Neutron Diffraction Residual Stress Measurements in Key-Hole Laser Formed Weldments

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Abstract

There is a new generation of lasers available for materials processing. The new lasers include fibre and disc laser are characterized by very high beam quality at very high power levels providing extremely high energy density. In general laser welding is selected over other welding processes because of the minimisation of the heat input, residual stresses and distortion, for this reason they are increasingly popular over a wide range of industries. The narrowness of the welds makes it challenging to resolve the details of the residual stresses produced by the welding process. Residual strain/stress measurements of two specimens produced using the fibre laser were performed on Engin-X. Across the weld and through thickness distributions are reported in this paper.

1. Introduction

Laser welding has many advantages compared with traditional electric arc-based methods. The most important is the high energy density available which allows welds with high depth to width ratio. This means that the same penetration depth can be obtained using less energy or with a faster processing speed compared with traditional welding methods [1]. This leads to a reduction of heat input into the material and results in high process efficiency. This is beneficial as heat input is the main cause of residual stresses and distortion of joined components.

New types of lasers such as fibre and disc are now available commercially and these allow even better control of the heat input through their inherent high stability. Also the high beam quality of these lasers enables further increases in energy density and therefore further reductions in heat input [2,3].

Residual stresses are formed in weld structures primarily as the result of differential plastic and elastic strain during the heating and cooling cycles. During heating a large amount of plastic strain occurs whilst on cooling most of the strain is accommodated elastically. This leads to large residual stresses developing in the region of the weld zone. These stresses can have important consequences on the performance of engineering components [4]. There are several ways of measuring residual stresses in small volumes. The most common ones involve mechanical invasive methods (e.g., hole drilling or cutting [5]) and non-destructive methods using radiation such as x-ray (laboratory or synchrotron) or neutron diffraction (ND) [6,7,8]. ND is outstanding in its ability to obtain residual stresses non-destructively within the subsurface and deep within the bulk of the components. Neutrons can evaluate the three principal directions of residual stress in the weld structures, with a spatial resolution of 1 mm (or less) and to a depth of many millimetres below the surface of the weld (up to 50 mm for steel). In order to investigate the relation
between heat input and residual stresses two bead-on-plate welds were produced with widely different process conditions. This approach enables comparison of welds obtained with relatively high and low heat inputs. The detailed residual stress distributions across the weld zone and through the plate thickness were measured and discussed in relation to the different heat inputs.

2. Materials and welding procedure.

The welds were made in 60mm by 200mm and 12mm thick S355 mild steel plates. A YLR 8000 IPG fibre laser with a maximum power of 8kW and a 630µm beam diameter was used to make the welds. Pure shield argon with a flow rate of 15 l/min was used as a shielding gas. All welds were sectioned, polished and investigated under the optical microscope. Two bead-on-plate welds were manufactured, one with a high heat input and one with a low heat input. Welding parameters for both samples are shown in Table 1. The macrographs are presented in Fig.1 (note the different magnification for the two pictures).

Table 1. Welding parameters used in the experimental work

| Sample | Laser Power [kW] | Travel speed [m/min] | Penetration depth [mm] | Weld width [mm] | Heat input (kJ/m) |
|--------|------------------|----------------------|------------------------|-----------------|------------------|
| A1     | 6                | 5                    | 3.24                   | 1.4             | 72               |
| A2     | 6                | 0.5                  | 9.15                   | 6.3             | 720              |

![Figure 1. Macrograph of (a) Sample A1, and (b) Sample A2 (note the change of scale).](image)

3. Residual stress measurements

The residual strain/stress measurements were performed on the ENGIN-X beam-line at ISIS [9]. For the longitudinal measurements the gauge volume was $2 \times 2 \times 2$ mm$^3$ but for the transverse, normal and reference sample measurements this gauge volume could be relaxed in one direction to $2 \times 2 \times 10$ mm$^3$. The gauge volume could be considered as being relatively large, especially for the Sample A1, However by using small steps across the weld zone (with the gauge volume overlapping at each step) we were able to extract the full detailed strain/stress distribution by deconvoluting the effect of the gauge size. The reference “stress free” value was measured at the corner of the reference sample cut from the parent metal (10x12x20 mm$^3$). The longitudinal, transverse and normal components of the residual stress field were calculated for each strain-measurement position in the weldment from the relevant three strain components. This was done using standard elasticity theory assuming an elastically isotropic material and
that the measurement directions correspond to the principal axes of the stress tensor [10]. For this conversion a Young’s modulus of 207 GPa and Poisson’s ratio of 0.3 were used. The focus of this research was on the detailed line scans across the weld 2mm below the surface and through the thickness of the plate (Fig. 4) in the middle of the weldments.

Figure 2a show the residual strain distribution across the weld for Sample A2. Figure 2b shows the comparison of longitudinal residual stress for Sample A1 and A2. Figure 3a shows the residual strain distribution through the thickness for Sample A2. Figure 3b shows through thickness comparison of longitudinal residual stress for Sample A1 and A2.

**Figure 2.** Across the weld distributions of (a) residual strain for Sample A2, and (b) longitudinal residual stress of Sample A1 and A2 (2mm below the surface of the plate).

**Figure 3.** Through thickness distribution of (a) residual strain for Sample A2, and (b) longitudinal residual stress of Sample A1 and A2.
4. Discussion

The use of a neutron beam as a non-destructive method of measuring residual stress produced by laser welding has been explored. The narrowness of the welds make the measurements more challenging as the spatial resolution of the neutron measurements is in range of 2 mm. However we have shown that it is still possible to resolve the residual stress distribution in all three directions of principal stress with a high level of detail by using small incremental steps across the weld zone.

The highest residual strain/stress was found in the longitudinal direction near the middle of the weld and heat affected zones (Figures 2 and 3) for both samples. The tensile residual strain/stress is then balanced by compressive stress away from the weld zone. Towards the edges (x=28mm) of the sample the residual stress was approximately zero in all three directions. The residual strain in normal and transverse directions for sample A2 was compressive in the area of the weld and nearby. As is shown in Figure 2b the width of the longitudinal tensile peak corresponds to the size of the weld. The larger the weld (i.e. higher heat input) the larger the tensile peak width (Figure2b). However the peak height of the longitudinal stress was independent of the heat input.

The largest residual strain through the thickness in the middle of the weld was observed in the longitudinal direction (Figure 3a). The normal residual strain was compressive throughout the thickness. The transverse strain on the other hand is compressive towards the both surfaces of the plate but tensile in the mid-thickness. Sample A1 has uniform tensile longitudinal stress throughout the depth (Figure 3b). In contrast Sample A2 varies from tension on the topside, where welding was performed, to compression on the bottom side. The difference is because Sample A2 is nearly full penetration (9mm deep in 12mm) whereas Sample A1 is only partial penetration (3.2mm deep in 12mm).

5. Acknowledgements

This work was conducted as a part of NEGLAP project funded by Corus and EPSRC through Cranfield IMRC.

6. References

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