

Results and Discussion of Residual Stress Analysis

This chapter provides details of the residual stress analysis carried out on the P92/304L dissimilar weld joint (DWJ) using deep hole drilling (DHD) technique. The through thickness residual stress was investigated for weld fusion zone and heat affected zone (HAZ).

6.1 Residual stress analysis for P92-Thermanit MTS 616-304L dissimilar weld joint

The DHD technique is a well-established method for measuring the welding-induced residual stresses. The DHD method is a semi-destructive method of measurements of residual stress. The DHD method was employed to measure the through-thickness welding residual stresses in the center of the weld fusion zone and the HAZ of P92 and 304L in as-weld (AW) and post weld heat treatment (PWHT) condition. The P92/304L DWJ prepared for longitudinal and transverse residual stresses assessment in through-thickness direction using DHD method is shown in Figure 6.1.

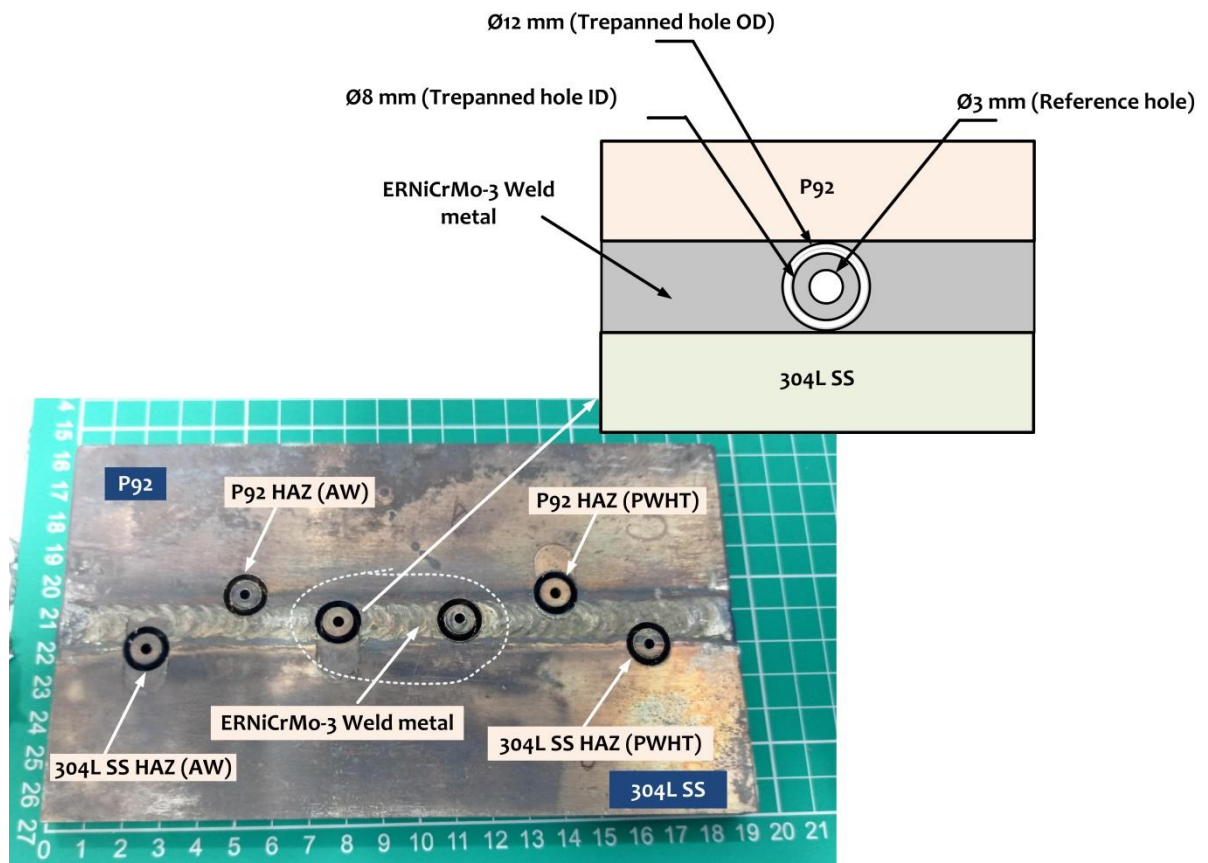


Figure 6.1: P92/304L DWJs prepared for the residual stress analysis using DHD technique

Figure 6.2(a-c) and Figure 6.3(a-c) show the longitudinal and transverse residual stress distribution for V and narrow groove geometry P92/304L DWJ prepared using

