



Examining Stress Modification in Dissimilar and Similar Metal Welds through Ultrasonic Impact Treatment

Ultrasonic impact treatment can address residual stress in similar and dissimilar metal welds

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Abstract

Residual stress (RS) from welding poses major challenges, especially in dissimilar joints such as 1018 steel and 304 stainless steel, where thermal expansion mismatches intensify tensile stress. Conventional post-weld heat treatments, although effective for homogeneous materials, often require substantial energy, specialized equipment, and extensive processing time, making them less practical for dissimilar metal weld applications. This study explores an alternative, energy-efficient method — ultrasonic impact treatment (UIT) — to address RS in both similar and dissimilar metal welds. This study employs UIT on the top and bottom surfaces of welds and measures RS in the longitudinal, transverse, and normal directions using neutron diffraction at a high flux isotope reactor. Findings reveal that UIT significantly reduces longitudinal RS in similar welds but introduces moderate increases in transverse and normal RS due to stress redistribution dynamics. UIT demonstrates strong potential for RS modification; however, its application to dissimilar welds, such as 1018 and 304, requires careful parameter control to account for asymmetric material behavior and ensure consistent stress relief.

Keywords

- Ultrasonic Impact Treatment (UIT)
- Residual Stress (RS) Modification
- Dissimilar Metal Welds (DMWs)
- Neutron Diffraction (ND)

Introduction

Residual stresses (RS) typically exist in all fusion welding processes due to non-homogeneous plastic deformation during thermal expansion and contraction, and microstructural changes. These stresses are a major cause of reduced component strength and service life, especially under dynamic loads and vibration (Refs. 1, 2). To improve fatigue strength and tensile load capacity, several post-treatment operations are being used, such as heat treatment (Ref. 3). However, this method requires substantial equipment investments and high energy consumption and is also highly dependent on the furnace dimensions. Moreover, this method is not effective in dissimilar welds, due to the considerable difference in thermal expansion of the joined alloys (Refs. 4, 5).

Ultrasonic Impact Treatment (UIT) is a modern technique used to reduce tensile RS in welded joints by applying high-frequency mechanical impacts (above 20 kHz) combined with ultrasonic oscillations (Refs. 6, 7). The process creates inherent strain on the surface, resulting in a compressive state of RS. This compressive stress is equilibrated by tensile stresses deeper within the bulk of the material. Additionally, UIT induces deformation in the tensile zone, relieving tensile stresses, closing cracks and voids, modifying weld toe geometry, and further inducing compressive RS through regional plastic deformation. Figure 1 schematically shows the mechanism of action of UIT. Ultrasonic transducers receive power from the generator, and blue waves are produced in the head. The wave's amplitude is later amplified in the concentrator and then transferred to the pin. Vibration of the pins affects the part surface (Wave 2) and induces plastic deformation. As a result of this plastic deformation, high compression of RS is exerted on the part's surface, and the magnitude of this stress decreases in the sublayers. Penetration of vibration energy (Wave 5) facilitates movement of the sublayers toward regions of residual tensile stress

Table 1 — Chemical Composition of Steel Plates (wt-%)

Composition	C	Mn	Si	P	S	Cr	Ni	Balance	Ni _{eq}	Cr _{eq}
1018 Steel (average)	0.13–0.20	0.30–0.90	0.15–0.30	0–0.04	0–0.05	–	–	Fe	≈ 6	0.3
304 Stainless (average)	0–0.08	1.7	0.52	0–0.045	0–0.035	18.9	7.5	Fe	≈ 10	≈ 20
304-1018 FZ (EDAX)	–	1.14	0.12	–	–	7.58	4.32	Fe	≈ 7	≈ 8

from previous processes and helps release these stresses (Refs. 8, 9).

Regions beneath the treated surface area in the welded specimen processed by UIT are categorized into three zones, which are plotted schematically in Fig. 2 with the approximate dimensions (Ref. 10). Rapid friction heating and cooling combined with severe plastic deformation at the surface form a nanocrystalline zone, or a white layer, with a thickness of up to approximately 100 μm . A region of up to 1.5 mm below the surface undergoes plastic deformation, and compressive stresses are introduced. The effect of the mechanical impacts extends up to 5 mm below the surface and leads to a reduction in RS of up to 70%. Ultrasonic waves affect the RS to a depth of up to 12 mm, resulting in a reduction of up to 50%.

