Comparison of welding induced residual stresses in austenitic andferritic steel weld joints

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Abstract

X-ray diffraction (XRD) based stress measurement is a well established technique for determination of residual stresses in components and is being widely used. In XRD technique, the distance between the crystallographic planes ('d' spacing) is measured at various ψ angles, where ψ is the angle between the normal of the sample and the bisector of the incident and diffracted beam. The two theta peak positions at each ψ tilts are accurately determined. From the slope of $\sin^2\psi$ vs. 2θ peaks/'d' spacing plot, the residual stresses are arrived by assuming a plane stress model.
Manufacturing processes like grinding, machining, shot peening, welding, cold work etc., introduces varying levels of residual stresses on the surfaces of the components. Welding induced residual stresses is of high importance as it's a major cause of failure in components. However, the compressive stresses on the surface improve the fatigue strength whilst the tensile residual stresses are undesirable and tend to decrease the fatigue strength. The present study compares the residual stresses that develop in 4 mm thick SS 304L and 3 mm thick P91 TIG weld joints using XRD technique. This study is aimed at understanding the influence of phase transformation that occurs in P91 steel during cooling of the weld pool. The development of residual stresses with respect to the volume changes taking place during phase transformation from austenite to martensite is addressed here.
Stress measurements on SS 304Land P91 were carried out using Cr Kβ(λ-2.0840 Å) and Cr Kα (λ-2.2896 Å) radiations respectively. The longitudinal residual stress profile observed across the weld centre line in both these welds would be discussed.

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1. Introduction

Residual stresses (RS) are the stresses that get introduced during manufacturing processes such as cutting, cold work, welding, grinding, shot peening etc.,Generally, tensile residual stresses on surfaces are undesirable as they decrease the fatigue strength. However, compressive stresses on surfaces improve the fatigue strength. Welding related stresses are of utmost importance and can

be a major cause for failure of components. The factors influencing the RS profiles in a weld joint are heat input, type of welding, pre-heating, thickness, electrode, weld groove design and properties of base metals. The stresses that are introduced during welding process are influenced bythe non-uniform heat distribution taking place during the welding process and the final distortion that is achieved after the constraints (if any) are removed. Additionally, in ferritic steels, phase transformation occurs when the weld pool cools from liquid state to solid, initially as austenite (fcc) later transforming to ferrite(bcc). This change in structure causes an increase in volume. This study tries to compare the residual stresses that develop in steels with bcc and fcc crystal structure. For this study, Modified 9Cr-1Mo ferritic steel (grade 91) and stainless steel SS304 are chosen. In the former, during cooling phase transformation takes place which is absent in the later.
Modified 9Cr-1Mo ferritic steel (grade 91) is extensively used in fabrication of high temperature components power plants and petrochemical industries due to its improved high temperature creep strength coupled with good thermal conductivity, low thermal expansion coefficient and immunity to stress corrosion cracking in aqueous and chloride environments [1].Similarly, SS 304L is used in nuclear industry as a structural material of various components [2].

2. Experimental

2.1 Sample details

Two modified 9Cr-1Mo steel plates of dimensions 125 mm × 300 mm × 3 mm were used to prepare a weld pad of dimension 300 mm x 240 mm x 3 mm using a heat input of ~ 600 J/mm. To compare the residual stress that develops in steels where phase transformation does not take place during cooling, two AISI type 304L stainless steel plates (thickness 4mm) of width 75 mm and length 150 mm were welded together autogenously by usinga heat input of 640 J/mm. The welding parameters are shown in Table 1. The other weld parameters like pulse on time was maintained at 40% with flow rate of argon fixed at 14 l/min across all the samples. Additionally, two more SS 304L plates were welded at a lower heat input of 480 J/mm and another at a level of 800 J/mm for comparison.

Table 1.Gas Tungsten Arc Welding parameters used for welding

Material	**P91**	**SS 304L**
Weld joint Dimension (mm)	*300×250×3*	*140×75×4*
Heat Input (J/mm)	*591*	*640*