Thermanit MTS 616 filler, respectively. From the residual stress profile for both V and narrow groove geometry, it can be concluded that longitudinal and transverse residual stress of compressive nature was observed for the Thermanit MTS 616 filler weld fusion zone. The compressive stresses were confined in the weld fusion zone because of the martensitic transformation of the Thermanit MTS 616 filler. The volume shrinkage effect due to the weld solidification and volumetric expansion due to the martensitic transformation of the weld are the two main factors that govern the nature of the welding induce residual stresses. The volume shrinkage effect due to the weld solidification induces the tensile residual stresses in the weld metal, while the volumetric expansion due to the martensitic transformation of the weld induces the compressive residual stresses in the weld metal. When P92 steel is heated above lower critical temperature (A_{c1} temperature) during welding, its body-centered cubic (BCC) structure transforms into a face-centered cubic (FCC) structure, during this volume decreases. When it is cooled, its FCC structure transforms into a body-centered tetragonal (BCT) structure, during this volume increases (Figure 6.4). This volumetric change causes the yield strength changes. This yield strength changes cause a change in residual stress magnitude and alter the sign of residual stresses (Deng and Murakawa, 2006a). In the present case, weld fusion zone was made of the martensitic filler, thus volumetric expansion due to the martensitic phase transformation was more dominant. This induces the compressive residual stresses in the weld fusion zone and P92 HAZ. After PWHT also, the compressive residual stresses were observed in the weld fusion zone and P92 HAZ. From the residual stress distribution for weld fusion zone, it can be stated that maximum longitudinal and transverse residual stresses were developed at the top surface of weld metal. For the Thermanit MTS 616 filler weld fusion zone of the V groove geometry, the maximum longitudinal compressive residual stress of 306 MPa was observed at the top surface of the weld and up to 5 mm. For the Thermanit MTS 616 filler weld fusion zone of narrow groove geometry, the maximum longitudinal compressive residual stress of 252 MPa was observed at the top surface of the weld. After PWHT for the Thermanit MTS 616 filler weld fusion zone of the V groove geometry, the maximum longitudinal compressive residual stress of 203 MPa was observed at the top surface of the weld. The high volume of the weld at the top of the V-groove design develops high residual stresses at the top surface of the weld. The less volume of the weld at the mid-section and root of the V and narrow groove geometry develop less residual stresses at the root and mid-section. After PWHT for the Thermanit MTS 616 filler weld fusion zone of narrow groove geometry, the maximum longitudinal compressive residual stress of 162 MPa was observed at the top surface of the weld. Similar kinds of trends were observed for the transverse residual stresses. Thus, it can be concluded that PWHT and narrow groove geometry minimizes the welding-induced residual stresses. However, the nature of residual stresses was almost the same before and after PWHT.

Also, for the P92 HAZ and 304L HAZ, the magnitude of the welding induced longitudinal and transverse residual stresses for the narrow groove geometry was less than the V-groove geometry in the AW state and after PWHT. For the P92 HAZ, longitudinal and transverse residual stress of compressive nature was observed for both the groove profile. It was observed that PWHT resulted in the significant minimization of the welding induces residual stresses. However, the nature of residual stresses was very much similar before and after PWHT. For the 304L HAZ, longitudinal and transverse residual stress of tensile nature was observed for both the groove profile. The tensile residual stresses are more detrimental as they may lead to the crack initiation and sudden fracture of the component (Woo et al., 2013). The high tensile residual stresses are developed in 304L due to its low thermal conductivity, heat transfer rate, and high co-efficient of thermal expansion. Due to the absence of the phase transformation in the 304L, the residual stresses were observed very much of the same nature before and after PWHT.

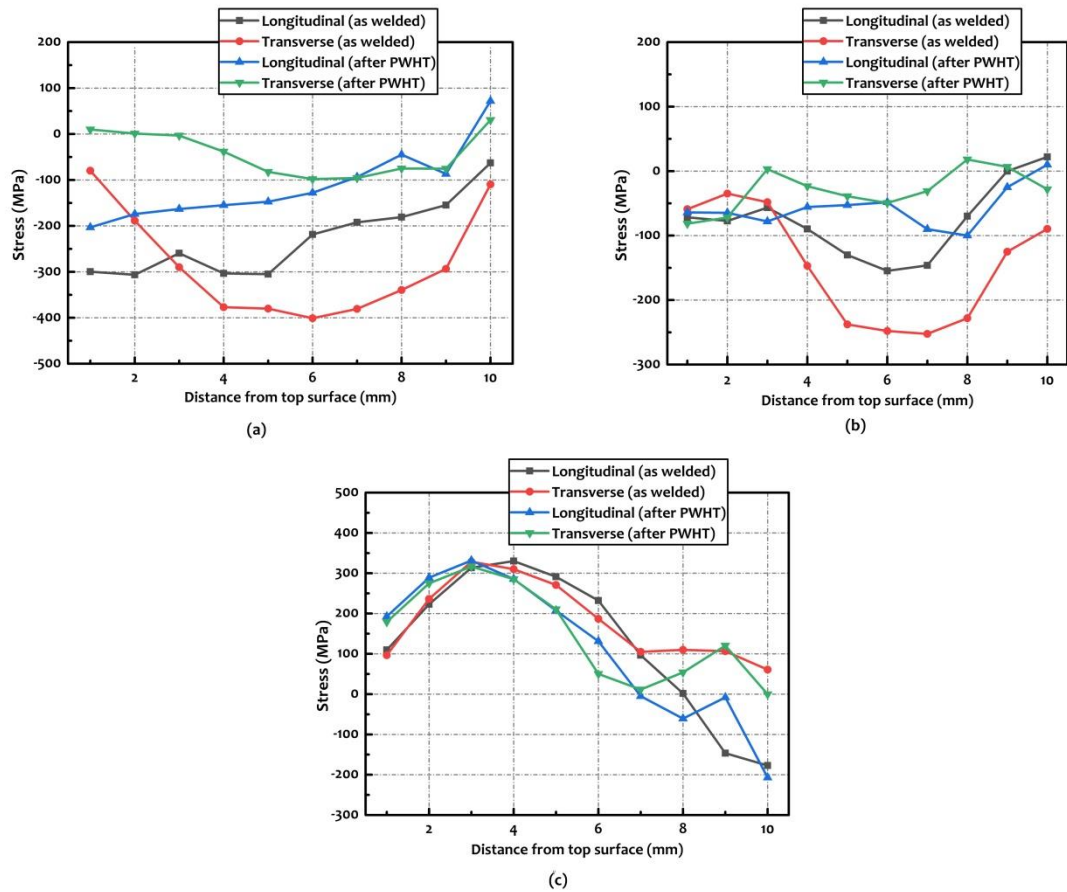


Figure 6.2: Distribution of welding induced residual stresses in AW and PWHT condition for (a) Thermanit MTS 616 weld fusion zone (b) P92 HAZ and (c) 304L HAZ for V-groove geometry

