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Residual stresses in a shape welded steel tube by neutron diffraction

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Abstract
Measurements of the triaxial residual strains in a composite tube from an austenitic stainless steel as a parent material and a shape welded ferritic steel were carried out by the time-of-flight neutron diffraction method on the POLDI instrument at the PSI SINQ neutron pulsed facility. The shape weld is used to build compressive stresses and, as a result, to suppress stress corrosion. Investigations of the residual stresses in such composite tubes are important for developing optimal welding techniques. Calculation of the residual stresses was performed using measurement results with a comb-sample, machined from the tube by the electro-discharge method, as the stress free reference sample. The results of the POLDI measurements of the stress state in the composite tube are presented and compared to the results of the destructive turning out method and theoretical predictions of calculations by the finite element method. Semiquantitative agreement between all the used methods was only observed for the tangential component of the stress tensor. In this case, the ferrite cladding produced a tangential compressive stress of about 800 MPa on the austenitic tube.

1. Introduction

At ECRS-5 [1], we have presented a report about the measurements of the triaxial residual stresses in a composite tube from an austenitic stainless steel with a welded ferritic steel cladding by the time-of-flight neutron diffraction (ND) method on the ENGIN instrument at the ISIS neutron pulsed facility. Cladding by a weld overlaying of the ferritic steel on the austenitic tube is used to build compressive stresses on its outer surface and, as a result, to suppress stress corrosion. Investigations of the residual stresses in such composite tubes are important for the development of optimal welding techniques.

However, in the ENGIN experiment, we have experienced difficulties with the determination of a stress free reference to calculate the residual strains. Also some uncertainty in the residual strain determination was introduced due to the absence of a strain state control at the last stage of cutting of the investigated sample from the tube. Nevertheless, we have observed a qualitative agreement of the ND experimental difference of the radial and tangential stress tensor components with the data obtained by the destructive turning out method (TOM) and the theoretical predictions of calculations by the finite element method (FEM), details of which are given in [2].

Taking into account these circumstances and the development of a new comb technique for stress free references in recent years (to our knowledge, the first application of this technique was done in [3]), we have performed the ND experiment on the POLDI instrument at the PSI SINQ neutron pulsed facility with well-formed geometry of a sample as well as with a comb-sample machined by the electro-discharge method (EDM) from the same composite steel tube.

2. Experimental details

The composite steel tube was fabricated in MPA, Stuttgart University [2] with the aim of the development and optimization of the shape welding techniques to produce high-pressure and corrosion-resisting components for the chemical industry. The seven layers of ferritic steel 3NiMo 1UP were welded on a 15 mm thick tube from austenitic steel X6CrNiTi 18 10 with an inner radius of 133 mm. The outer radius of the manufactured tube was 168 mm. Thus, the thickness of the

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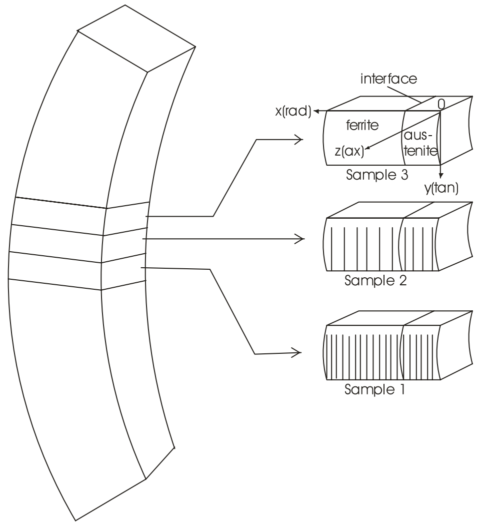

Figure 1. The small 70° circumference segment of 10 mm thickness (left) and the EDM machined samples (right).

Table 1. Stress release results for the truncated tube segment [2].

