Neutron diffraction residual stress mapping in same gauge and differential gauge tailor-welded blanks

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Abstract

Neutron diffraction has been used to determine the residual stresses in the weld region of laser-welded tailor-welded blank (TWB) samples. Residual stresses in same gauge and differential gauge TWB samples are examined in the as-welded condition as well as after uniaxial loading to 0.5, 3.0 and 7.0% strain. Results indicate that stress distributions can be quite complex, particularly following deformation. Overall, however, two major conclusions were drawn: first, residual stresses around laser welds in these TWBs tend to be small compared with stresses reported for conventional welding processes. Secondly, in most cases the peak residual stresses tend to remain the same or diminish with subsequent deformation.

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1. Introduction

With the increasing demand for stronger, lighter and safer cars, the automotive industry is adopting many new manufacturing methods. One of the most prominent of these uses tailor-welded blanks (TWB) in automotive stampings. With TWBs, welding occurs prior to, rather than after, the stamping process. A typical TWB is laser-welded and comprised of two or more sheets. Each sheet typically has a different thickness, although sheets with different strengths, formabilities, and/or coatings are also common. The trend toward TWBs is driven principally by industry’s move towards ‘lightweighting’ but also to lowering production costs by reducing the number of forming and materials handling operations.

The concept of laser-welded TWB processing raises a number of interesting issues with respect to residual stresses. First, the welding procedure itself produces residual stresses. While weld-induced residual stresses have been well-documented (e.g. [1–4]) the authors are aware of no experimental studies to determine residual stresses in TWBs. Some residual stress finite element modelling has been done, however, this study [5] considered a weld with a discontinuous geometry rather than a simple linear weld. In addition to welding-induced stresses, stamping or drawing of the TWB may lead to further residual stress accumulation. This is particularly true given the different sheet thicknesses and the fact that the weld typically has a higher yield strength than the parent material [5].

Since neutrons penetrate readily into most materials, neutron diffraction has become a well-established method for non-destructively measuring residual stresses in engineering components. As in X-ray diffraction, the lattice spacing provides an intrinsic strain gauge for measuring the stress state of the sample. The particular advantage of neutrons is that they are not absorbed as easily as X-rays, and can therefore penetrate centimeters into most metallic components, permitting measurements ‘at depth’.

In the present study neutron diffraction was used to measure the residual stress state around the weld in same gauge and differential gauge TWBs. Measurements were made both in the as-welded condition and after tensile deformation, with two different weld orientations examined—parallel and perpendicular to the sample axis, which was also the direction of applied load.
2. Experimental

2.1. Sample preparation

Tensile testing samples having a 24.5 mm (1 in.) wide gauge length were cut from steel, laser-welded TWB samples of two types: “same gauge” samples in which the parent sheets were both 1.5 mm thick, and “differential gauge” samples with one sheet of 1.5 mm thickness and the other 0.9 mm thickness. The weld profile for the differential gauge samples is shown schematically in Fig. 1a. Samples were cut into two different orientations:

- Transverse weld: with the weld transverse to the sample axis (Fig. 1b).
- Longitudinal weld: with the weld lying along the sample axis (Fig. 1c).

In addition to examining samples in the as-welded condition, additional samples were subjected to progressively increasing tensile strains. An Instron tensile testing machine was used to apply loading up to 1, 3 and 7% strain (well into the plastic deformation range of the parent metal), followed by unloading. These unloaded samples were also examined using neutron diffraction.

2.2. Neutron diffraction

In neutron diffraction methods a neutron beam of constant wavelength $\lambda$ is diffracted through a scattering angle ($2\theta$). The spacing $d$ between atomic planes in the lattice is then calculated according to Bragg’s law

$$\lambda = 2d \sin \theta$$

(1)
Neutron diffraction was carried out on the E3 diffractometer at the NRU reactor at Chalk River, Ont. The (1 1 5) planes of a Ge monochromator crystal were employed to produce a neutron beam of fixed wavelength \( \lambda = 1.53 \) Å. The sampling region (termed the gauge volume) at each measurement point was defined by 0.75 mm horizontal and vertical slits. This gauge volume was positioned halfway through the sample thickness (i.e. the wall centre). Strain was determined using the Fe (1 1 2) reflection.

