Stress Distributions in P91 Martensitic Steel and in AISI 316LN Steel Welds for Gen IV Nuclear Applications

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Abstract—Neutron diffraction has been used to investigate the stress field in two different welds developed for nuclear applications, namely those obtained by tungsten inert gas welding of P91 martensitic steel (Cr 9, Mn 6, Mo 1, C 0.1, and Fe bal wt %) and hybrid (laser beam and gas metal arc) welding of AISI316LN austenitic steel (17.8 Cr, 12.3 Ni, 1.7 Mn, 2.4 Mo, 0.3 Si, and Fe bal wt %). The sizes of the investigated samples were 100 × 50 × 12 mm for the P91 weld and 220 × 160 × 15 mm for the 316LN weld; unstrained references were prepared for both welds. The neutron diffraction measurements have been carried out utilizing the E3 diffractometer at the BER II reactor in Berlin, with a gauge volume of 2 × 2 × 2 mm³. Lines perpendicular to the weld direction were scanned at different depths inside the material and at different distances from the weld centerline, including the heat affected zone and the weld centerline. Strain and stress values were determined in the three principal directions. In the TIG P91 weld, the stresses are almost completely relieved after a post weld heat treatment for 2 h at 760°C. In the laser beam and gas metal arc 316LN weld not submitted to post weld heat treatment, nearly balancing longitudinal and transverse stress components as high as 300–350 MPa are found within a range of approximately 3 mm around the centerline of weld.

Keywords: neutron diffraction, stress measurements, nuclear welds
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INTRODUCTION

The availability of advanced welding procedures constitutes a crucial pre-requisite in the development of safe and sustainable Gen IV reactors, where structural components including a large number of welds will be simultaneously exposed to high temperature, high neutron irradiation doses and aggressive environment [1–4]. In fact, the failure in metallic components occurs very often in and around welds; therefore, their integrity is critical for the safe performance of nuclear components. It depends on a number of factors, such as residual stresses, mechanical properties of the weld, base material and heat affected zones, as well as geometrical factors which also depend on the basic material properties and on the welding process. Therefore, it is clear that the bulk characterization of nuclear welds is much more complicated than for base materials and that neutron diffraction is indispensable for such investigations [4–6].

This contribution presents experimental results obtained by neutron diffraction of the stress distributions present in two different model welds for nuclear application. These welds were produced in the frame of the European grant MATTER (MATerials Testing and Rules) [7] focused on the definition of experimental protocols for nuclear materials and components and further characterized in the frame of European research program on nuclear materials EERA JPNM (European Energy Research Alliance Joint Program Nuclear Materials) [8]. The first tungsten inert gas (TIG) weld of P91 martensitic steel has been selected from a series of similar welds prepared to investigate systematically the effectiveness of various post weld heat treatments in reducing the residual stresses and improving the mechanical properties. The second AISI316LN austenitic steel hybrid (laser beam and gas metal arc) (LB–GMA) weld has been prepared with the multiple aim of obtaining narrower heat affected zones, reducing distortions and producing less severe thermal cycles with respect to conventional welding techniques. The two different steels were selected taking into account the different function of the respective welds, particularly the higher resistance of P91 steel to radiation damage. Both samples have been characterized by standard metallography, microhard-
improving the design of nuclear components.

The effectiveness of the adopted welding procedures is conclusive, but as a first necessary step for understanding the results presented below should not be considered as absolute and metallurgical treatments. Therefore, the sample to another, even for identical chemical composition and microstructure, demonstrates microstructural differences from one another, despite the standardization of welding procedures, can be noted that the studied welds are quite complex and, different welds and materials, but rather as two separate contributions provided by neutron diffraction to different milestones of the MATTER Project. It is also noted that the studied welds are quite complex and, despite the standardization of welding procedures, can demonstrate microstructural differences from one sample to another, even for identical chemical composition and metallurgical treatments. Therefore, the results presented below should not be considered as conclusive, but as a first necessary step for understanding the effectiveness of the adopted welding procedures in improving the design of nuclear components.

