A comparison of residual stresses in multi pass narrow gap laser welds and gas-tungsten arc welds in AISI 316L stainless steel

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ABSTRACT

Thick-section austenitic stainless steels have widespread industrial applications, especially in nuclear power plants. The joining methods used in the nuclear industry are primarily based on arc welding processes. However, it has recently been shown that narrow gap laser welding (NGLW) can weld materials with thicknesses that are well beyond the capabilities of single pass autogenous laser welding. The heat input for NGLW is much lower than for arc welding, as are the expected levels of residual stress and distortion. This paper reports on a preliminary investigation of the through-thickness 2D residual stresses distributions, distortions, and plastic strain characteristics, for the NGLW process using material thicknesses up to 20 mm. The results are compared with those obtained with gas-tungsten arc (GTA) welding. While further work is required on thicker test pieces, preliminary results suggest that the longitudinal tensile residual stresses in NGLW joints are 30–40% lower than those for GTA welds.

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1. Introduction

Fusion welding processes generally involve material melting, phase transformations, and multiple thermal cycles. In the welding of thick components, localised heating or cooling cycles can lead to large thermal gradients. The non-uniform expansion and contraction of the material, when coupled with the material constraint in the bulk of a component, introduces misfit strains into the parts being welded. If these misfit strains are modest, they can be accommodated by elastic strains. If, however these misfit strains become too large to be elastically sustained, localised plastic deformation is induced, which leads to the development of residual stresses. Significant residual stresses reside in the vicinity of the weld region after the component has reached thermal equilibrium [1]. This is particularly the case for thick section welds as the number of weld passes can be large, with several heat-up/cool-down thermo-mechanical cycles. Indeed, the accumulated level of plastic deformation and the associated cyclic hardening of the material can be significant.

Residual stresses can play a significant role in accelerating or delaying many failure processes [2,3]. Residual stresses in welded

joints are usually tensile in the fusion zone and heat-affected zone, although compressive stresses can be generated under some circumstances if solid-state phase transformations take place during the welding thermal cycle [4]. Tensile residual stresses are of particular concern because they can contribute to fatigue crack development in a structure even under compressive cyclic loading [5]. They are also considered to be the main reason for the initiation and propagation of stress corrosion cracks (SCC) in austenitic weldments [6]. In addition, the kinetics of defect growth can be affected by residual stresses. Therefore, significant research effort has been directed to understanding the development of residual stresses in power plant welds [4].

The safe operation of a nuclear power plant is highly dependent upon the application of robust structural integrity assessment procedures. The residual stresses arising due to welding operations can be critical in affecting the structural integrity of a power plant. However, there are significant technical challenges associated with measuring residual stresses in thick section welds [7], and without an accurate knowledge of the welding residual stresses, it is likely that conservative or incorrect assumptions will be made, which can ultimately affect the assessment of power plants.

AISI 316L stainless steels are employed frequently in nuclear power plants because they have a high resistance to SCC. However, welding thermo-mechanical cycles have a significant influence on the mechanical properties and on the condition of the material. For example, the development of plastic strain and cold work in the

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vicinity of a welded joint can have a significant influence on the resistance to degradation by SCC in stainless steels [8]. Indeed, time–temperature–sensitization curves generally move toward shorter times with increased levels of cold work [9]. Thus, while the control and minimization of residual stresses at welded joints are critical in designing against failure and improving the lifetime of engineering structures [10], residual stress mitigation techniques such as shot peening, laser shock peening, and low-plasticity burnishing [11] can be difficult to apply to large components, and they will lead to increased cold work at the surface of the material.

Laser welding is an effective, low-distortion joining process, due to the combination of high welding speeds and a low heat input to the welded joint. The development of residual stresses in autogenous laser welds has been investigated previously [12,13]. However, multi-pass NGLW can be an efficient process for the welding of thick-section components. Zhang et al. [14], and Starling et al. [15] demonstrated thick section welding using a NGLW approach. Zhang et al. [16] studied the feasibility of applying this technique to the welding of 50 mm thick stainless steels using an 8 kW laser. In another study, Salminen et al. studied filler wire interactions with the laser beam in a narrow gap laser welding process [17,18]. Despite NGLW being a very promising technique for thick section welding, detailed through-the-depth residual stress investigations have not been reported in previous studies. Zhang et al. [14], for example, only measured surface residual stresses using the X-ray diffraction technique.