Compared with other mechanical surface-treatment techniques, such as shot peening, UIT provides deeper, more controlled residual-stress modification. Shot peening relies on random high-velocity particle impacts and typically induces a shallow compressive layer limited to approximately 0.1–0.5 mm beneath the surface (Ref. 13). In contrast, UIT applies high-frequency (20–30 kHz) mechanical strikes through a vibrating pin, generating a more uniform plastic deformation and compressive residual-stress field that can extend 1–2 mm or more into the material. UIT also produces smoother weld-toe geometries and lower levels of near-surface cold work, which have been shown to improve fatigue performance more effectively than conventional shot peening, especially in welded joints where deeper stress redistribution is required.

Building on these distinctions, several recent studies have demonstrated that UIT is highly effective in reducing RS in welded structures. Cheng et al. (Ref. 14) measured the RS induced by UIT using both x-ray and neutron diffraction (ND) techniques for the first time in a similar weld. They observed that the UIT method produced a compressive stress layer less than 1 mm in depth at the weld toe. Almost the same results were obtained on an 8 mm-thick 304L stainless steel plate by Turski et al. (Ref. 13). Moreover, Ahmad et al. (Ref. 15) showed that the weld RS was affected by UIT at a depth of 4–6 mm. Recently, Gao et al. (Ref. 9) investigated the effect of UIT on the RS in a 16 mm-thick high-strength steel multi-pass welded joint with synchrotron x-ray diffraction (XRD). They revealed that mechanical effects on the treated surface effectively transmit ultrasonic waves into the workpiece,

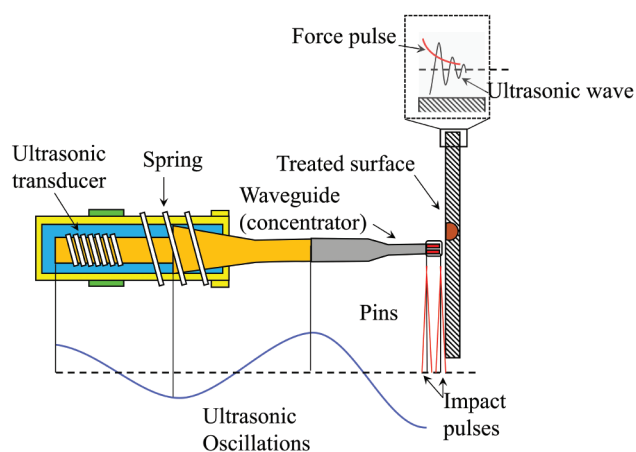


Fig. 1 — Mechanism of UIT (Refs. 8, 10).

reducing stress to a depth of 6–8 mm below the surface. In addition, they found that the stresses in the surrounding regions are redistributed after UIT to maintain the stress equilibrium. More recently, Liu et al. (Ref. 16) applied UIT to a 45 mm-thick high-strength steel welded joint. They found that UIT can introduce compressive stress layers up to 4 mm deep in the fusion zone (FZ) and eliminate tensile stress at the treated surface.

In addition to the welding process, UIT is applied during or after additive manufacturing to improve material properties (Ref. 17). Studies have shown that UIT helps reduce defects, alter microstructure, increase strain hardening, and redistribute RS (Refs. 18, 19). Studies also have shown significant improvements in strength and ductility across various alloys and additive manufacturing processes, such as laser powder bed fusion (LPBF), directed energy deposition, and wire arc additive manufacturing (Refs. 20, 21). For instance, UIT enhanced the yield strength, ultimate strength, and elongation in steels such as SS316L, 304, and 17-4 PH. In LPBF IN718, UIT followed by heat treatment, improved YS, UTS, and modulus by up to 67%. Similarly, laser shock peening, which also induces plastic deformation, improved strength and ductility in LPBF Ti–6Al–4V by refining the grain structure.