**SAMPLES CHARACTERIZATION AND EXPERIMENTAL TECHNIQUE**

The chemical composition of the base metal in the studied TIG weld of P91 martensitic steel is the following: Cr 9, Mn 6, Mo 1, C 0.1, and Fe bal wt %. The size of the sample is 100 × 50 × 12 mm. It was welded in one pass of TIG with 60° chamfer, and then submitted to 2 h at 760°C. After heat treatment, a decrease in hardness and mechanical testing [9, 10]. The neutron diffraction measurements were carried out to obtain distributions of bulk averaged residual stresses, necessary to predict the weld resistance to fatigue cracking, which cannot be obtained by other experimental methods. It is emphasized that the joint presentation of stress measurements of two such different samples should not be considered as a comparison of two different welds and materials, but rather as two separate contributions provided by neutron diffraction to different milestones of the MATTER Project. It is also noted that the studied welds are quite complex and, despite the standardization of welding procedures, can demonstrate microstructural differences from one sample to another, even for identical chemical composition and metallurgical treatments. Therefore, the results presented below should not be considered as conclusive, but as a first necessary step for understanding the effectiveness of the adopted welding procedures in improving the design of nuclear components.

![Fig. 1. Microhardness measurements as a function of the distance from the weld centerline in the P91 TIG weld (1) before and (2) after post weld heat treatment for 2 h at 760°C.](image)

Reference to [11] and to previous publications [5, 6] is made for description of strain and stress measurements by means of neutron and X-ray diffraction. The neutron diffraction measurements were carried out at room temperature utilizing the E3 diffractometer, installed at the BER II reactor [12]. A Si(400) monochromator was used providing a neutron wavelength \( \lambda = 1.47 \text{ Å} \). A diffracting volume of 2 × 2 × 2 mm\(^3\) was selected to optimize counting time, metallurgical significance and benchmarking with future numerical simulations. For the martensitic body-centered cubic P91 steel weld the 211 reflection was exploited at a Bragg angle \( 2\theta \approx 78.8° \). The 311 reflection of the austenitic face-centered cubic 316LN steel was exploited at a Bragg angle \( 2\theta \approx 85.5° \). The strains were measured in three independent directions, namely longitudinal, transverse and normal with respect to the weld. The reference comb-like sample was glued to the welded sample in correspondence with the points selected for the stress mapping. This comb-like sample is shown in Fig. 3. Thus, reference stress measurements were made for each selected location in the welded sample in order to account for possible variations in local chemistry and microstructure as a result of welding.

The chemical composition of the base metal in the studied LB–GMA weld of AISI 316LN austenitic steel is the following: Cr 18, Ni 12, Mn 1.7, Mo 2.4, C 0.03, and Fe bal wt %. The size of the sample is 220 × 160 × 15 mm; its transverse cross-section around the weld is shown in Fig. 4. Bohler Thermanit 19/15 was used as filler material. The weld was not subjected to any post weld heat treatment; therefore, high stress gradients near the welded region should be expected. The weld was distorted by approximately 5.8°, as shown in the cross-section (Fig. 5a). The comb-like reference sample with eroded coupons (Fig. 5b) was also obtained by cutting a 6 mm thick slice from the welded sample.