	Inner side		Outer side	
Strain/Stress	Axial	Tangential	Axial	Tangential
$\Delta\varepsilon$ (10^{-4})	−2.7	21.3	4.3	−15.3
$\Delta\sigma$ (MPa)	80 (4)	−450 (2)	6 (3)	307 (2)

welded cladding of the ferritic steel was equal to 22.5 mm. The elastic constants and tensile strengths were found to be equal to $E = 176$ GPa, $\nu = 0.3$, $R_m = 536$ MPa for austenite and $E = 205$ GPa, $\nu = 0.3$, $R_m = 695$ MPa for ferrite.

The samples for ND measurements were prepared in a few stages. First, the 200 mm long tube was cut from the manufactured tube. Then a 70° of arc circumference segment was truncated from the 200 mm tube. With rosettes of extensometers placed in the middle of the segment oriented in the axial and tangential directions, the effect of stress release was measured at the inner and outer surfaces (table 1). This release has to be accounted for in a recalculation of the segment experimental data as applied to the whole tube.

To avoid a prohibitively large neutron path length, the investigated samples were further simplified by cutting two small segments of 70° arc and of 10 mm thickness in the axial direction (figure 1, left) from the large 70° segment. One of them was used as the main sample for the measurements of the radial, axial and tangential components of the residual strain tensor. From another small segment, the three samples of 10 mm thickness along the tangential direction were prepared by EDM (figure 1, right). For the POLDI measurements, only the comb-sample no. 2 was used. It had eleven teeth of 3×10 mm^2 cross-section and 8.5 mm height, machined by EDM. The width of the slits between the teeth was equal to 0.3 mm.

An investigated sample was installed on the neutron strain scanner of the POLDI instrument. The gauge volume inside the sample was formed by a diaphragm in the primary neutron beam and a radial collimator with a space resolution of 2 mm in the scattering beam, respectively. For measurements of the radial and axial components, the height and the width of the diaphragm were equal to 10 and 2 mm, respectively, whereas the diaphragm height was decreased to 2 mm to measure the tangential component. Strain scanning of the sample was done at a depth of 5 mm from the surface along the radial direction of the composite tube, begun at $x = 2$ mm and finished at $x = 34$ mm where coordinates $x = 0$ and 35 mm correspond to the inner and outer edges of the tube, respectively. The scan step was equal to 1 mm in the austenite and ferritic (close to the interface between phases) layers and to 2 mm further from the interface.

The initial processing of measured diffraction spectra was carried out using the in-house single peak fit program 'Poldiausfit' which determined positions of the selected diffraction peaks in the d-spacing. Eight and seven resolved single peaks were observed in the austenite and ferrite phases, respectively. Using a set of the selected peak positions, the phase lattice parameters for each spectrum were calculated by applying the autoindexing program 'Autox' [4].

3. Experimental results

The autoindexing lattice parameters of the austenite and ferrite phases of the main sample (figure 1, left) are presented in figure 2 for all three neutron scattering vector directions.

Absolute values of the stress tensor components from the experimental data were calculated within the framework of the elastic model approximation:

$$\sigma_i = \frac{\mathbf{E}}{1+\nu}\left[\varepsilon_i + \frac{\nu}{1-2\nu}(\varepsilon_{\rm rad} + \varepsilon_{\rm ax} + \varepsilon_{\rm tan})\right]. \quad (1)$$

For this calculation, it is critically important to use the best approximation of the parameter a_0 to a true stress free lattice parameter. An evaluation of the phase strain free lattice parameter was carried out from the measurements with comb-sample no. 2 at the teeth top ($z = 2$ mm) for the radial and axial directions of the scattering vector. Note both directions were perpendicular to the axes of the teeth. The selective measurements along an axis of some teeth (at $x = 2.75$ and 9.3 mm in austenite and at 16.3 and 29.5 mm in ferrite) have shown an insignificant variation of the phase lattice parameter for both directions, in agreement with similar measurements in [5]. Note that in the same work a noticeable variation of a relative strain was observed in some teeth for the direction parallel to their axes.