The aim of this work was to investigate the development of through-thickness residual stresses in NGLW of AISI 316L stainless steel, using the contour method. In some cases, surface X-ray diffraction measurements were also carried out on the same specimens for the purpose of validation. In this preliminary study, material thicknesses up to 20 mm have been investigated, and the results are compared with the residual stresses that were measured in conventional GTA welds for the same thickness. The distortions associated with each technique are also compared, and the cumulative plastic strains arising due to each process have been estimated. It is hoped that this preliminary study will provide an

insight to the way in which NGLW affects two of the factors that have a critical influence on the integrity of nuclear welds, namely the development of residual stresses, and the cyclic hardening of the material during multipass welding. It is also hoped that this work will provide a foundation for future work involving welds in thicker sections of material.

2. Description of welding techniques

Multi-pass GTA welding and NGLW of 10 mm thick AISI 316L stainless steel plates was carried out. The welds were 150 mm long, and after welding the samples measured 150 mm × 200 mm × 10 mm. Fig. 1a shows the joint preparation and a representative weld macrograph for the NGLW. The joint preparation consisted of a 1 mm root gap with a 1.5 mm deep root face, and a bevel at an inclination of 3° on each side. Ten passes were required in order to complete the NGLW with a 1 kW fibre laser, using a spot diameter of 70 μm, and with the focal point being located 2 mm above the upper surface. For the NGLW, an AISI grade 316L stainless steel filler wire with a diameter of 0.8 mm was used. The welding parameters were based on the results of an optimization process which was reported in a previous study by the authors [19]. In that study, the objective was to eliminate weld defects and to achieve a desirable weld bead profile, but no consideration was given to the influence of the chosen welding parameters on the development of residual stresses. In this work, a laser power of 950 W was used, together with a welding traverse speed of 590 mm/min, a wire feed rate of 1.08 m/min, and a stand-off distance of 8 mm, while using pure argon as the shielding gas.

The joint preparation for the GTA welding, and a macrograph with the track sequences highlighted, are shown in Fig. 1b. The bevel angle for the joint was 30° on either side. Twelve passes were required to fill the gap. The diameter of the tungsten electrode was 3.2 mm, with a vertex angle of 60° for the conical tip. The electrode polarity was direct current, electrode negative (DCEN). The filler wire diameter was 2 mm, and the GTA welding parameters are

Fig. 1. Joint preparation and weld bead profiles for 10 mm thick stainless steel welds using a) NGLW and b) GTA welding. All dimensions in mm.

shown in Table 1. The weld width at the upper surface was around 10 mm, while at the lower surface it was approximately 6 mm.

Multi-pass GTA welding and NGLW of 20 mm thick AISI 316L stainless steel plates was also carried out. The welds were 150 mm long, and after welding the samples measured 150 mm × 200 mm × 20 mm. Fig. 2 shows the configurations for the welded joints in the 20 mm thick plates. The welding parameters were nominally identical to those used for the 10 mm thick plates. The NGLW and GTA welds both followed a two-sided welding sequence. Thirty-four weld passes were required to fill the groove for GTA welding, whereas only 20 passes were required for NGLW. The heat input and number of passes for each welding process and plate thickness are summarised in Table 2.

3. Residual stress measurement methods

The contour method was used for the measurement of residual stresses in the welded AISI 316L stainless steel plates manufactured with both the NGLW and the GTA welding techniques. X-ray diffraction was also used to measure residual stresses at the surface, and these measurements served as a check on the residual stress measurements that were made with the contour method.

3.1. Contour method

The contour method involves measuring the deformations that occur, due to the relaxation of stresses, when a component is cut in order to evaluate the residual stresses that existed within the component before the cut was made. The method allows one to

Table 1
Summary of GTA welding parameters.

Voltage (V)	Current (A)	Wire feed (mm/min)	Traverse speed (mm/min)	Gas flow rate (l/min)
11.5	120	260	130	10

Table 2

Heat input and number of weld passes for each joint type.

