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THE NON-DESTRUCTIVE MEASUREMENT OF RESIDUAL STRESSES IN STAINLESS STEEL ROLL FORMED SECTIONS

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Abstract. *During the manufacture of roll formed structural members the production and storage of sheet materials, as well as their subsequent forming causes plastic deformation in varying degrees around the resulting cross section. Plastic deformation causes both an increase in material strength in the section material through cold working and it also affects the residual or internal stress distribution present throughout the resulting structural section. Both the material strength and the residual stress distribution influence the structural behavior of the cross section, therefore it is important to map both these properties in order to achieve efficient structural design. Destructive techniques have commonly been used to map residual stresses in structural sections. To achieve a high resolution of measurements these techniques are extremely labor intensive and sensitive to the measurement technique and it is almost impossible to measure the strain relaxation that occurs in three orthogonal components by this process. Non-destructive residual stress measurements are relatively infrequently used for structural engineering applications. The presented experimental program demonstrates the applicability of the non-destructive technique of neutron diffraction for mapping residual stresses in structural members at four locations through the thickness of a roll formed stainless steel section. The measurements were made using the ENGIN-X instrument at the UK's pulsed neutron source: ISIS in Oxford.*

1 INTRODUCTION

Cold formed structural sections are a comparatively novel type of structural section that started to be more widely used for construction in the 1940s. They now comprise 15% and 13% of all new structures in the housing market in the USA and Australia respectively [1] and expansion in the UK markets is being actively encouraged for both environmental and economic reasons [2]. Since cold formed sections are produced by plastically deforming metal sheets at room temperature the thickness of the sections can be less than the minimum thickness required to retain the high temperatures essential to manufacture the more conventional hot rolled sections. Hence cold formed sections which are used to carry light loads and span short distances can be lighter and structurally more efficient than the hot rolled alternatives.

Roll formed sections are the most prevalent type of cold formed section. During the manufacture of roll formed sections plastic deformation can occur at several stages and plastic deformation will have been experienced to varying degrees around the resulting cross section. Through a process termed cold working the regions of the section that have experienced plastic deformation exhibit an increase in material strength and a decrease in ductility [3]-[4]. The resulting distribution of material strength around roll formed sections has been mapped and used in structural design codes of both carbon steel and stainless steel roll formed sections to increase the material efficiency [5]-[6]. However the plastic deformation which causes the increase in material strength also influences the distribution of residual or internal stresses. Residual stresses are stresses that exist within a structural member in its unloaded state and their magnitude and distribution can affect the structural behaviour of structural cross sections.

Since hot rolled sections have been used in the construction industry for a much longer period of time than roll formed sections there is a deeper understanding of their structural behaviour. Furthermore the techniques for measuring factors that can influence structural behaviour, such as residual stresses, have been developed to capture the significant aspects of the magnitudes and distributions observed in hot rolled sections. However, these techniques have been shown to give an incomplete picture of the magnitude and distribution of residual stresses in roll formed sections [7]-[9]. This paper will therefore present data from a pilot study that used a non-destructive technique, namely neutron diffraction, to measure residual stress distributions in a roll formed stainless steel box section to demonstrate the potential of adopting this technique.

2 STAINLESS STEEL STRUCTURES

Whilst carbon steel is the most commonly used structural metal in the construction industry one disadvantage of carbon steel is its potential to corrode. It has been only in relatively recent times that the use of a non corrosive alternative such as stainless steel as a structural material has been explored. This is principally because stainless steel as a material is more expensive than carbon steel. Despite its initial expense stainless steel has been adopted for applications in exposed conditions such as bridges and offshore structures because the cost saving associated with its ease of maintenance can outweigh the high initial cost [10]. Due to the expense of stainless steel and the efficiency of the roll forming process most structural sections currently available are roll formed sections.