In the austenite part of the comb-sample, the radial dependences of the radial and axial components of the lattice parameter were weakly variable, in that, both dependences were close to each other in the limit of the experimental errors. This has given us the basis for averaging the comb lattice parameters for both directions in a coordinate interval of $x = 2$–6 mm and to use the obtained value of 3.594 39(59) Å as the stress free austenite reference. The last value is comparable with 3.594 00(18) Å calculated using the uniaxial residual stress hypothesis for the inner edge of the tube ($x = 2$ mm in figure 2, left). As the stress free reference for the ferrite part of the comb-sample, we have used the radial dependence of

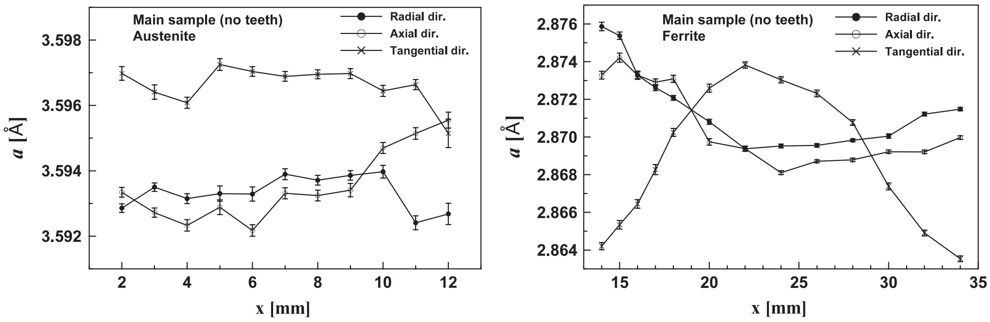

Figure 2. Radial distribution of the lattice parameters of the austenite (left) and ferrite (right) phases in the radial, axial and tangential directions.

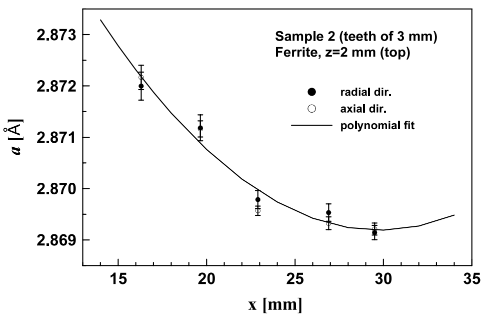

Figure 3. Radial distribution of the ferrite lattice parameter of the comb at the top of the teeth.

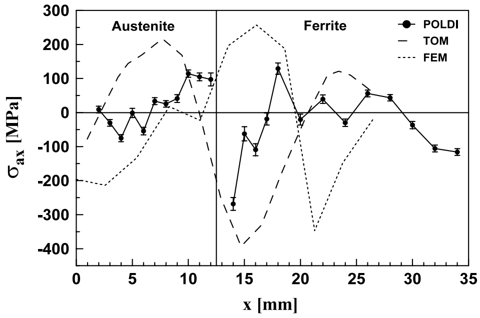

Figure 5. Radial distribution of the residual stress in the axial direction.

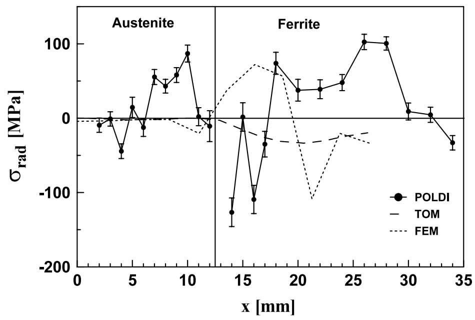

Figure 4. Radial distribution of the residual stress in the radial direction.

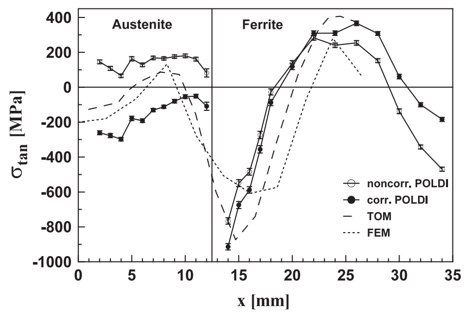

Figure 6. Radial distribution of the residual stress in the tangential direction.

the lattice parameter obtained by averaging the comb-sample results under radial and axial directions and then a polynomial fitting of the averaged experimental points (figure 3).