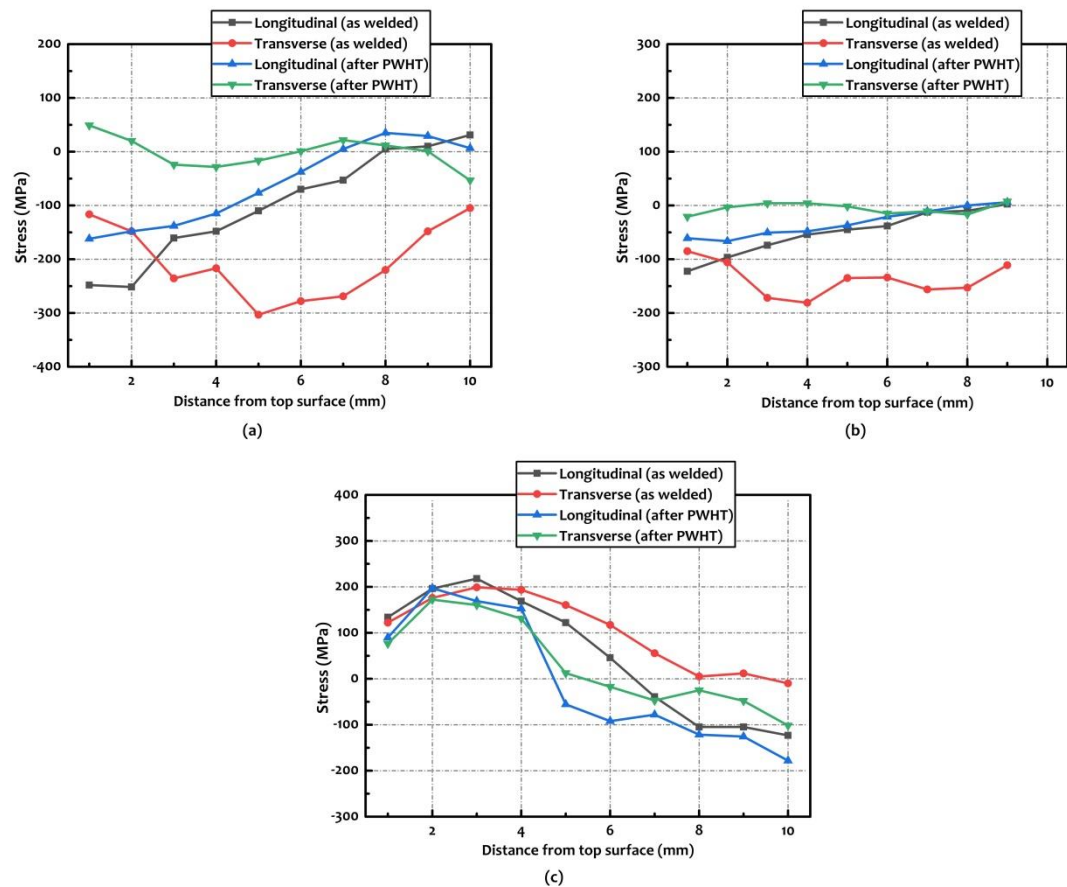


Figure 6.3: Distribution of welding induced residual stresses in AW and PWHT condition for (a) Thermanit MTS 616 weld fusion zone (b) P92 HAZ and (c) 304L HAZ for narrow groove geometry

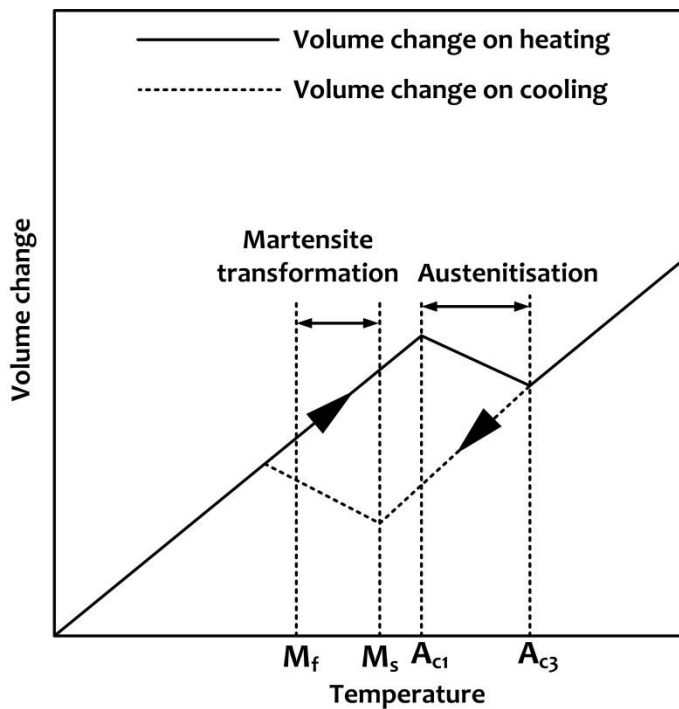


Figure 6.4: Schematic of volume change due to austenite and martensite phase transformations (Hyde et al., 2009)