There are three different microstructures of stainless steel: austenitic, ferritic and martensitic. The most commonly used grade of stainless steel for structural applications is 1.4301 which has an austenitic microstructure. Cold working of austenitic stainless steel causes a significantly larger increase in material strength than in carbon steel. This offers a relatively larger increase in design efficiency which has clear benefits to realizing stainless steel as a competitive structural material. However the co-existing residual stresses can, depending on their magnitude and distribution and on the loading condition of the roll formed section, have a negative effect on structural behavior by causing a loss of stiffness and early yielding.

3 ROLL FORMING

Roll forming is a highly automated and therefore efficient production process. There are two types of sheet material that are commonly used as the starting material for roll forming: hot and cold rolled sheet material. Stainless steel can be rolled whilst hot to produce hot rolled sheet of a minimum thickness of approximately 3mm (see stage 1 in figure 1). If thinner sheet material is required, since the sheet will be too thin to retain the heat needed to allow for hot rolling to occur, the stainless steel is passed through rollers whilst it is at room temperature, therefore plastically deforming the sheet to reduce its thickness. This process produces cold rolled sheet material.

For reasons of efficient storage and to enable the sheet material to be used as the starting material of this completely automated section forming route both hot and cold rolled sheet material are wound into coils as shown in stage 2 of figure 1. To manufacture roll formed sections the coil material is unwound (see stage 3 in figure 1) and then fed into shaping rollers which plastically deform the sheet material into the required cross sectional shape. To roll form a box section the sheet is rolled into a circular cross section, welded closed and then this tube is crushed into a rectangular cross section as shown in stages 4-6 in figure 1.

Roll formed structural sections can therefore experience plastic deformation at three stages in their manufacture. Firstly plastic deformation can be experienced in cold rolled sheet production, secondly during the coiling and uncoiling of the sheet material and finally during the forming of the cross section.

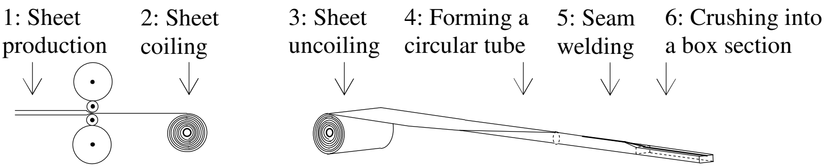
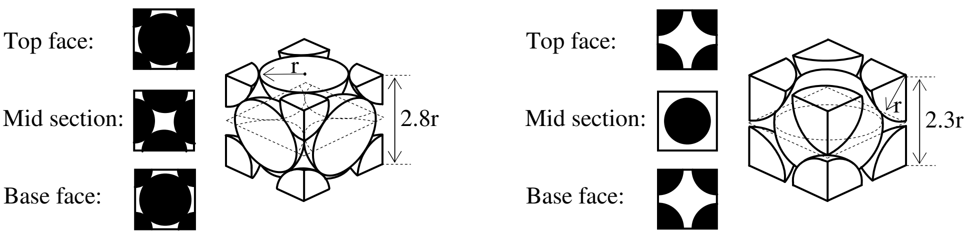


Figure 1: Manufacture of a roll formed box section.

4 COLD WORKING

In general cold working, or the increase of material strength through plastic deformation, can be explained by considering the effect of plastic deformation on the ordered arrangement of atoms in a metallic lattice. Plastic deformation can be described on the atomic scale as the movement of planes of atoms with respect to one another in the metallic lattice. In carbon steel and stainless steel this causes an increase in dislocations in the metallic lattice. The creation of more dislocations in the metallic lattice increases the number of obstacles to planes of atoms moving. Therefore the cold worked material is observed on the macro scale to increase its resistance to further plastic deformation and so exhibit an increase in material strength [11].