Welding technique	Plate thickness (mm)	Number of passes	Heat input per pass [J/mm]
GTAW (1 side)	10	12	305
NGLW (1 side)	10	10	42
GTAW (2 sides)	20	34	305
NGLW (2 sides)	20	20	42

measure the component of residual stress that acts in a direction normal to the plane of the cut, over the expanse of the cut surface – i.e. it provides a two-dimensional map of residual stresses. The technique was developed by Prime and it is based on a variant of Bueckner's superposition principles [20,21]. The potential of the contour method was demonstrated on a 12-pass GTA weld, where complex stress variations were captured across the weld cross-section [22]. The results obtained with the contour method were in acceptable quantitative agreement with the outcome of non-destructive measurements based on X-ray diffraction. Many researchers, including Kartal et al. [23], Withers et al. [24] and Edwards et al. [25], have used this technique successfully for the evaluation of the residual stresses in various welds. The technique consists of three main steps. The first step includes cutting the stressed part in a straight path. Electric Discharge Machining (EDM) with skim cutting conditions is believed to be the best processing technique for work piece sectioning [26]. Fig. 3 shows the set-up for the residual stress measurements that were made on the 10 mm thick plates, and it highlights the three main directions with respect to the work piece: the longitudinal direction (L), the transverse direction (T), and the normal direction (N). Welding was carried out in the longitudinal direction (L), and the cutting occurred in the transverse direction (T).

The second step is scanning the profile (the contour) of the surface in order to quantify the deformation due to the relaxation of stresses. The contours of the surfaces can be measured with a non-contact measuring technique (i.e. laser scanning) or using a

Fig. 2. Macrographs for 20 mm thick welds in AISI 316L stainless steel using a) NGLW and b) GTA welding. All dimensions are in mm.

Fig. 3. Welding and cutting directions for the EDM preparation of experimental samples for the contour method measurements.

coordinate measurement machine (CMM) with a touch probe. The final step is data processing, which can be further divided into three sub tasks: data preparation (cleaning up noise, smoothing the scanned surfaces, and averaging the data), calculation of the stresses, and displaying the results.

3.2. X-ray diffraction (XRD)

X-ray diffraction is a non-destructive technique which can be used to determine the residual stresses at the surface in crystalline materials [27]. The analytical volume for each measurement is restricted to material within a few micrometres of the surface, due to limited beam penetration. The technique allows the changes in the interplanar spacing within the crystal lattice to be determined. Bragg's law is used to determine the interplanar spacing, d , at a particular point, corresponding to a scattering angle, θ , and wave length, λ , by exploiting the relationship in equation (1):

$$\lambda/2 = d \sin \theta \quad (1)$$

The changes in the interplanar spacing, d , can be related to the elastic strain, ϵ . The strain value is calculated according to the lattice spacing, d , and reference spacing d_{ref} according to equation (2):

$$\epsilon = \frac{d - d_{\text{ref}}}{d_{\text{ref}}} \quad (2)$$

The strains in different directions can be calculated in this manner, and the normal stress acting on the free surface can be assumed to be zero. A generalized version of Hooke's law was used to calculate the in-plane components of stress.

4. Experimental procedures

4.1. EDM cutting of specimens

Specimen cutting is the first and the most critical step when using the contour method, as subsequent procedures are reliant on the quality of the cutting. It is assumed that the cutting process leads to an entirely elastic stress relaxation process, and that cutting does not introduce any stresses to the material. Ideally, the cutting process should be perfectly straight with minimum material removal [28]. All cutting in this work was carried out using a 5-axis EDM cutter. The cutting wire was pure copper with a 250 μm diameter, following the manufacturer's recommendation for the best cutting results, i.e. minimising the stresses introduced by the cutting operation and the extent of the recast layer.

4.2. Surface scanning (contour measurement)

A laser scanner with a non-contact laser head was used for scanning the EDM cut surfaces. The profile of each surface was

scanned with an accuracy of $\pm 10 \mu\text{m}$. The scanned profiles showed small deformations due to the relaxation of residual stresses. For example, the dashed line in Fig. 4 represents the edge of the work piece, before distortion due to the welding process. The induced deformation (parallel to the welding direction) is clear in Fig. 4, and some "butterfly" distortion of the specimen is also evident. The contour data for all points on the surface were scanned and saved in the form of $z = f(x, y)$. The scanning was then repeated on the other half of the work piece, before the data were input to a stress analysis module in order to calculate the residual stresses.