6.2 Residual stress analysis for P92-ERNiCrMo-3-304L dissimilar weld joint

Figure 6.5 (a-c) shows the contour of the welding induced residual stress in AW and after PWHT condition for P92-ERNiCrMo-3-304L DWJ. The peak longitudinal and transverse residual stress magnitude at the weld fusion zone in AW condition reached 287 and 188 MPa, respectively, at a depth of nearly 3 mm from the top surface of the weld as shown in Figure 6.5 (a). After PWHT, significant reductions in the peak residual stress magnitudes were observed in the longitudinal (75%) and transverse (53%) directions. In the P92 HAZ, the longitudinal and transverse residual stress magnitudes at the top surface were found near the neutral axis. Volumetric changes attributed to the phase transformation of the P92 steel struggle to impose compressive residual stresses. In the present scenario, the anticipated tensile residual stress fields at the HAZ of the P92 got balanced with the volumetric changes due to phase transformation, and significantly lesser residual stress fields were observed, Figure 6.5 (b). However, after PWHT, the volumetric changes got boosted due to grain growth, leading to increased compressive longitudinal residual stress magnitudes at the upper half of the P92 HAZ. On the other hand, after PWHT, the transverse residual stress magnitude in the P92 HAZ increased at the top surface. It is a known fact that the coefficient of thermal expansion of the ERNiCrMo-3 filler is comparatively higher than the P92 steel. So, the ERNiCrMo-3 weld fusion zone, which was previously held in tension in the AW condition, exhibits higher thermal contraction during stress relaxation following PWHT. Thus, the P92 HAZ adjacent to the ERNiCrMo-3 weld fusion zone experiences tension towards the weld material in the transverse direction after PWHT. This can be a potential reason behind the increased transverse residual stress fields at the top surface of the P92 HAZ after PWHT. In the 304L HAZ, it can be observed that the peak longitudinal residual stress was found to be crossing the yield limit. Here, one thing needs to be noted that during the DHD operation at the HAZ, the core column containing the reference hole also covers some portion of the weld material. As the ERNiCrMo-3 filler weld possesses higher yield strength than the 304L, the high magnitude of residual stresses at the weld fusion zone actively influences the

maximum residual stress fields of the 304L HAZ. The maximum transverse residual stress value was 208 MPa, obtained at a depth of 4 mm from the top surface in the 304L HAZ in AW condition. After PWHT, the 304L HAZ exhibited a 35% and 27% decrease in the peak longitudinal and transverse residual stress magnitudes, as shown in Figure 6.5 (c).

