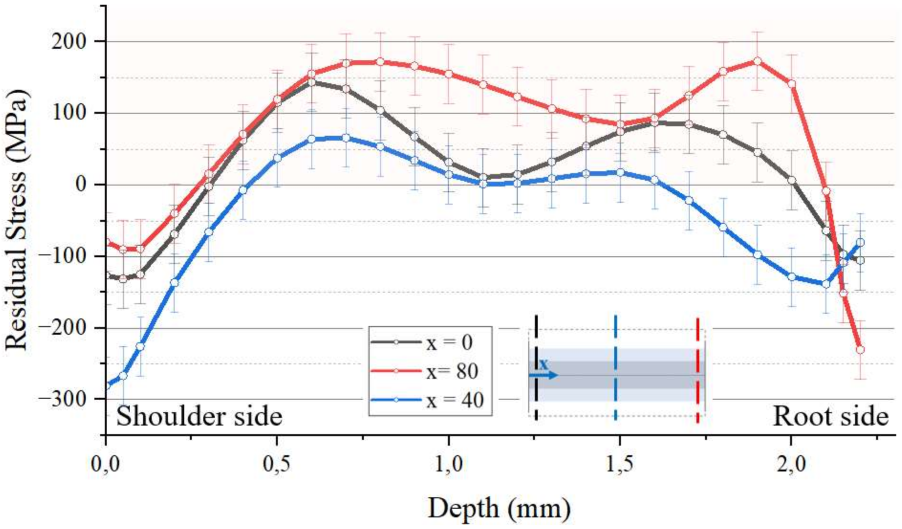


Figure 4: Residual stress measurement results using the contour method for three sections along the width of the sample.

The findings reveal that at the surface of the middle position (X=40 mm) of the weld/sample the compressive residual stresses are significantly larger in magnitude, reaching nearly 300 MPa on the shoulder side. Conversely, on the root side, the surface stress is lower, with a peak of 140 MPa located 0.1 mm below the surface. The peening treatment employed in the study produced a penetration depth of approximately 0.4 mm on the shoulder side and 0.7 mm on the root side. Furthermore, balancing internal tensile residual stresses peaked at 0.65 mm away from the shoulder surface, measuring close to 66 MPa.

The stress results for the two free edges of the weld are also depicted in the figure. As evident from the plot, the compressive surface stresses on the shoulder side are noticeably lower in comparison to those in the middle section, with values ranging from 80 to 126 MPa. The penetration depth decreased from 0.4 on the middle section to 0.3 at the free edges. On the root side, the surface stresses are close to 100 MPa for x=0 and 225 MPa for x=80. The penetration depth is considerably lower than that observed in the middle section, ranging from 0.10 to 0.20 mm. Additionally, the overall balancing tensile stresses as observed in the middle of the specimens are significantly higher near the edges, and their peak magnitude are 173 MPa for x=80 and 155 MPa for x=0 as compared to 50 MPa for the middle section.

DISCUSSION

The results obtained using both XRD and the contour method were in agreement with the residual stress data reported in previous investigations for other samples that underwent the same laser peening treatment using the ICHD method [3]. These findings highlight the reliability and consistency of the residual stress measurements obtained using XRD and the contour method in the context of laser peening treatments.

Based on the residual stress results presented, it is evident that the compressive stresses near the free edges were significantly lower when compared to those in the middle section of the weld. In fact, the average stress in the middle section is compressive in nature and approximately 52 MPa. In contrast, the average stress at the free edges is tensile in nature, and between 60 and 17 MPa. This discrepancy can be attributed to the laser peening mechanism, which relies on constraining the surrounding material to create compressive residual stresses. When peening next to a free edge, there is less material available for constraining the deformation induced by propagation of the laser shock wave, which results in ineffective peening causing lower magnitude of compressive residual stress state [5]. Therefore, the reduction in compressive stress observed in the vicinity of the free edges should be expected.

This would impact the findings from fatigue testing, in developing understanding and predictive modelling of life improvement from peening - the weld regions are expected to be subjected to reduced local average cyclic stress levels due to the high magnitude of compressive RS measured at the sample middle section. However, given that the stress profile is not uniform across the width of the sample, particularly in the areas next to the free edges, the effective average local cyclic stress would be much higher than expected, leading to early crack initiation at these critical locations.