Exploring the effectiveness of UIT in dissimilar metal welds (DMWs) through both experimental and numerical

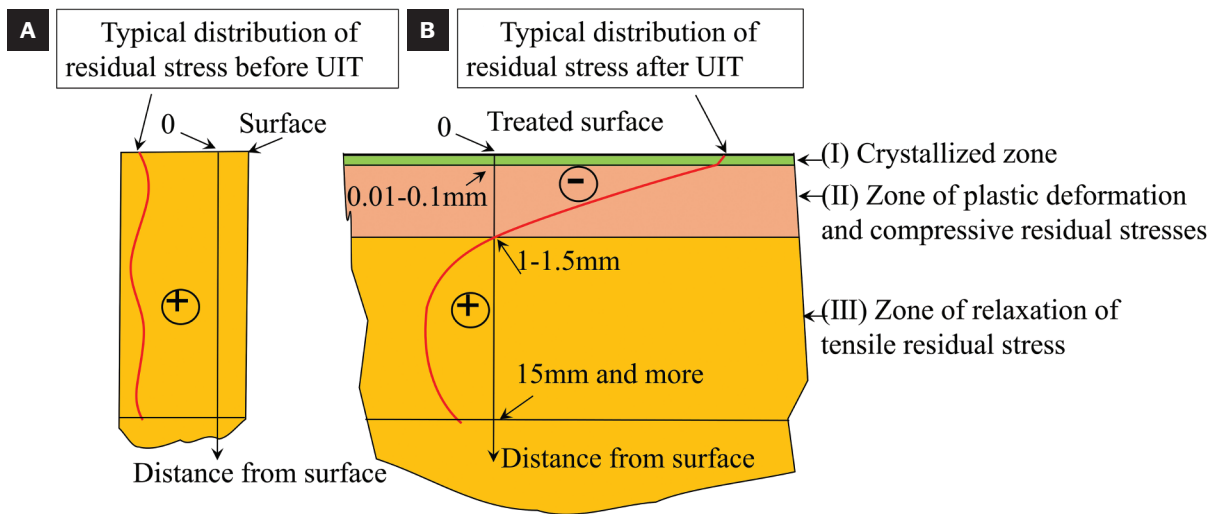


Fig. 2 — Schematic view of the cross section of: A — Part without UIT; B — Part improved by UIT. Improved characteristics of regions I, II, and III are listed as follows: I — corrosion, wear, fatigue at elevated temperature; II — fatigue, corrosion, wear, distortion; III — distortion, crack propagation (Refs. 11, 12).

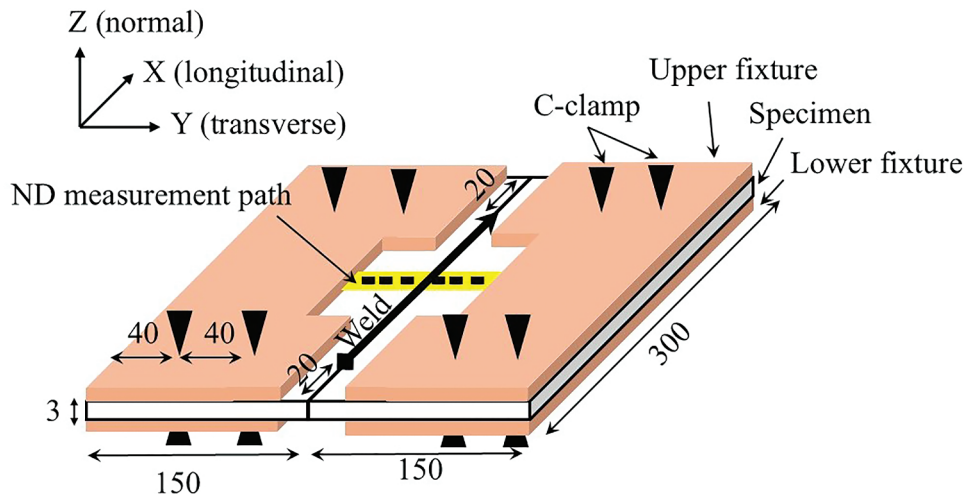


Fig. 3 — Dimensions, measurement directions, and clamping configuration of the specimen. All dimensions are in millimeters (mm).

approaches offers potential to improve weld performance and strengthen joint mechanical properties. In a recent study, Sidorov et al. (Ref. 22) examined the impact of repeated UIT on RS in dissimilar-thickness girth welds of low-alloy steel pipes. Their x-ray diffraction analysis revealed that when UIT was applied at optimal speeds (0.06–0.12 m/min), it converted tensile stresses on the inner surface of the weld into compressive stresses. Similarly, Song et al. (Ref. 23) investigated the effects of UIT on electron beam-welded TA15/BTi-6431S dissimilar titanium alloys. X-ray diffraction results showed that UIT effectively transformed high tensile RS into compressive stresses near the FZ. While these studies provide valuable insights into UIT's impact on RS in DMW, the application of UIT in this context is still relatively unexplored.