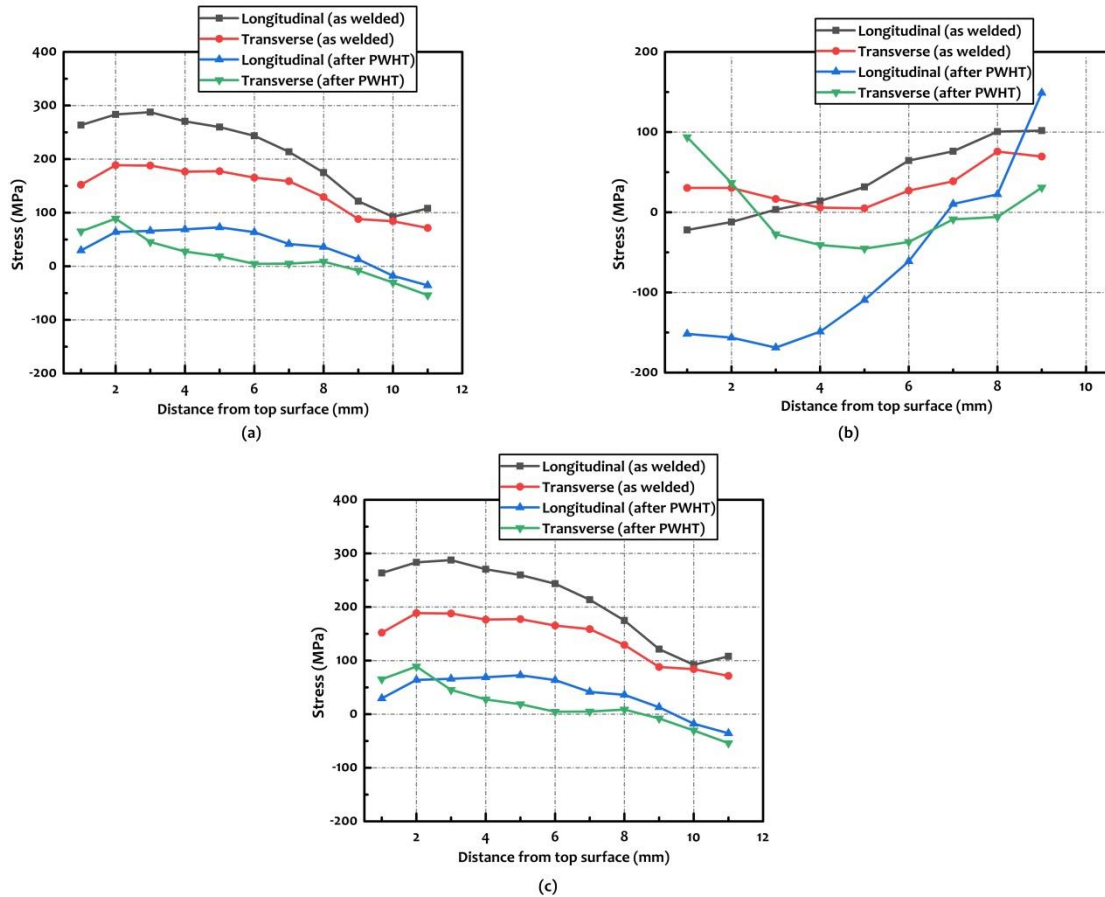


Figure 6.5: Distribution of welding induced residual stresses in AW and PWHT condition for (a) ERNiCrMo-3 weld fusion zone (b) P92 HAZ and (c) 304L HAZ for V-groove geometry

For narrow groove profile, the through-thickness residual stress distribution in AW and PWHT condition for the ERNiCrMo-3 weld fusion zone, P92 HAZ, and 304L HAZ is shown in Figure 6.6(a-c). The peak longitudinal residual stress of magnitude 269 MPa was observed at a depth of 3 mm for the weld fusion zone. The longitudinal residual stress of tensile nature was observed throughout the weld. The transverse residual stress of tensile nature was observed up to 5 mm depth, and later it converted into a compressive nature. The high tensile residual stress in the weld fusion zone is due to the shrinkage during the weld solidification. The tensile residual stresses are more detrimental as they are responsible for the weld's stress corrosion cracking, fracture, and fatigue damage (Deng and Murakawa, 2006b). For the ERNiCrMo-3 weld fusion zone in the AW condition, the maximum transverse tensile residual stress observed was 101 MPa. After PWHT, the longitudinal residual stress of tensile nature was observed up to 5 mm thickness, and later it converted into the compressive nature. After PWHT, peak longitudinal stress magnitude reduced from 269 MPa to 49 MPa. Thus, PWHT lessens the residual stresses up to a great extent. Also, due to the multipass welding, the tempering effect takes place after each pass. This tempering effect also relaxes the residual stresses. The longitudinal and transverse residual stress magnitude was less due to the less weld metal available for the solidification for the narrow groove geometry. (P.K. Taraphdar et al., 2021) also concluded that narrow groove geometry is beneficial in reducing the peak longitudinal residual stresses in the weld zone.

For P92 HAZ, the stress observed was compressive due to the volume change during the phase transformation. (Li et al., 2021) also reported a similar kind of observation. After welding, the P92 steel undergoes the solid-state phase transformation (SSPT) during rapid cooling (austenite to martensite transformation). The P92 steel contract during the austenitization process (Ac_1 to Ac_3), and then it expands from the martensite start temperature (M_s , 375 °C) to the martensite finish temperature (M_f , 280 °C). During the austenitization process, steel changes its crystal structure from BCC to FCC. Then, it changes from FCC to BCT during M_s to M_f (Venkata et al., 2014). This phase change results in the volumetric change into the P92 steel and induces the plasticity known as transformation induced plasticity (TRIP) (Deng et al., 2016). This phenomenon changes the yield strength and the nature of the residual stresses from longitudinal to compressive and vice versa. The tensile residual stress was developed in the weld fusion zone due to the shrinkage during the weld metal solidification, while compressive stress was developed in P92 HAZ due to the volume expansion during martensite transformation (Maduraimuthu et al., 2012). For the 304L HAZ, the maximum transverse tensile residual stress observed was 169 MPa. Also, after PWHT, the maximum transverse tensile residual stress observed for narrow groove design was 71 MPa. The mismatch in the coefficient of the thermal expansion between the P92 steel and 304L result in the non-uniform residual stress distribution. When residual stresses are very high the material become poor in tensile strength.