4.3. Data processing

The raw displacement data for the two halves of the cut were averaged to remove any asymmetric effects associated with wire deviation during cutting, and to compensate for any miss-clamps, and to eliminate the contribution of shear stresses to the measured displacements. The next step was to smooth the data, through creating a least-squares spline curve fit, to eliminate errors associated with cutting stresses, or the measurement conditions, or distortion caused by welding operations. This step is crucial if an accurate evaluation of stresses is to be achieved with the contour method [29]. Fig. 5 shows examples of rough and smoothed scanned surfaces.

Stress analysis is the final step. The smoothed spline surface was input to a finite element (FE) model to create displacement boundary conditions. An arbitrary plane was defined, which represented the initial cut surface, and this was assumed to be perfectly flat. The stress field on the cut surface was calculated as a function of the deformation distance (with the opposite sign), using appropriate material properties for AISI 316L stainless steel. The Young's modulus of the material was assumed to be 193 GPa, with a Poisson ratio of 0.3. The FE model was developed using ABAQUS 6.1-CAE.

Fig. 4. A scanned surface profile for a GTA weld.

Fig. 5. Contour maps of (a) rough surface contour (b) smoothed spline fit.

5. Results and discussion

The 2D residual stress profiles through the thickness of the welds were compared in order to understand the influence of the different thermal cycles on the residual stresses induced by each welding technique. The influence of the welding strategy (i.e. one-sided or two-sided welding) and the degree of constraint were also investigated.

5.1. Residual stresses in 10 mm thick single-sided GTA weld

Fig. 6 shows the distribution of longitudinal residual stresses for the single-sided GTA weld. The residual stress distribution is approximately symmetrical about the weld centreline. The stresses in the vicinity of the weld centreline are highly tensile, with the peak tensile stress being close to 500 MPa in magnitude. The peak stresses occur at a location that is 2 mm below the top surface of the weld. The stresses decay gradually with increasing distance from the weld centreline. It is not surprising that the peak tensile stresses occur closer to the upper surface of the specimen, since this is the side of the specimen from which heat was applied during welding. Nine weld passes were required to fill the weld groove, as can be seen in Fig. 1b. The width of the area with a significant

tensile (i.e. >50 MPa) residual stress is approximately 55 mm (Fig. 6), and the butterfly distortion angle was 3.9°.

5.2. Residual stresses in 10 mm thick NGLW

Fig. 7 shows the distribution of longitudinal residual stresses for the single-sided NGLW. It can be seen that the residual stresses for the NGLW are lower than those for the single-sided GTA weld. Again, the residual stress distribution is approximately symmetrical about the weld centreline. The stresses in the vicinity of the weld centreline are tensile, but the peak tensile stresses are closer to 300 or 350 MPa in magnitude, and they occur approximately 3 mm below the upper surface of the specimen on the weld centreline. Four passes were required to fill the lower half of the groove, while six passes were required to fill the upper half, as can be seen in Fig. 1a. The tensile stresses decrease rapidly with distance from the weld centreline, and compressive stresses were measured over significant areas of the measurement plane. There are three reasons for the decrease in the magnitude of residual stresses in the plate joined using NGLW. Firstly, the laser is a high power-density heat source with a very small spot diameter (the spot size was approximately 70 μm). Secondly, the welding speed (590 mm/min) was very high compared with that for the GTA weld (130 mm/min), and

Fig. 6. Residual stress distribution for 10 mm thick single-sided GTA weld (in MPa).

Fig. 7. Residual stress distribution (in MPa) for a single-sided NGLW joint.

finally the width of the weld groove was very small (~ 1.25 mm) as can be seen in Fig. 1a. As such, the volume of filler metal required to fill the groove with laser welding is lower than for GTA welding. Consequently, the number of passes and the cumulative heat input to the weld are lower for laser welding than for GTA welding. The width of the region with significant tensile stress (>50 MPa) was approximately 15 mm for the NGLW, and it decreased towards the upper surface. The magnitude of the stresses was close to zero toward both edges of the specimen, and the butterfly distortion angle was 1.8° . A detailed comparison of the results for each welding process is presented in the next section.

5.3. Residual stresses near top surface for 10 mm thick GTA weld and NGLW

Fig. 8 shows a comparison of the residual stress profiles for the NGLW and the GTA welding processes, measured along a line 1.5 mm below the upper surface with the contour method. The results suggest that the NGLW technique induces lower residual stresses over the entire width of the specimen. The maximum tensile stress for the NGLW was 310 MPa. The tensile stresses for this process decayed sharply with distance from the weld centreline, to a value close to zero, at a distance of approximately 10 mm from the weld centreline.