For stainless steel with an austenitic microstructure an increase in dislocations is not the only mechanism that can increase the material strength of the cold worked material. The arrangement of atoms in an austenitic microstructure, prior to experiencing cold working, can be described by the unit cell shown in figure 2a. When this unit cell is duplicated and stacked together the arrangement of atoms in the metallic lattice of an austenitic microstructure is described. This particular unit cell is termed a Face Centred Cubic (FCC) unit cell.



a) Face Centred Cubic (FCC) unit cell of the austenitic microstructure.

b) Body Centred Cubic (BCC) unit cell of the martensitic microstructure.

Figure 2: Microstructures in cold worked austenitic stainless steel.

The austenitic microstructure of stainless steel grade 1.4301 is a metastable microstructure which means that work done to the material through plastic deformation will cause the austenitic microstructure to, in part, transform into a martensitic microstructure. The unit cell of the martensitic microstructure is shown in figure 2b and it is termed a Body Centred Cubic (BCC) unit cell. The BCC unit cell is smaller and has a higher ratio of volume of atom to volume of unit cell compared to the FCC unit cell. This ratio is commonly termed the Atomic Packing Factor (APF) and it is an indication of the density of the unit cell. In addition, unlike the FCC unit cell, the BCC unit cell has within its geometry no planes where the atoms are as tightly packed together as possible. This is of significance because owing to the geometry of these close packed planes they can easily slide past one another and the lack of these in the BCC unit cell causes the martensitic microstructure to give the cold worked stainless steel its increase in strength and reduction in ductility [12]. The relationship between the two microstructures, and therefore the transformation that occurs during plastic deformation, is shown in figure 3 by identifying the atoms that will create the unit cell of the martensitic microstructure within the metallic lattice of the austenitic microstructure.

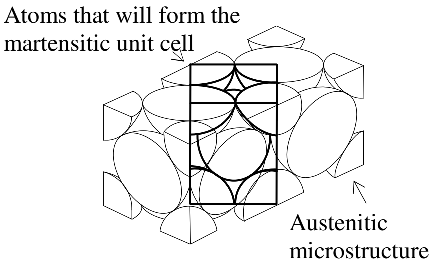


Figure 3: Transformation from an austenitic microstructure to a martensitic microstructure.

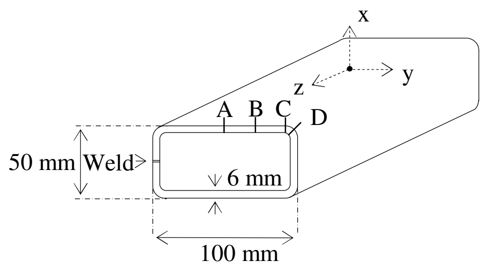


Figure 4: Test sample.

5 RESIDUAL STRESSES

Uneven plastic deformation also creates residual or internal stress distributions that equilibrate over the whole cross section. Residual stresses are defined at three different scales by the distance over which they equilibrate. Type I residual stresses relate to the macro scale, where equilibrium is achieved over distances that relate to the scale of the structural cross section. It is this type of residual stress that is considered to have the greatest importance for structural behavior. Type II and type III residual stresses relate to the micro scale. Type II residual stresses are defined as equilibrating over several metallic grains (regions where the metallic lattice is continuous) and type III residual stresses are defined as equilibrating within metallic grains [13].

Residual stresses σ_x, σ_y and σ_z act in three orthogonal directions; normal to the surface of the section, transverse to the section length and along the section length, respectively. This coordinate system is defined in figure 4. Because of the influence that residual stresses can have on structural behavior it is important to measure the magnitude and distribution of residual stresses in cold formed sections and there are two distinct types of techniques which have been employed to date: destructive and non-destructive.

6 DESTRUCTIVE RESIDUAL STRESS MEASUREMENT TECHNIQUES

Destructive techniques used to measure residual stresses all involve mechanically removing material from the test sample in order to disturb the equilibrium of the residual stress distribution, thereby causing a geometrical relaxation. This geometrical change can be measured in order to quantify the released stress. Owing to the size of sample required for material to be mechanically removed the destructive techniques are commonly used by structural engineers because the measurements are made over the macro scale and therefore result in determining type I residual stresses.