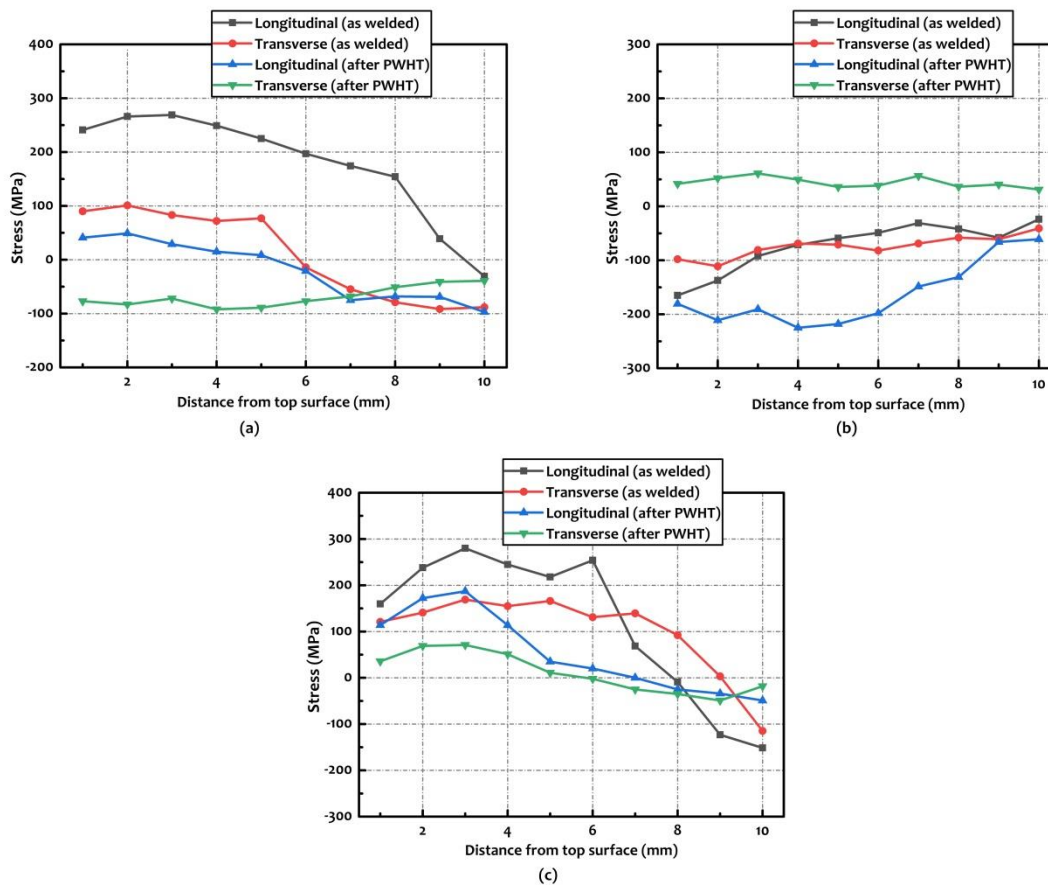


Figure 6.6: Distribution of welding induced residual stresses in AW and PWHT condition for (a) ERNiCrMo-3 weld fusion zone (b) P92 HAZ and (c) 304L HAZ for narrow groove geometry

6.3 Residual stress analysis for P92-ERNiFeCr-2-304L dissimilar weld joint

The through-thickness longitudinal and transverse residual stress distribution in the AW state and after PWHT for the ERNiFeCr-2 filler weld fusion zone, P92 HAZ, and 304L HAZ is presented in Figure 6.7(a-c) and Figure 6.8(a-c). For the ERNiFeCr-2 filler weld fusion zone, tensile longitudinal and transverse residual stresses were present in AW

and PWHT situation. In the present case, nickel-based filler metal was used. Thus volumetric shrinkage effect due to the weld solidification was more dominant. This induces the tensile residual stresses in the weld fusion zone. After PWHT also, the tensile residual stresses were observed in the weld fusion zone. The significant difference in the coefficient of thermal expansion value between ferritic and austenitic steel develops the high tensile residual stresses at the weld interface. For the ERNiFeCr-2 filler weld fusion zone of the V groove geometry, the maximum longitudinal tensile residual stress of 377 MPa was observed at the top surface of the weld. The tensile residual stress was reduced at the root pass because of the tempering effect from the subsequent passes. For the ERNiFeCr-2 filler weld fusion zone of narrow groove geometry, the maximum longitudinal compressive residual stress of 304 MPa was observed at the top surface of the weld. After PWHT for the ERNiFeCr-2 filler weld fusion zone of the V groove geometry, the maximum longitudinal tensile residual stress of 192 MPa was observed at the top surface of the weld. After PWHT for the ERNiFeCr-2 filler weld fusion zone of narrow groove geometry, the maximum longitudinal tensile residual stress of 187 MPa was observed at the top surface of the weld. Similar kinds of trends were observed for the transverse residual stresses. Thus, it can be concluded that PWHT and narrow groove geometry minimize the welding-induced residual stresses. Also, the residual stress distribution shows that the welding-induced residual stresses were maximum between the top surfaces of the weld up to the depth of 5 mm. From the center (after the depth of 5 mm) to the bottom of the weld, residual stresses were gradually decreased. Also, for the P92 HAZ and 304L HAZ, the longitudinal and transverse residual stresses for the narrow groove geometry were lesser than that for the V groove geometry in the AW state and after PWHT. For P92 HAZ, compressive residual stresses were observed because of the volumetric expansion due to the martensitic transformation. For 304L HAZ, tensile residual stresses were observed in AW and after PWHT. (Li et al., 2021) investigated the residual stresses for P92/SUS 304 dissimilar metal butt weld joints with single V-groove and X-groove geometry. They concluded that X-groove geometry is superior compared to the single V-groove design in reducing tensile residual stresses. The authors also reported that martensitic phase transformation in P92 steel, strain hardening in the SUS 304 steel, and discrepancy in the co-efficient of thermal expansion are the key factors influencing the residual stress variation. (Zhao et al., 2014) performed the numerical simulation of residual stresses for P92/304H dissimilar metal butt weld joints with single V-groove geometry of varying groove angles. They concluded that a small groove angle with more welding passes decreases the residual stresses.