2.2 Residual stress measurements

Residual stress measurements were carried out using a portable X-ray stress analyzer (RigakuStrainflex MSF-2M). This instrument has a back reflection type goniometer with a 2θ scan range from 140° to 170° having parallel beam geometry. The X-ray diffraction (XRD)intensity profilesat each of the measurement locations wereobtained at various ψ angles, which is defined as the angle between the diffraction vector and specimen normal. The obtained data is corrected for background and absorption. The peak 2θ values are obtained at various ψ angles by suitable peak fitting algorithms. From the slope of $\sin^2\psi$ *vs* peak 2θ or d plot, the residual stress is determined based on equation 1 which is given as

$$\sigma = \left(\frac{E}{1+\nu}\right)_{(hkl)} \frac{1}{d_0} \left(\frac{\partial d_\Psi}{\partial \sin^2 \Psi}\right) \qquad (1)$$

where E and ν denote the Young's modulus and Poisson's ratio [3,4]. At all the identified locations of measurements, two sets of measurements were carried out and the values reported are averaged stress values based on the combined analysis of the change in the peak location with varying ψ. The residual stress measurements were carried out along the longitudinal direction on the welded plate across the weld joint using the experimental parameters listed in Table 2.A Young's modulus of 210 GPa for P91 and 196 GPa for SS 304L was used.

Table 2. Experimental parameters used for residual stress measurements

Material	P91	SS 304 L
Operating Voltage	*30 kV*	*30 kV*
Current	*7 mA*	*7 mA*
X-ray radiation	*Chromium* K_α	*Chromium* K_β
Wavelength	*2.2896 Å*	*2.0848 Å*
ψ range	*0˚ to 45°*	*15.5˚ to 55.75°*
2θ range	*151°-162°*	*142°-154°*
StepWidth	*0.2°*	*0.2°*
DwellTime	*3 s*	*8 s*
Aperture	*2×4* mm^2	*2×4* mm^2
Filter	*Vanadium*	*No Filter*
Soller slit	*1 °*	*1 °*
Plane	*(211)*	*(311)*

3. Results& discussions

3.1 P91 weld pad

XRD based longitudinal residual stress measurements were carried out based on procedures mentioned in §2.2. The variation of peak 2θ with $\sin^2\psi$ at 10 mm from the weld centre (WC) and 50 mm from WC (which is the parent material) of P91 weld pad is shown in Fig. 1. The linear nature of this plot shows that the plane stress model (based on equation 1) used to estimate the stresses is valid and there is no gradient of stress in the sampled volume. A higher (magnitude) negative slope is observed at 10 mm (black line) indicative of high tensile residual stress (RS) level at this location. Far away from the WC, i.e., in the parent material, the residual stresses are compressive (positive slope) as indicated by red line.

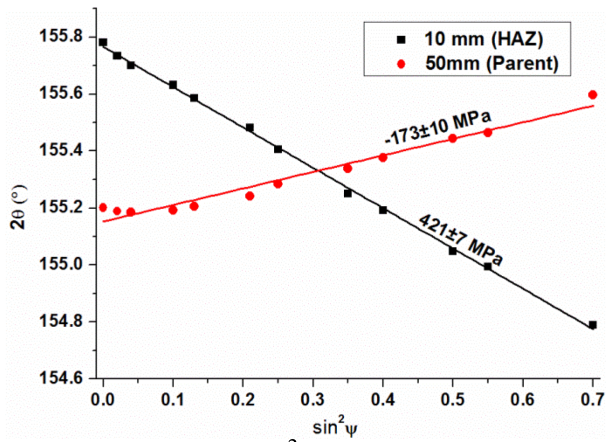

Fig. 1 Variation of peak 2θ location with $\sin^2\psi$ at 10 and 50 mm from WC in P91 weld pad

The variation of longitudinal residual stresses across the P91 weld pad is shown in Fig. 2. At the WC of the P91 weld, tensile RS of ~270 MPa was observed. At 10 mm from the WC, peak tensile RS of 560 MPa was observed. In the parent material, at 50 mm from the WC, compressive residual stresses of 170 & 150 MPa were observed on either side. The residual stress profile across the weld pad is found to be asymmetric. This may be attributed to the errors involved in the heat source moving marginally away from the line bifurcating the two plates or due to the measurement location being not exactly at the WC. The WC is identified based on the centre of the visible bead width. The residual stress profile shows typical M profile indicative of reduction in RS at the WC due to the phase transformation that occurs during cooling of the weld pool. The measured stress profile is found to be in agreement with the results from finite element modeling and the details of the thermo-mechanical analysis carried out are discussed elsewhere [5].