Type I longitudinal residual stresses, σ_z that exist along the length of a structural member are considered to be the most significant in determining a member's structural behaviour and they have been commonly quantified by a destructive technique termed sectioning. This destructive technique cuts the cross section into strips, thereby disturbing the equilibrium of residual stresses as illustrated in figure 5. The strain caused by geometrical relaxation on the surface of each sectioned strip can be measured once each strip has re-established equilibrium and used to identify two types of residual stress. Uniform tensile or compressive strain is used to identify the longitudinal membrane residual stress, $\sigma_{z,m}$ and the curvature of the sectioned material indicates a variation of stresses through the material thickness, which is commonly assumed to be linear [14] and which is used to quantify the longitudinal bending residual stress, $\sigma_{z,b}$. However this measurement technique has disadvantages when used to measure residual stresses in roll formed sections.

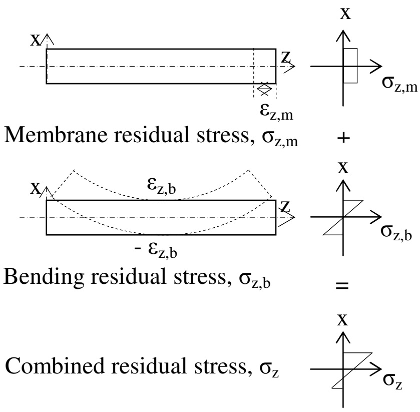


Figure 5: Residual stresses released during sectioning.

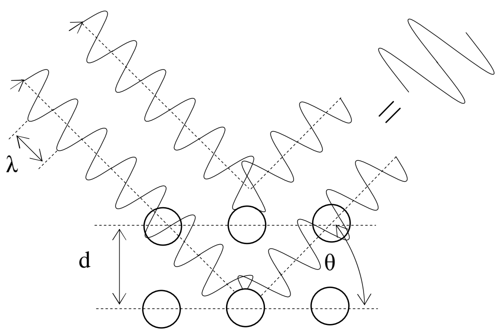


Figure 6: Neutron diffraction.

Using the sectioning technique, combined with an electrolytic technique to remove layers of section material, longitudinal residual stresses, σ_z were measured at different depths through the thickness of a cold formed carbon steel box section in [7]. From these measurements it was observed that the longitudinal residual stress distribution through the thickness of the section was not a linear variation as commonly assumed [14] and therefore that the membrane and bending residual stresses could not be the only residual stresses to exist in the section. Through this study [7] a third residual stress component termed the layering residual stress was identified, which is not released and therefore not measured during sectioning, since it has no resultant axial force or moment. This unmeasured layering residual stress is important to quantify to determine peak residual stresses in the section material. Analytical models that map the coiling, uncoiling and cold forming of stainless steel and carbon steel sheet material into structural sections [8]-[9] have also determined that the variation of longitudinal residual stresses, σ_z through the thickness of a cold formed section does not conform to the assumed linear model.

Longitudinal residual stresses, σ_z in roll formed stainless steel sections were determined through the sectioning technique in [15] where both a linear and a rectangular block through thickness distribution were assumed to calculate the longitudinal bending residual stresses, $\sigma_{z,b}$. It was observed that for sectioned material with a rectangular cross section, there was a difference of two thirds in the magnitude of the bending stresses between the two assumed distributions. This study showed that assuming a linear through thickness residual stress distribution can cause large errors in determining the longitudinal residual stresses.