The diffracted peak was obtained using a multiple (32 wire) detector spanning an angle of \( \sim 2.5 \)°. The scattering angle (2\( \theta \)) of the peak was determined by fitting the experimental profile of counts versus angular position to a Gaussian peak shape on a sloping background. \( \theta \) was then used in Eq. (1) to determine the value of \( d_{112} \). To derive a strain value, a reference spacing \( d_{112} (\text{ref}) \) was obtained by measuring a region far from the weld on the samples that had not been subjected to tensile stress. The strain at any measurement point on each sample was then calculated from:

\[
\epsilon = \frac{d_{112} - d_{112} (\text{ref})}{d_{112} (\text{ref})} \tag{2}
\]

At each measurement point, strain was measured in three orthogonal directions: along the sample axis (axial strain \( \epsilon_A \)), transverse to it (transverse strain \( \epsilon_T \)) and through the wall (normal strain \( \epsilon_N \)). This was achieved by mounting each sample in three different orientations as shown in Fig. 2 (the strain measurement direction bisects the incident and diffracted beam directions). For each sample the three strain components were determined at approximately 25 positions along the scan lines shown in Fig. 1b and c. These scan lines were about 24 mm long with the weld at the centre position.

With the three measurements of strain at each position, the residual stress could be calculated through a generalized Hooke's law, for example, axial stress (\( \sigma_A \)) was calculated by:

\[
\sigma_A = \frac{E}{1 + \nu} \left\{ \epsilon_A + \frac{\nu}{1 - 2\nu} (\epsilon_A + \epsilon_T + \epsilon_N) \right\} \tag{3}
\]

where \( E \) is Young's modulus and \( \nu \) the Poisson's ratio.

3. Results and discussion

3.1. Residual stresses in as-welded samples: same gauge TWBs

Fig. 3 shows typical as-welded residual stress results for same gauge TWB samples. In this case the results are shown only for the transverse weld sample (as seen in Fig. 1b) since the longitudinal weld sample displayed essentially similar results. It should be noted that the fusion zone of the TWB welds is approximately 1 mm wide. Results are not shown for the exact centreline of the weld since the diffracted beam from these regions tends to have a very low intensity due to weld grain size and texture effects. Typical errors, for each data point are \( \sim 25 \) MPa (see error bar on graph).

Although all three components in Fig. 3 show a relatively symmetrical stress pattern, the most significant results are for the stress component parallel to the weld (in this case \( \sigma_T \), since the weld is also transverse). These display a noticeable residual tensile stress in the fusion zone (\( \sim 60 \) MPa), with stress decreasing as it moves away from the weld until it becomes compressive at around 4 mm from the weld centre. These residual stress trends illustrated by these samples are very similar to those found in other welding studies [1–4], however, the scale of the stresses is significantly smaller in these TWBs. Withers and Holden [2], for example, report similar residual stress trends in a bead-on-plate electron beam weld in Waspalloy plate, however, the maximum stress close to the weld centreline is \( \sim 1000 \) MPa. In butt-welded, 114 mm OD ferritic steel tube, Root et al. [4] found similar stress patterns but with maximum stresses of \( \sim 250 \) MPa. Also of note in the Root et al. study [4] is the fact that the stress does not go compressive until \( \sim 25 \) mm away from the weld zone.

1 Note that the sample axis was chosen as the reference direction rather than the weld direction. This is because the weld direction was not consistent (it could be either transverse or axial) for all of the samples.
The trend in the residual stress parallel to the weld is explained, as in other studies [1–4], by considering that the shrinkage in the weld direction is constrained by the parent material during cooling of the fusion and heat affected zone. This results in residual tension developing in the weld direction near the fusion zone. This stress is balanced by compressive stresses away from the fusion zone. The low value of residual stress in the as-welded TWB samples, compared to those reported in other studies [2,4] likely can be accounted for by a number of factors:

1. the sample is thinner than those in the other studies [2,4], thus reducing the constraint during cooling;
2. the heat input is comparatively small with laser welding, which leads to a relatively narrow fusion zone.