The peak tensile residual stress for the GTA weld was 520 MPa, and the width of the region with significant tensile stress (>50 MPa) was approximately 50 mm. The tensile stresses at the weld centreline were approximately 40% lower for the NGLW sample than for the GTAW sample. Fig. 8 shows that the distribution of residual stresses is approximately symmetric about the weld

centreline for both processes, with peak stresses occurring at the weld centreline, and with the stresses gradually decreasing until they become compressive further from the weld centreline, which is in agreement with previous studies for GTA welding [3].

5.4. Residual stress distributions on the weld centreline

The variations in the residual stress values along the weld centreline, as measured with the contour method, are shown in Fig. 9. The red and blue arrows (in web version) highlight the locations of the measurement lines, and the direction corresponding to an increase in the distance parameter on the horizontal axis, for the GTAW and NGLW samples respectively. There are similar features in the residual stress distributions for each sample. Starting from the lower surface of each sample, the residual stress increases up to an initial peak value, which is approximately 550 MPa for the GTA weld and 250 MPa for the NGLW. With increasing distance from the bottom surface, the stress decreases to approximately 100 MPa for the NGLW, and 150 MPa for the GTA weld, near the mid section. In both samples, the stresses then increase again to the second peak, which is approximately 500 MPa in magnitude for the GTA weld and approximately 400 MPa for the NGLW. Finally, the stresses decrease in both samples towards the top surface, having values of approximately 330 MPa for the GTA weld and 125 MPa for the NGLW. Overall, the average residual stress values are noticeably lower in the NGLW.

5.5. Surface residual stress measurements with X-ray diffraction

The residual stress measurements made with the contour method were validated using the X-ray diffraction technique. The

Fig. 8. Residual stress distributions 1.5 mm below the top surface of the 10 mm thick specimens for the NGLW and GTA welding processes, measured with the contour method.

Fig. 9. Variation in residual stresses along the weld centreline for the NGLW and GTAW samples.

longitudinal residual stresses on the upper surface of the NGLW specimen, as measured by the contour method and XRD, are depicted in Fig. 10. The highest value of tensile stress at the upper surface was 190 MPa.

Fig. 10 shows that there is good agreement between the stresses measured with the two measurement techniques. It is evident that both techniques capture similar distributions for the longitudinal stresses, with the maximum tensile stresses coinciding with the weld centreline. The stresses quickly become compressive with increasing distance from the weld centreline, and then decay towards the far edges of the specimen. There are small discrepancies in the stress values on the left hand side of the plot. These discrepancies may have arisen, in part, due to the distortion of the welded specimen, which may have affected the accuracy of XRD measurement on this side of the sample. However, the results achieve acceptable agreement across the welded joint.

5.6. Influence of welding strategy on residual stresses

The results that have been discussed thus far were all based on welding from a single side. When welding was performed from both sides as shown in Fig. 11, the NGLW technique required 4 passes from each side to fill the gap, with the same parameters that were used for single-sided welding, and the GTAW process required 3 passes from each side to fill the gap. Some features of the double-sided joint preparations were similar to the single-sided weld preparations. The results for the two welding techniques (Fig. 12) show approximately symmetrical residual stress distributions with respect to the weld centreline. The magnitude of the residual stresses is noticeably lower for the NGLW technique. There are two peaks of tensile residual stress on the weld centreline. The peak value for NGLW is 300–350 MPa as shown in Fig. 12a, and the width of the tensile region near each surface is approximately 5 mm. The residual stress distributions for the GTA weld reveal highly tensile

peaks with a magnitude of 500 MPa as shown in Fig. 12b. In contrast with the NGLW sample, for GTAW the width of the region with significant tensile stresses is approximately 40 mm.

The two-sided welding strategy resulted in a decrease in the number of passes required to fill the gap. This may have had an influence in reducing the magnitude of the residual stresses for the NGLW, but on the other hand any such effect was insignificant for the GTA welding technique. Finally, it can be seen that using the two sided welding strategy leads to a decrease in the distortion angle to almost zero for both welding techniques.