This study investigates UIT as a potential alternative to traditional heat treatments for reducing tensile RS in DMW. To evaluate the effectiveness of UIT, ND was employed as the

primary experimental technique. ND provides a non-destructive method for accurately measuring RS distributions within the material, offering detailed insights into how UIT modifies stress profiles across different orientations within the weld. Similar and dissimilar metal weld samples were subjected to UIT, and the RS in the longitudinal, transverse, and normal directions were then measured. This approach allowed us to capture the specific effects of UIT on RS modification and to identify directional variability that might influence the overall performance of the treated joints.

Material and Welding Procedures

Experimental work was conducted on two butt welds: one similar weld using AISI 1018 and one DMW using AISI 1018 and AISI 304 plates. The material compositions are presented in

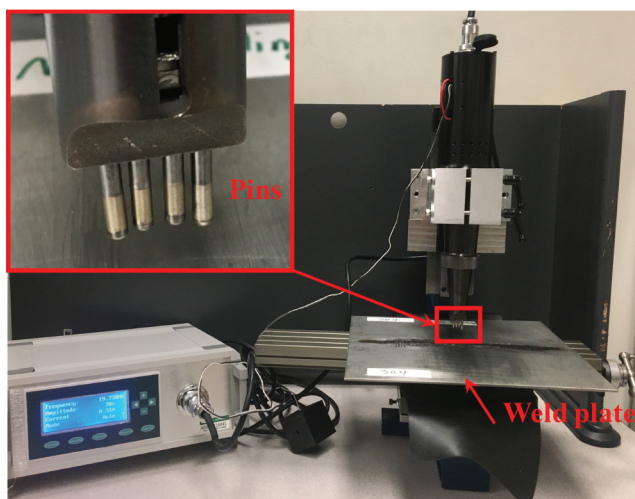


Fig. 4 — Experimental UIT setup. Restraining plates and clamps are omitted for clarity; the full configuration is shown in Fig. 5.

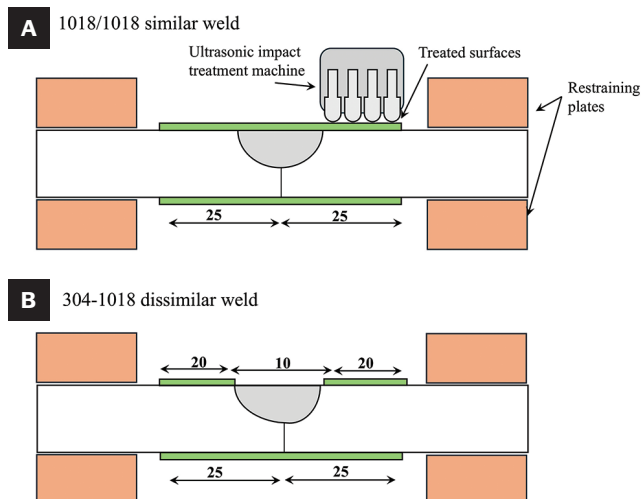


Fig. 5 — Schematic picture of UIT arrangement: A — Similar metal welds; B — dissimilar metal welds. All dimensions are millimeters (mm).

Table 2 — Welding Parameters Used in This Study

Arc Voltage (V) DCEN	Arc Current (A)	Electrode Diameter (mm)	Arc Length (mm)	Travel Speed (mm/s)	Argon Gas (m ³ /s)	Arc Efficiency 80%
18	150	2.4	1.5	4	0.0136	80% (Ref. 24)

Table 1. Single-pass autogenous gas tungsten arc welding was employed for both welds. The welding parameters outlined in Table 2 were selected to achieve partial penetration, as no auxiliary argon gas was used for weld protection beneath the joint. After welding, the specimens were allowed to cool for 2000 s until the temperature had nearly equilibrated, with the C-clamps remaining in place. The specimens were then kept in the same fixture and transferred to the UIT station for treatment. The sample dimensions are shown in Fig. 3.