Furthermore residual strains released normal to the surface of the section, ε_x and transverse to the length of the section, ε_y are not easily quantified in the same location as the longitudinal strain, ε_z through the use of the sectioning technique. However all strain components contribute to the normal, transverse and longitudinal residual stresses (σ_x, σ_y and σ_z respectively) through the three dimensional definition of Hookes' Law, given in equations 1-3. Where E is the Young's modulus and ν is Possion's ratio.

$$\sigma_x = \frac{E}{(1+\nu)(1-2\nu)}\left[\varepsilon_x(1-\nu)+\nu(\varepsilon_y+\varepsilon_z)\right] \tag{1}$$

$$\sigma_y = \frac{E}{(1+\nu)(1-2\nu)}\left[\varepsilon_y(1-\nu)+\nu(\varepsilon_x+\varepsilon_z)\right] \tag{2}$$

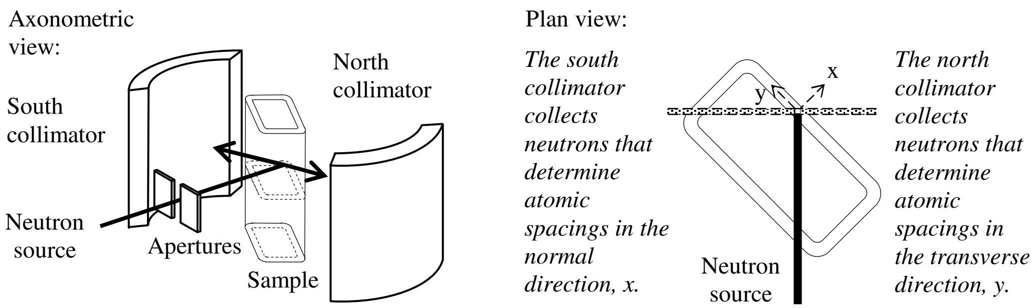
$$\sigma_z = \frac{E}{(1+\nu)(1-2\nu)}\left[\varepsilon_z(1-\nu)+\nu(\varepsilon_x+\varepsilon_y)\right] \tag{3}$$

Using sectioning to measure residual stresses has the disadvantage that the complete residual stress distribution is not fully released and therefore not measured and the strains in the normal, transverse and longitudinal directions are hard to measure simultaneously to correctly determine the corresponding residual stresses. Also the method of removing material can affect the residual stress pattern through plastic deformation and heating that might occur during mechanical interventions.

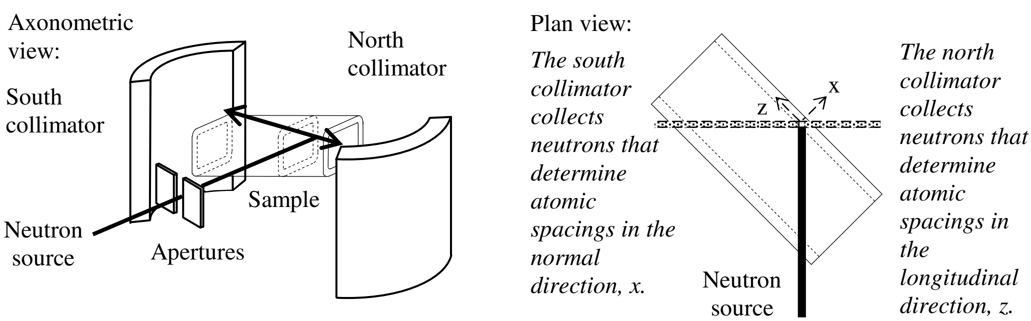
7 NON-DESTRUCTIVE RESIDUAL STRESS MEASUREMENT TECHNIQUES

The alternative way to measure residual stress distributions is with a non-destructive technique where it is the effect of the test sample on magnetic fields, X-rays or a neutron beam which is used to determine residual stresses and no material need be removed from the test sample. The use of magnetic techniques to measure residual stresses is not possible in this case since the austenitic microstructure of stainless steel is nonmagnetic. However X-ray diffraction techniques have been used to measure through thickness residual stress distributions in an austenitic stainless steel roll formed section [16] but the depth of penetration was not sufficient, so electrolytic material removal was used to obtain measurements at greater depths. Problems were also experienced making measurements by X-ray diffraction due to the large size of metal grains in cold worked stainless steel [16]. Whilst neutron diffraction does not offer such a fine resolution as is possible using X-ray diffraction this technique does offer a suitable penetration depth for roll formed cross sections. In addition the larger volume over which the measurements are made, compared to X-ray diffraction could reduce the potential problems associated with diffraction measurements made in a large grain microstructure.