The influence of the degree of restraint on the nature of the longitudinal residual stresses in the welded joints was investigated. Fig. 13 shows the residual stress distributions for unrestrained NGLW and GTA welds made from one side. These results also show approximately symmetrical residual stress distributions with respect to the weld centreline. The NGLW residual stress distribution is shown in Fig. 13a. The peak residual stress value is between 500 and 550 MPa. The butterfly distortion angle is 9.6°. The width of the tensile residual stress region on the weld surface is very narrow at around 10 mm. The GTA welding residual stress distribution is shown in Fig. 13b. The peak residual stress value is also between 500 and 550 MPa. The butterfly distortion is far greater at 37.2°. Even though decreasing the level of restraint resulted in an increase in the residual stress magnitudes, especially for the NGLW technique, the NGLW technique still generated significantly smaller tensile regions when compared to GTA welding.

5.7. Residual stresses in 20 mm thick samples

Fig. 14 shows the residual stress maps for the 20 mm thick samples made with each welding technique. The NGLW technique required 9 passes from each side to fill the prepared gap, while the GTA process required 17 passes from each side to fill the gap. The colour maps show clearly that the stresses for the NGLW technique are lower in magnitude than those for GTA welding. The peak stresses for NGLW are in the range between 300 and 400 MPa (Fig. 14a), while the peak stresses for GTA welding are in the range between 400 and 500 MPa (Fig. 14b). The butterfly distortion is almost zero for each process since the welding followed a two sided welding strategy. The stress maps for each welding technique are similar to the maps corresponding to the two-sided technique for the 10 mm thick samples. This would suggest that the welding strategy (one-sided versus two-sided) has a more significant effect on the induced residual stresses than the thickness of the sample.

5.8. Micro-hardness characteristics of 10 mm thick one-sided welds

Hardness traverses across the 10 mm thick NGLW and GTAW specimens were carried out, using a 300 N load, in order to assess the extent to which the material was work hardened by welding

Fig. 10. Comparison of residual stress profiles at top surface of 10 mm thick NGLW plate, as measured with the contour method and X-ray diffraction.

Fig. 11. Weld macrographs for 10 mm thick welds made from both sides. The narrow gap laser weld appears on the left and the GTA weld on the right. Weld passes are numbered in each case.

thermo-mechanical cycles. The location of the measurement line with respect to welded joints is highlighted by a black arrow in Fig. 15. The hardness traverse was located at the mid-thickness position in each sample. The extent to which work hardening occurs can have a significant influence on the tendency of a welded joint to undergo stress corrosion cracking [6]. The hardness distributions across the NGLW and GTAW joints are shown in Fig. 15. The NGLW had a “M” shaped hardness distribution with a peak value of 240 HV. The peaks in hardness were located approximately 1–2 mm from the weld centreline. The hardness then dropped rapidly with increasing distance from the weld centreline to plateau at 160 HV (base material value). The width of hardened material for the NGLW was approximately 15 mm. In contrast, the peak hardness for the GTA weld was 264 HV, while the width of hardened material was approximately 80 mm.

5.9. Micro-hardness characteristics of two-sided welds

The distribution of hardness was investigated for the two-sided welds (Fig. 16). The results show M-shaped distributions for hardness in all cases (10 and 20 mm thick samples made with NGLW and GTAW processes). The peak hardness values for the GTA welds in the 10 and 20 mm thick samples were approximately 255 and 260 HV respectively. The location at which the peak hardness arises is closer to the weld centreline for the 10 mm thick sample, being approximately 5 mm away in comparison to an offset of

approximately 8 mm for the 20 mm thick sample. The peak value of the hardness for the 10 mm thick NGLW sample is approximately 230 HV, while it is approximately 250 HV for the 20 mm thick NGLW sample. The peak hardness was offset from the centreline by approximately 2 mm at both thicknesses, as can be seen in Fig. 16.