Ultrasonic Impact Treatment

To study the effects of UIT, initial testing was carried out by placing the ultrasonic transducer on the top surface of the weld sample (see Fig. 4). Since no significant reduction in distortion was observed, the UIT was extended to treat both the top and bottom surfaces of the weld samples. For the similar 1018 weld, UIT was applied first to the top surface and then to the bottom surface. In the case of the dissimilar 304-1018 weld, UIT was applied first to the top surface on the 304 side, then to the 1018 side, followed by treatment of the bottom surface on the 304 side, then on the 1018 side. During UIT, the weld samples were translated along the weld direction (longitudinally) at a constant speed of 10 mm/s, and successive passes were performed with incremental transverse shifts to cover the full ± 25 mm region relative to the weld centerline.

As shown in the schematic in Fig. 5, both the top and bottom surfaces of the similar weld samples were surface-treated.

However, the FZ in the dissimilar weld was not treated due to the pre-existing compressive stress induced by martensite formation during cooling.

In dissimilar 304-1018 welds, the chemical composition gradient and rapid cooling rate promote a transformation from austenite (FCC) to martensite (BCT) within the FZ. This transformation causes local volume expansion, generating compressive stress in the FZ and tensile stress in the surrounding base metals. Microhardness and microstructural analyses in our previous study (Ref. 25) confirmed that the FZ of the dissimilar weld primarily consists of martensite with partial penetration across the plate thickness. The corresponding Schaeffler diagram analysis indicated the local composition favored the formation of martensite.

Because of this transformation-induced compressive stress, applying UIT directly to the FZ could lead to excessive plastic deformation or surface cracking due to the superposition of compressive fields. Therefore, UIT was applied only to the surrounding regions of the dissimilar weld, excluding the FZ itself.

The operating frequency of the transducer was set to 20 kHz, with a vibration amplitude of 20 μ m, based on previous studies that have shown these parameters are effective for inducing the desired compressive RS (Refs. 16, 26). Four steel pins (3 mm in diameter) were attached to the transducer's head to focus the ultrasonic energy more precisely on the weld surface. The treatment was performed after the welded plate had completely cooled to room temperature while it was still constrained by the clamps. This ensured that the UIT was

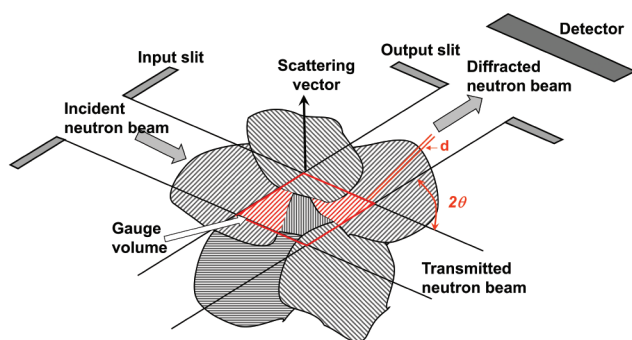


Fig. 6 — Scattering vector for a Bragg reflection from a single crystallographic plane family (Refs. 25, 28, 29).

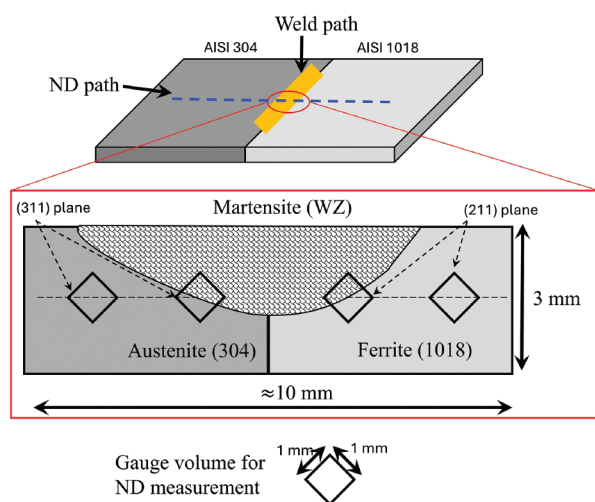


Fig. 7 — Location of the neutron diffraction gauge volume within the welded plate. The Fe (211) and Fe (311) reflections were used for the AISI 1018 and AISI 304 sides, respectively.

applied under stable conditions, minimizing any distortions from residual heat. After the treatment, the clamps were released from the sample, and the samples were allowed to return to ambient conditions before further analysis.