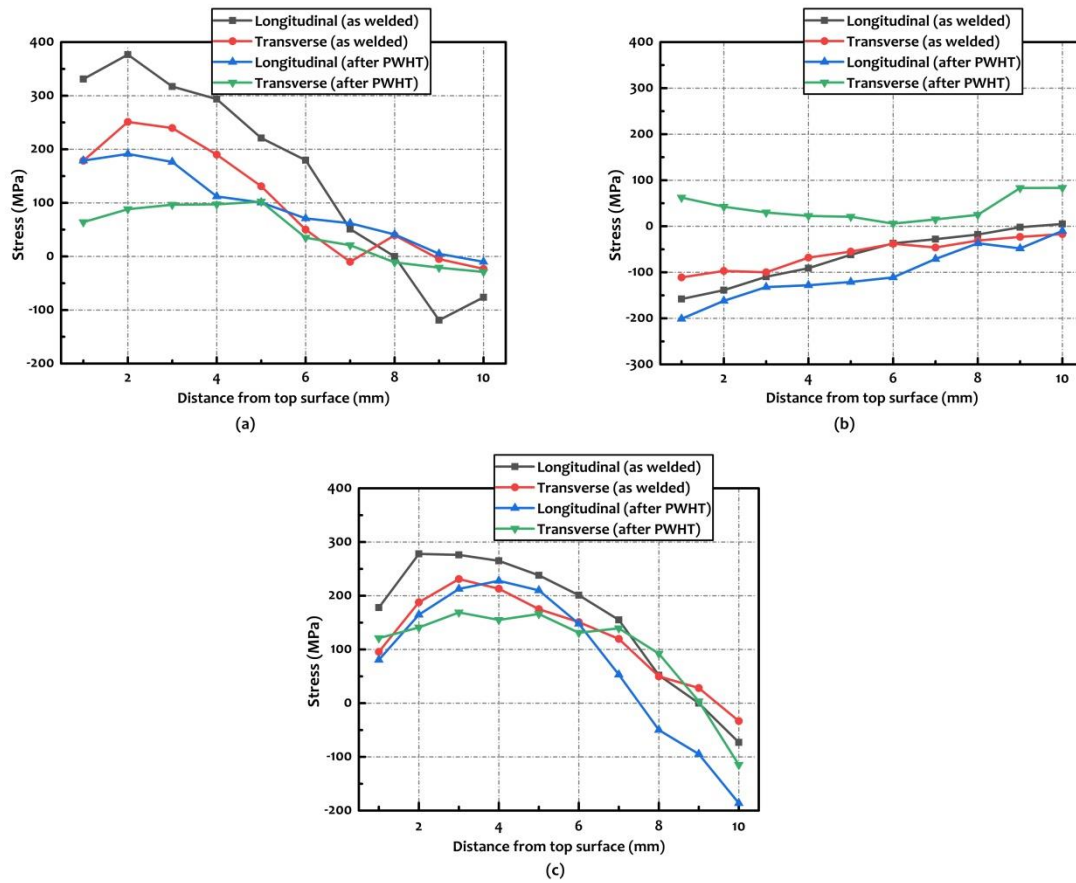


Figure 6.7: Distribution of welding induced residual stresses in AW and PWHT condition for (a) ERNiFeCr-2 weld fusion zone (b) P92 HAZ and (c) 304L HAZ for V-groove geometry

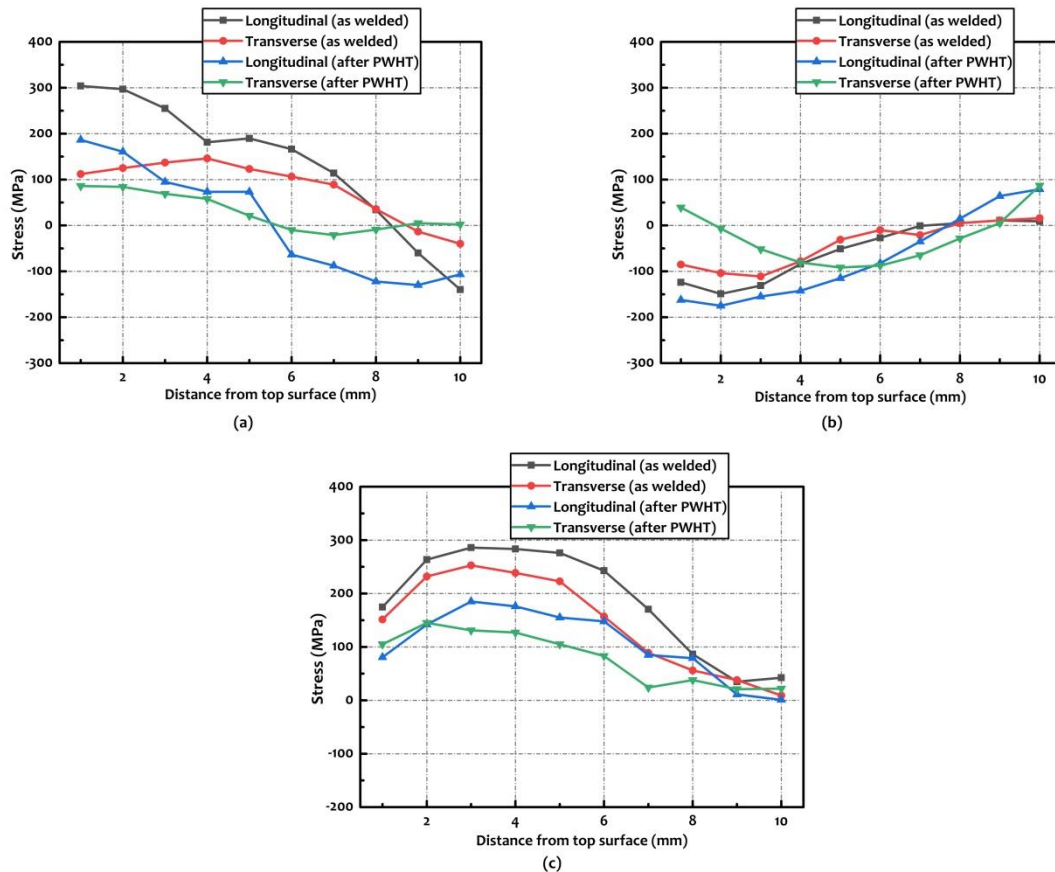


Figure 6.8: Distribution of welding induced residual stresses in AW and PWHT condition for (a) ERNiFeCr-2 weld fusion zone (b) P92 HAZ and (c) 304L HAZ for narrow groove geometry