5.10. Estimation of cumulative plastic strains in 10 mm thick welds

The thermo-mechanical cycling that occurs during multi-pass NGLW and GTA welding is sufficient to produce plastic strain [8]. This could lead to the rupture of the protective oxide film and, if a crack is initiated, a sustained tensile stress at the crack tip is likely to lead to crack propagation [30]. Plastic deformation has a significant influence on the susceptibility to SCC for “L grade” austenitic stainless steels [8]. Consequently, an investigation into the influence of plastic strain upon the hardness was carried out in order to assist in estimating the cumulative plastic strains across the welded joints. A set of tensile tests was carried out on coupons extracted from the parent material, with the tests being terminated at progressively increasing levels of plastic strain (1%, 3%, 5%, 9%, 15%, 30% and 70% which corresponds to the point of failure). The hardness values across the samples were recorded. The results reveal a similar trend to that reported by Katayama et al. [8]. Fig. 17 shows the plastic strain – hardness relationship in the stainless steel parent material. Each point on this graph was obtained by taking the average value of hardness, as measured on three separate

Fig. 12. Residual stress distributions in 10 mm thick plates for two-sided welding strategy (MPa) a – NGLW b – GTA welding.

Fig. 13. Residual stress profiles for 10 mm thick unrestrained welded plates. a) NGLW stress profile b) GTAW stress profile.

Fig. 14. Residual stress profiles for 20 mm thick double-sided welds. a – NGLW stress profile b – GTAW stress profile.

tensile test specimens, for each value of strain. The plotted relationship was then used to relate the hardness that was measured at each point across the welded joint to an estimate for the cumulative plastic strain at that location.

In Fig. 15 we saw that the maximum value across the 10 mm thick NGLW was 240 HV. This value would correspond to an estimated cumulative plastic strain of 13% according to the data shown in Fig. 17. The maximum value across the 10 mm thick GTAW sample was 260 HV. This value would equate to an estimated cumulative plastic strain of 19%. These results would suggest that the accumulated plastic deformation (or cold work) for the GTAW welding process is higher than that in NGLW. It could be inferred, therefore, that the GTAW welding technique will produce joints that will be more susceptible to SCC than the NGLW technique. This inference can be

drawn from the combination of the higher residual stresses and the higher apparent level of plastic strain in the GTAW weld. The double-sided welding strategy was also investigated using the same approach. According to the peak values of hardness shown in Fig. 16, the accumulated values for plastic strain were lower for two-sided welding. For the 10 mm thick specimens the estimate for the accumulated plastic strain was 11% for NGLW while it was 17% for GTAW welding. These results suggest that a double-sided welding strategy will lead to lower levels of accumulated plastic strain.

Clearly, there are limitations associated with the above analysis. For example, the plastic strain – hardness relationship in Fig. 17 was established based on the results of uni-axial tension tests, which had been carried out on coupons that were machined from material that was nominally homogeneous. In contrast, welded

Fig. 15. Hardness distributions for 10 mm thick single-sided NGLW and GTAW specimens.

Fig. 16. Hardness distributions for 10 and 20 mm thick two-sided NGLW and GTAW samples.

joints are heterogeneous and they are often associated with highly tri-axial stress states. Nevertheless, the authors believe that such an analysis provides a useful qualitative comparison of the extent to which plastic strain is induced with each welding technique.

6. Conclusions

The following conclusions can be drawn based on the work carried out in this study:

- The results obtained in this study indicate that NGLW may offer significant advantages for the structural integrity of components in cases where tensile residual stresses and accumulated cold work can accelerate material degradation and crack growth.
- The residual stresses were generally 30–40% lower in magnitude for the narrow gap laser welds in comparison to those for GTA welding. For the restrained 10 mm thick welds, the peak tensile stress was ~520 MPa for the GTA process and ~310 MPa in the case of NGLW. Furthermore, the NGLW technique resulted in a very narrow tensile stress region close to the upper surface of the welded plates, with the expanse of the tensile stress region being less than 5 mm to either side of the weld centreline.

- The accumulation of plastic strain due to thermo-mechanical cycling in GTA welding was higher than for NGLW, and a double-sided welding strategy led to lower levels of strain in comparison to a one-sided welding strategy, for both welding processes.
- The butterfly distortion angle for the GTA welds was approximately 3 times higher than for NGLW.
- The welding strategy (single sided welding or double sided welding) had a significant influence on the induced residual stresses, especially for the NGLW technique, while it had a less significant influence for the GTA welding technique.
- The thickness of the welded samples had a less significant influence on the induced residual stresses than the choice of welding process.

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Fig. 17. Variation in Vickers Hardness ($HV_{0.3}$) with homogeneous strain in tensile coupons extracted from AISI grade 316L base material. The peak hardness values for the 10 mm thick single-sided and double-sided NGLW samples, together with the values for the corresponding GTAW samples, are highlighted to give an indication of the accumulated cold work.

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