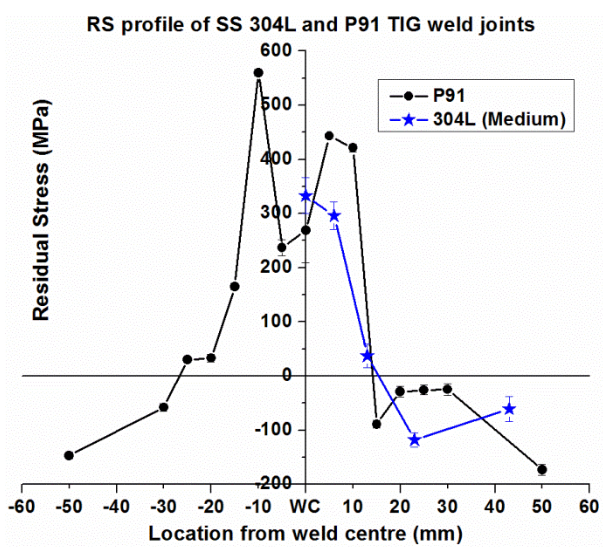

Fig. 2 Variation of longitudinal residual stress across the P91 and SS 304 L weld joint

3.2SS 304L weld pad

Though thickness of the material plays a key role in the final residual stress that is achieved, to study the influence of phase transformation, 4 mm SS 304L weld pad is chosen and compared with the results obtained with 3 mm P91 weld pad. It is to be noted that the heat input used in these two weld pads are comparable with each other as shown in Table 1. The variation of longitudinal RS with distance from the weld centre is shown as blue stars in Fig. 2. The weld profile shows typical inverted V profile with peak stresses of 325 MPa being found in the weld centre. This is indicative of shrinkage induced stressescaused by the differential shrinkage between the weld pool and the parent material which is close to the weld pool.

3.3Comparison of RS profiles

A comparison of the RS profiles between the two weld pads shows that the stress affected zone extends up to 12 mm in both the weld pads which is due to the similar heat inputs adapted for these two weld joints. However, significant reduction in the RS is observed in the heat affected zone (HAZ) which is ~5 mm from WC ofSS 304L weld pad, as compared to the peak RS of 500 MPa observed in the HAZ of P91 weld pad. Zubairuddin et al. [6] had carried out simulations on the influence of phase transformation on RS developmentin P91 welds and concluded that magnitude of RS reduces substantially at the WC, whereas the reduction is marginal in the HAZ. The results presented herein are in confirmation with these observations.

In SS 304L, the magnitude of RS measured at the WC is lower than that observed in P91 weld pad. This is attributed to the higher thermal expansion coefficient and lower conductivity of SS 304 L. A value of 300 MPa has been reported at the WC for 3 mm thick 316 LN weld pads studied experimentally and from models [7]. Since heat input plays a significant role in modifying the cooling rate, thereby influencing the RS that develops, additional measurements on SS 304L weld pads welded at lower and higher heat inputs as discussed in §2.1 were carried out. The RS at the WC and the average RS which is RS-at-WC/2+RS-at-HAZ/2, of these 3 SS 304 L plates are shown in Fig. 3 along with that of the P91 weld pad. The open legends in Fig. 3 indicate the average RS across the weld. It is clear from Fig. 3 that lower heat inputs show higher levels of RS due to the faster cooling causing higher levels of RS. However, the stress levels are around 320 MPa in all the weld pads except in the 304 L weld pad prepared at lower heat input.

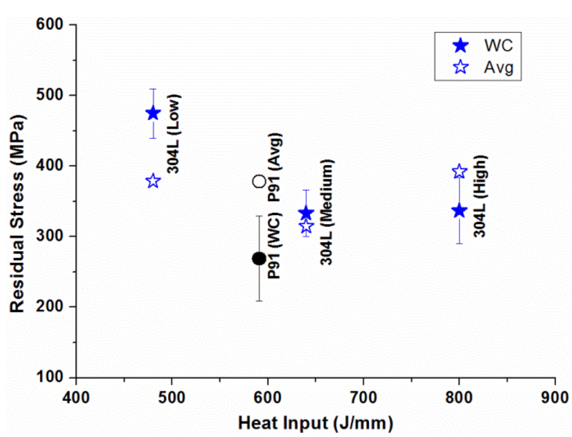

Fig. 3 Variation of residual stress with heat input in SS 304 L and P91 weld pad (filled symbols are indicative of measurements at WC whereas open symbols are for average stress)

4. Conclusion

- Comparison of RS that develops in equivalent thickness ferritic P91 and austenitic SS 304 L weld pads reveals that phase transformation reduces the peak stresses at the weld centre in ferritic steel leading to M type profiles.
- The comparison presented herein shows that the extent of RS affected zone remains uniform in both ferritic and austenitic weld pads. The magnitude and profile vary.
- The average of stresses at the weld centre and HAZ remain same for similar heat input welds.
- The measured RS is in agreement with results obtained from finite element modeling as shown in literature.

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