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![Fig. 2. Optical micrography observation of P91 TIG weld. HAZ is heat affected zone.](image)
An overview of the stress mapping obtained for the TIG weld of P91 steel is shown in the 2D plots (Fig. 6). These stress values have been obtained by measuring approximately 2 mm inside the welded samples in the positions shown in Fig. 3, so that each eroded coupon could serve as a guide for the corresponding point inside the weld. For the ferritic P91 weld, the reference variation in all measurements (parent and weld region) was $2\theta = 77.665^\circ \pm 0.005^\circ$ which corresponded to $\pm 17$ MPa. The full width at half maximum of the peak (FWHM) increases by 11% in the weld region compared to the parent material. The 1D plot (Fig. 7) shows the stresses as a function of the distance from the weld centerline, measured along a line close to the weld cap; similar trends are found for 1D plot at different depths with respect to the weld cap. Very low stresses, comparable with the experimental uncertainty, are found to be homogeneously distributed throughout the weld. A measurement of the stresses in this same weld before post weld heat treatment would be necessary to make a more general assessment. However, these results show that in the sample after treatment for 2 h at 760°C the stress field is perfectly compatible with the engineering requirements and expected service conditions.

In the sample of LB–GMA weld of 316LN steel, the stresses were determined at 11 different distances from the weld centerline and at three different heights from the weld root, both in the straight and in the distorted side of weld and reference sample. The bending of the distorted side was corrected for 5.8°. The stresses were determined assuming zero longitudinal stresses in the reference sample and zero normal stresses in the welded sample: the agreement of the corresponding reference values is good, which means that such assumptions are correct. In fact, the reference sample was a slice cut perpendicular to the longitudinal direction of the weld. It was expected that the out of plane stress in the slice (weld longitudinal direction) will be very low, close to zero, and therefore a zero normal stress could be assumed. Similarly, the actual weld has the shortest dimension in the weld normal direction, being geometrically a plate. The normal stress is usually very small, close to zero in this direction in the geometrical configuration of this type. The variation in the austenitic 316LN weld reference was typically $2\theta = 85.450^\circ \pm 0.007^\circ$ in the parent region which corresponds to $\pm 19$ MPa. The reference value was very different in the weld region, usually around $2\theta = 85.18^\circ$. The FWHM of the peak increases by about 15% in the weld region compared to the parent region.

The stress profiles measured at the weld cap, in the middle length and at the weld bottom are shown in Fig. 8. The measurements were affected by some addi-
Fig. 5. (a) Cross-section of LB–GMA weld of 316LN steel and (b) comb-like unstrained reference sample.

Fig. 6. 2D stress mapping (X and Y axes are defined as in Fig. 3) for P91 TIG weld: (a) transverse stresses, (b) normal stresses, (c) longitudinal stresses measured at a depth of approximately 2 mm. A vertical line indicates the weld centerline.
tional uncertainty due to a grainy microstructure inside the weld, which is the reason for some higher values of the error bars. It is anyhow clear that in the absence of a suitable post weld heat treatment, the more innovative welding procedure applied to this steel can produce complex and relatively high stress distributions, especially in the mid-thickness line (Fig. 8b), with longitudinal tensile stresses as high as 300 MPa partly compensated by transverse compression.

**DISCUSSION AND CONCLUSIONS**

The obtained results show once more the capability of neutron diffraction to provide bulk averaged stress distributions in complex welds, including the heat affected zone and the centerline of the weld. In fact, uncertainties relating to metallurgical phase inhomogeneity in these regions are strongly reduced by the method selected for preparing comb-like reference samples perfectly coinciding with the original weld, as described above. A more detailed study of such critical regions, heat affected zone, and weld centerline requires a resolution of the Bragg peaks significantly exceeding the resolution available for such experiments, in order to attempt a profile analysis and obtain information on phase changes as a function of depth inside the weld.

These results provide a useful contribution to the development of protocols for nuclear welds. Namely, the P91 TIG welds were designed to be as stress-free as possible and this is now confirmed, at least for the test sample. The stress distributions obtained for the LB–GMA weld will help in adjusting the parameters of the welding procedure in view of improving its quality and performance in service. Obviously, a larger number of samples of the two model welds should be studied to obtain broader and more general information. Other microstructural investigations are currently in progress using destructive or semi-destructive techniques (transmission electron microscopy, small punch test, contour method) to complete the characterization of these welds and compare them with the neutron diffraction results. Numerical simulations of the stress distributions will also be carried out to compare with the experimental ones.
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