3.2. Residual stresses in as-welded samples: differential gauge TWBs

Fig. 4 shows typical as-welded results for the differential gauge TWB samples (again, only the results from the transverse weld sample are shown). The figure indicates the thick and thin side of the sample. In this case the residual stress distribution appears much more complex and with higher maximum stresses than for the same gauge samples. However, even these maximum stresses are much lower than those reported in other studies involving more conventional welding processes [1–4] (discussed above). Fig. 4 shows that the stress parallel to the weld \((\sigma_T)\) does not display the symmetrical residual stress pattern seen in the same gauge samples (Fig. 3), rather it is slightly tensile on the ‘thick’ side and compressive on the ‘thin’ side of the weld. The other two components also vary significantly from the same gauge case, the pattern for both being fairly similar: strongly compressive at the weld centre, with stresses gradually rising away from the weld region. Stresses are generally smaller on the thinner side of the weld, consistent with less constraint. Although the axial and normal stress components do not sum to zero over the measurement region, this is likely because (due to beam time constraints) data points were not taken past the 12 mm point.

The complex nature of the as-welded stress distribution is not unexpected given the lack of symmetry around the weld. As the fusion and heat affected zone contract, the physical constraint will be less from the thin side of the weld than from the thicker side. Compared to the same gauge case (Fig. 3) reduced constraint from one side of the weld lowers the tensile residual stresses parallel to the weld direction \((\sigma_T)\). However, the lack of symmetry appears to manifest itself in significant residual stresses in the other two principal stress directions. This complex stress situation cannot be explained readily and will require modeling with finite element analysis to fully understand.
3.3. Residual stresses in pulled samples: same gauge TWBs

3.3.1. Same gauge, axial weld (weld and scan geometry shown in Fig. 1c)

Typical as-welded results for these same gauge samples were shown in Fig. 3. Fig. 5 shows the result for the 7.0% strained sample (note because of experimental difficulties only one-half of the weld region was measured). The results for the other applied strain levels (0.5 and 3.0%) were similar and are therefore not shown. It is important to note that the results in Fig. 3 were for a transverse weld sample; whereas those in Fig. 5 are for a sample with the weld along the sample axis, where $\sigma_A$ lies along the weld direction.

A comparison of Figs. 3 and 5 indicates that tensile loading followed by unloading appears to have lowered the overall stresses in the normal component and also in the component perpendicular to the weld ($\sigma_A$ in Fig. 3 and $\sigma_T$ in Fig. 5). Conversely, the stress parallel to the weld ($\sigma_T$ in Fig. 3 and $\sigma_A$ in Fig. 5) has a similar trend to that before deformation except with more significant compressive stresses away from the weld region.

3.3.2. Same gauge, transverse weld (weld and scan geometry in Fig. 1b)

Again for comparison, the as-welded results for these same gauge samples are shown in Fig. 3. Fig. 6 shows the results for 7.0% strain (again 0.5 and 3.0% are similar to 7.0%). In this case the imposed deformation appears to have produced a relatively uniform residual stress transverse to the weld, however, the stress variations in the other two components are more exaggerated compared with the as-welded case in Fig. 3.

3.4. Residual stresses in pulled samples: differential gauge TWBs

3.4.1. Differential gauge, axial weld (weld and scan geometry in Fig. 1c)

The as-welded results for these differential gauge samples were shown in Fig. 4, and revealed a fairly complex residual stress pattern. Fig. 7 shows the result of applying a 7% tensile strain to the axial weld sample, followed by unloading (again, results for 0.5 and 3.0% are similar). It is again important to note that for the result in Fig. 4 the residual stress parallel to the weld is $\sigma_T$; perpendicular to the weld is $\sigma_A$. The opposite is true for these axial weld samples, i.e. for Fig. 7, $\sigma_A = \sigma_T$ parallel to the weld, $\sigma_T = \sigma_A$ perpendicular to the weld.