6.4 Residual stress analysis for P92-ERNiCr-3-304L dissimilar weld joint

The longitudinal and transverse residual stress profile for the ERNiCr-3 weld fusion zone is presented in Figure 6.9(a). The longitudinal and transverse residual stress of the tensile nature was observed throughout the thickness of for ERNiCr-3 weld fusion zone. The maximum longitudinal tensile stress value is 490 MPa at a depth of 3 mm. The maximum tensile residual stresses were observed at the top surface of the weld fusion zone, while minimum tensile residual stresses were observed at the root of the weld fusion zone. After PWHT, the maximum longitudinal tensile stress value is 273 MPa at a depth of 3 mm. Thus, PWHT resulted in significant minimization of the residual stress in the weld fusion zone. From the residual stress measurement for the ERNiCr-3 weld fusion zone, it was observed that longitudinal residual stresses were higher than the transverse residual stresses. It was observed that transverse residual stress was high at the top layer of the weld fusion zone, and it was gradually reduced from mid-section to the root of the weld fusion zone. The maximum circumferential tensile stress value is 442 MPa at a depth of 3 mm, while after PWHT, the value is around 273 MPa. The PWHT decreases both the longitudinal and circumferential residual stresses. The peak transverse stress in the AW state and after PWHT was also observed at the top surface of the weld. The longitudinal and transverse residual stress trend was similar throughout the thickness. Figure 6.9(b) shows the longitudinal and transverse residual stress profile for the P92 HAZ in AW state and after PWHT. For the P92 HAZ, compressive longitudinal and transverse residual stresses were observed in AW and PWHT situation. The compressive stresses are generally advantageous; however, it reduces the buckling load-carrying capacity of the structure (P. K. Taraphdar et al., 2021). For the 304L HAZ, a tensile longitudinal and transverse residual stress was observed throughout the thickness in AW and PWHT state, as shown in Figure 6.9(c).

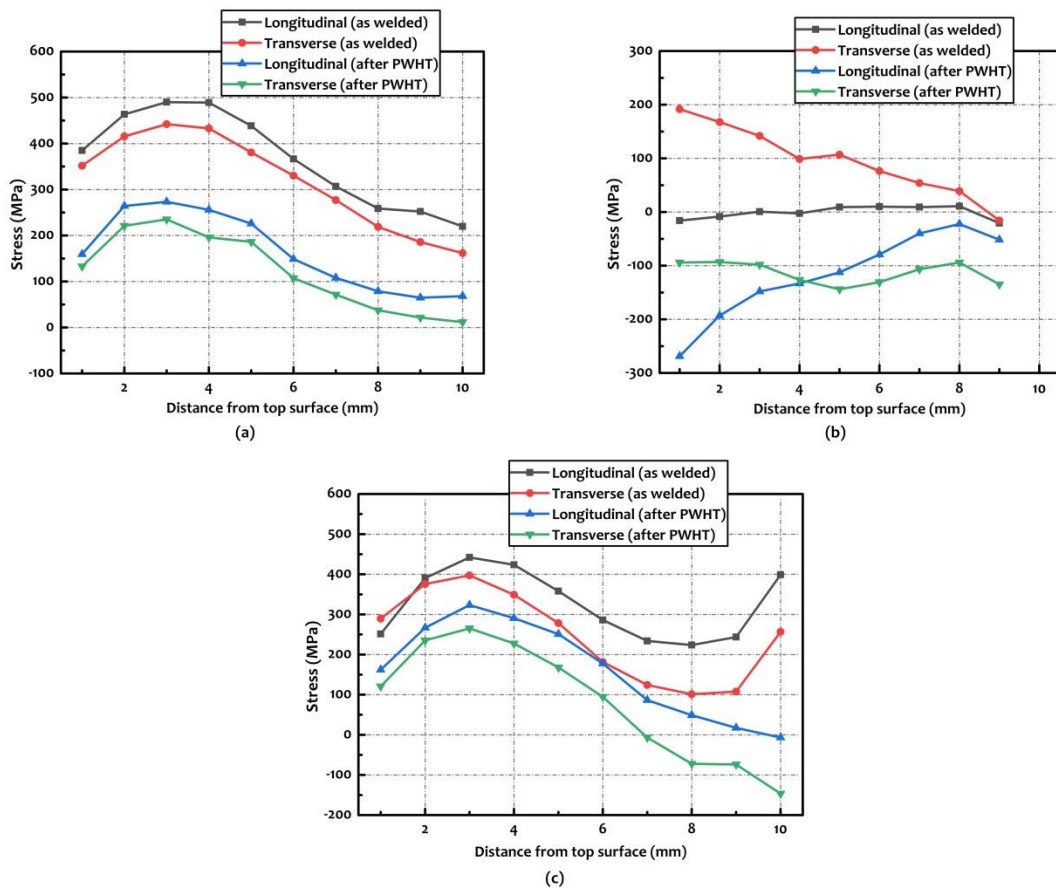


Figure 6.9: Distribution of welding induced residual stresses in AW and PWHT condition for (a) ERNiCr-3 weld fusion zone (b) P92 HAZ and (c) 304L HAZ for V-groove geometry

...