Unfortunately, the lattice parameter of the comb-sample in the tangential direction was not measured for lack of beam time. Therefore, we cannot assert with certainty about a full stress relief in the comb-sample. However, the elastic anisotropy analysis of the selected diffraction peaks has shown that, although the dependence of the lattice parameter a_{hkl} in the teeth tops of both phases versus the anisotropy factor $G = (h^2k^2 + h^2l^2 + k^2l^2)/(h^2 + k^2 + l^2)^2$ had a noticeable scattering of the experimental points, on the whole, we can ascertain the practical absence of a slope in the anisotropy curves. This could point to the almost complete relief of the residual macrostresses in the comb-sample. The observed radial dependence of the ferrite lattice parameter in the comb-sample (figure 3) can be put down to a variation of the chemical composition, especially, carbon content. The residual stress tensor components in the composite tube calculated in these assumptions are presented in figures 4–6 in comparison with the FEM and TOM results.

As the ND data were obtained for a small part of the composite tube they have to be corrected for the stress released during the cutting procedure. Assuming that the released stress (table 1) varied linearly over the interval from the outer to the inner edge of the tube and that the radial component did not change essentially during cutting, the residual stresses in the whole tube can be predicted from the ND data. The corrected

ND results for the tangential component are shown in figure 6. The results in the austenite phase had the greatest correction for the stress relief, but the same correction has not introduced the principal changes in the ferrite phase. The ND results for the radial and axial directions were also corrected for stress relief but the corrected results are not shown in figures 4 and 5 as the corrections were insignificant.

4. Discussion

The presented methods have shown that the results for the radial direction (figure 4) completely contradict each other. The radial stress component related to the TOM was not directly determined, but calculated from a condition of the balance of forces with use of the TOM results for two other stress components. A less contradictory picture is observed for the axial direction (figure 5). Note that the TOM and FEM dependences for the axial direction are shifted to about 5–6 mm, where the peak values of the axial stresses are nearly equal. The ND results correspond better with the TOM data, especially near to the interface between the austenitic and ferritic parts of the composite tube where both experimental methods show a compressive stress of 300–400 MPa in the ferrite phase. Only for the tangential direction can we establish a semiquantitative agreement of the results of all the presented methods, especially, for the ferritic phase (figure 6). For the austenitic phase, some disagreement is certainly related to the uncontrollable influence of microstresses of the II type on the results of the ND measurements. As is visible from figure 6, the cladding produced a compressive tangential stress of about 800 MPa close to the interface. Thus, the ND measurements have appeared useful by giving essentially new information on the compressive stress in the axial direction and by confirming data on the compressive stress in the tangential direction for the ferrite phase.

Comparison of the curves in figures 4–6 clearly shows a reason for the qualitative agreement of the results of the difference calculation of the radial and tangential stress components from the ENGIN data with the FEM and TOM results. In reality, the tangential stress component prevails over two others, namely, for it we have noticed qualitative agreement of all the methods with each other.

5. Conclusion

The present study has demonstrated the application of the time-of-flight neutron diffraction, realized on the POLDI stress-diffractometer at the SINQ neutron spallation source, to measure the triaxial residual stresses in the composite tube from austenitic stainless steel with ferritic steel cladding fabricated by the welding overlaying technique.

The comb technique was applied to evaluate the phase stress free lattice parameters for the residual stress calculations. A clear indication of the radial dependence of the ferrite stress free lattice parameter was obtained. We attribute this dependence to non-uniform redistribution of the chemical composition during the welding process, namely, fixed carbon. Triaxial residual stresses were revealed in the composite tube using the comb-sample lattice parameter results.

Comparison of the stress results from the POLDI measurements with the FEM and TOM results has shown that there was a semiquantitative agreement among all of the used methods only for the tangential direction. For two other stress components, the contradictions between these methods were strong, especially, for a weak radial component. A strong compressive tangential residual stress of about 800 MPa was observed in the ferrite cladding close to the interface between the parent tube and the cladding. The cladding has created a smaller but quite sufficient tangential compressive stress in the austenite phase, which can prevent stress corrosion of the austenite layer in service.

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