Tensile deformation changes the stress distribution considerably in this samples. In comparison with the as-welded case (Fig. 4):

- The normal stress component varies slightly but is approximately zero across the weld.
Fig. 5. Results for the axially welded, same gauge sample pulled to 7% strain. Results for the 0.5 and 3% strained samples were similar and are therefore not shown. Note that due to experimental difficulties results were obtained from one side of the weld only. Symbols: (•) normal stress ($\sigma_N$); (○) axial stress ($\sigma_A$); (□) transverse stress ($\sigma_T$).

Fig. 6. Results for the transverse weld, same gauge sample pulled to 7% strain. Results for the 0.5 and 3% strained samples were similar and are therefore not shown. Symbols: (•) normal stress ($\sigma_N$); (○) axial stress ($\sigma_A$); (□) transverse stress ($\sigma_T$).
Fig. 7. Results for the longitudinally welded, differential gauge sample pulled to 7% strain. Results for the 0.5 and 3% strained samples were similar and are therefore not shown. The thick and thin side of the sample are noted. Symbols: (•) normal stress ($\sigma_N$); (○) axial stress ($\sigma_A$); (□) transverse stress ($\sigma_T$).

- The stress component perpendicular to the weld (compare $\sigma_A$ in Fig. 4 with $\sigma_T$ in Fig. 7) has changed from entirely compressive to approximately zero on the thick side and tensile ($\sim$60 MPa) on the thin side.
- The stress parallel to the weld has undergone the most significant change (compare $\sigma_T$ in Fig. 4 with $\sigma_A$ in Fig. 7). Prior to deformation it varied from slightly tensile on the thick side to compressive on the thin side. After 7.0% straining, both sides of the weld exhibit a tensile residual stress, the thin side more significant than the thick side.

3.4.2 Differential gauge, transverse weld (weld and scan geometry in Fig. 1b)

The as-welded result for these differential gauge samples is shown in Fig. 4. Unlike the previous three cases, these samples display a difference between the residual stresses at 0.5, 3.0 and 7.0% applied strain levels, shown in Fig. 8a-c, respectively. Comparison of Fig. 8 with Fig. 4 (as-welded) shows a gradual and progressive change from zero applied strain to the highest strain level. The changes in individual components are described as follows:

- The stress component parallel to the weld ($\sigma_T$) was initially tensile in the thick section and compressive in the thin side (Fig. 4). With increasing strain this trend disappears and the residual stresses become more symmetrical across the weld line (although there is considerable scatter in the data).
- The stress components perpendicular ($\sigma_A$) and normal ($\sigma_N$) to the weld behave similarly with progressively applied deformation (Fig. 8). In general, the significant compressive peak and asymmetry is reduced, and replaced with a roughly symmetrical residual stress distribution with a slight tensile peak in the weld region.

4. Summary

This study has shown that the residual stress distributions in the weld region of TWBs can be quite complex, particularly after deformation. Finite element modelling combining welding with plastic deformation is needed before these complex stress patterns are fully understood. An important point, however, is that residual stresses around laser welds in TWB samples tend to be relatively small in comparison with those observed in conventionally welded, thicker material [1–4]. Furthermore, in most cases the peak residual stresses tend to remain the same or diminish with
Fig. 8. (a)–(c) Results for the transverse weld, differential gauge samples, pulled to (a) 0.5% strain, (b) 3.0% strain, and (c) 7% strain. The thick and thin side of the sample are noted. Symbols: ∆ normal stress (\(\sigma_N\)), ▲ axial stress (\(\sigma_A\)), ◇ transverse stress (\(\tau_T\)).
subsequent deformation. These results are very positive ones for the automotive industry, since they should reduce concerns that TWB manufacturing may suffer from forming and coating problems associated with residual stresses.

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