Furthermore, this effect was also evident in samples containing lack of penetration (LoP) defect. This type of defect is usually found at the root side of the weld due to improper processing condition during friction stir welding. In this study, samples were manufactured by deliberately introducing this defect, with an anticipated depth of 400 μm spanning the entire length of the FSW joint. From analysing the contour stress measurement results, it would be expected that at 400 μm depth from the root surface of a peened sample, the defect tip will be under compression at the middle section, but under tension near the two free edges. This will likely multiply the stress concentration at the defect tip, resulting in crack initiation near the edges of the sample. Examples of the fractured surfaces of two peened and unpeened samples containing a LoP defect and fatigue tested with the same applied load can be observed in Figure 5.

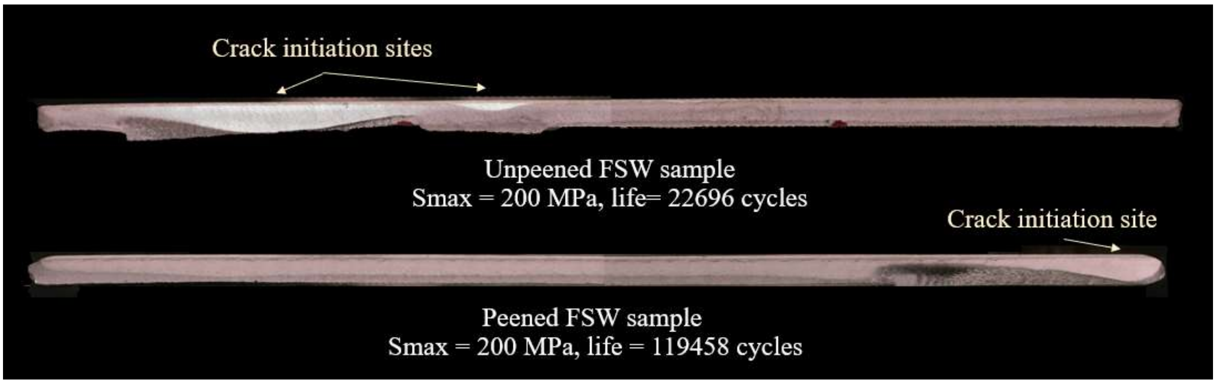


Figure 5: Fractured surfaces of unpeened and peened samples with a lack of penetration defect, after fatigue testing.

As shown in the figure, the unpeened sample exhibited two distinct sites of crack initiation. From testing of all other unpeened samples, no discernible trend emerged as to where crack initiation would occur along the width of the specimen. However, in the peened samples, all of the fracture surfaces exhibited similar characteristics, with cracks originating from one of the free edges. This trend aligns well with the residual stress results obtained from the contour method and XRD.

Previous investigations have indicated that unpeened samples exhibited a near-surface residual tensile stress of approximately 20-30 MPa [3]. The results obtained from the contour method demonstrate that peening effectively transformed these tensile residual stresses into compressive stresses, which can be associated with the previously observed enhancements in fatigue life. However, the present study has revealed an additional and unwanted consequence of the peening treatment: the free edges of the sample have become critical fracture locations, thereby hindering the full potential of laser peening. This finding implies that the previously reported life improvement following laser peening could be even more significant if the issues at the free edges can be addressed. Future studies could focus on optimising the laser peening parameters and developing an improved layout/strategy to compensate for the reduced compressive residual stress near the free edges, thereby potentially enhancing the fatigue life in these critical regions. Alternatively, machining the edges could be considered as a means to alleviate the tensile stresses present in the material, however, this needs to be studied through full three-dimensional residual stress measurement in a non-destructive manner.

In summary, the present study provides valuable insights into the residual stress distribution induced by LSP treatment in FSW samples, highlighting the need for a more comprehensive approach towards designing and manufacturing fatigue test specimens.

CONCLUSIONS

1) The laser peening treatment demonstrated lower effectiveness in generating compressive residual stresses near the free edges of the samples. Specifically, the average measured stress in the middle section of the weld was found to be 52 MPa compressive, whereas the stress ranged from 60 to 17 MPa tensile at the free edges.

2) The analysis of fractured surfaces after fatigue testing provided further evidence supporting the measured residual stress results obtained through XRD and the contour method. It was consistently observed that laser-peened samples failed at one of the free edges, aligning with the locations where lower stress magnitudes were measured.

3) The presence of local regions with reduced compressive residual stress near the free edges of the sample is a limiting factor that hinders the full benefits of peening. In order to achieve optimal improvements in fatigue life, it is crucial to identify and implement a solution to address the reduction in compressive residual stress at these critical locations.

4) The contour method proved to be a reliable technique for accurately measuring residual stresses in the vicinity of sample edges.

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