8 NEUTRON DIFFRACTION



a) Sample positioned to measure atomic spacing in the normal and transverse direction.



b) Sample positioned to measure atomic spacing in the normal and longitudinal direction.

Figure 7: Test setup.

The non-destructive technique of neutron diffraction uses the interaction of a neutron beam and the specimen's atomic structure, as governed by Bragg's law, to measure the spacing between atomic planes, d. Bragg's law is given in equation 4 and the variables λ, d and θ, are defined in figure 6.

$$n\lambda = 2d\sin\theta \qquad (4)$$

When n in equation 4 is an integer the diffracted neutrons interfere constructively. This causes the collimators either side of the test sample to detect a peak of neutrons at atomic spacings characteristic of the arrangement of atomic planes in the microstructure under observation. Just such neutron diffraction measurements were performed during a three day pilot study using the ENGIN-X instrument at ISIS. Through thickness residual stress distributions were measured in four locations A-D around a roll formed austenitic stainless steel grade 1.4301 box section of dimensions 100×50×6 mm, as shown in figure 4. At each location, A-D, seven diffraction measurements were made over a $2\times2\times2mm^3$ gauge volume at intervals of 0.5 mm through the thickness of the section. Measurements were made with the test sample held in two orientations in order to measure atomic spacings in three orthogonal directions, as illustrated in figure 7. The atomic spacings measured at different locations in the test sample were compared with a stress free atomic spacing measured in $2\times2\times2\ mm^3$ cubes, cut using an Electric Discharge Machine from locations A-D in the same cross section. The atomic strains held in the roll formed cross section were thus determined and converted to residual stresses using equations 1-3 and material data obtained from tensile coupon tests performed on material cut from locations A-D in the test sample.

9 RESULTS

Figure 8 shows a longitudinal through thickness residual stress distribution taken from location D with vertical error bars and horizontal lines indicating the overlapping of each measurement.

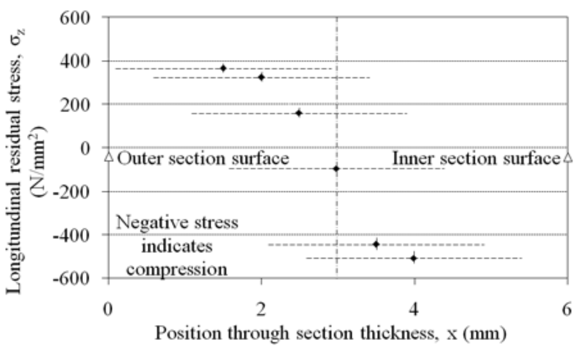


Figure 8: Longitudinal residual stress profile from location D.

The atomic spacings measured at locations A-D in the test sample were characteristic of an austenitic stainless steel microstructure with no detection of the presence of a martensitic microstructure. This could be because the martensitic microstructure created during cold working is small or it could be very localized and its presence was not detected due to the use of a large gauge volume.

10 CONCLUSIONS

Despite the significant overlap of the through thickness measurements this pilot study successfully demonstrates that neutron diffraction can be used to obtain through thickness residual stress data to a good accuracy and that the variation of longitudinal residual stresses through the thickness of roll formed stainless steel sections is clearly not linear as conventionally assumed. Further measurements using a smaller gauge volume are planned to allow the measurement of through thickness residual stress distributions to a higher resolution and thereby reduce any smoothing effect of the overlapping measurements and also increase the chance of detecting any martensite present.

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