Microstructure and Neutron Diffraction Measurement

Analyzing the weld microstructure prior to ND measurements is important for data accuracy. This is because ND focuses on the specific lattice plane spacing of a subset of grains, with orientations relative to the scattering vector (see Fig. 6). By choosing specific $\{hkl\}$ lattice planes, ND separates strain responses from different phases in a multiphase material. This ability is valuable in materials with multiple phases, where different phases may undergo different stress responses under similar conditions. For instance, in multi-phase materials like duplex steel, which is composed of approximately equal parts austenite and δ -ferrite, each phase may carry distinct stresses depending on its microstructure and mechanical properties (Ref. 27). The material

in this study consists of a single phase, except for the FZ in the DMW, where phase differences exist.

The phase composition and microstructural characteristics of both similar and dissimilar welds were previously established through optical microscopy, micro-hardness testing, EDS analysis, and Schaeffler diagram evaluation (Ref. 25). These prior results confirmed the presence of ferrite in AISI 1018 steel and austenite in AISI 304 steel, with a localized martensitic region in the dissimilar FZ. Based on these findings, a single diffraction plane was selected for each phase: the (211) plane for ferritic material and the (311) plane for austenitic material. These reflections are commonly used to approximate the bulk elastic strain response and are relatively insensitive to intergranular effects (Ref. 27). In the dissimilar weld, although the neutron gauge volume partially overlaps the FZ and adjacent base materials, the localized martensitic region in the FZ was not separately characterized by ND, as no martensite-specific diffraction plane was selected. Instead, ND measurements were performed using the (211) reflection on the 1018 side and the (311) reflection on the 304 side, as illustrated in Fig. 7. A detailed discussion of the d_0 determination approach across the weld region is provided in our previous study (Ref. 25).

To evaluate the RS distribution associated with these phases, ND was employed due to its deep penetration and ability to provide volume-averaged measurements of internal stresses. ND offers three-dimensional mapping capability and millimeter-scale resolution, making it a powerful tool for determining RS in welded structures (Ref. 27). In this study, the ND measurements were carried out at the High Flux Isotope Reactor of Oak Ridge National Laboratory on the 2nd Generation Neutron Residual Stress Facility. The beam geometry and the samples mounted in the fixture are shown in Figs. 3 and 8, respectively. The sample translation stage and goniometer can perform precision motions (0.01 mm) for the placement of an instrumental gauge volume. The gauge volume is defined by a set of gadolinium slits. Two different gauge-volume geometries were used, as shown in Fig. 8. The gauge volume geometry was chosen based on the direction of the measured strain. For the transverse and normal directions, a gauge volume of 1 mm $\times$ 1 mm $\times$ 4 mm (width, depth, and height) is used. The extended height is along the weld direction and is a direction of symmetry in the sample. For the longitudinal case, the gauge volume was changed to 1 mm $\times$ 1 mm $\times$ 1 mm so the height would coincide with the welding direction.

Because of its deep penetration and large gauge volume, ND measures subsurface (bulk) RS and is not suitable for surface stress characterization. ND primarily quantifies Type I (macrostress) distributions but can also provide insight into Type II and Type III stresses under specific experimental conditions. In this study, the ND volume was positioned at the plate's mid-thickness (~ 1.5 mm from the surface) to capture the subsurface RS, which can still show the redistribution in subsurface RS, often a reduction in stress, induced by UIT.

The incident wavelength of the instrument is defined by a bent-silicon-crystal focusing monochromator. For the experiment, a wavelength of 1.73 Å is used. This defines the Fe (211) reflection at a 2θ of ~ 95.1 deg for the 1018 side and the Fe (311) reflection at a 2θ of ~ 106 deg for the 304 side.

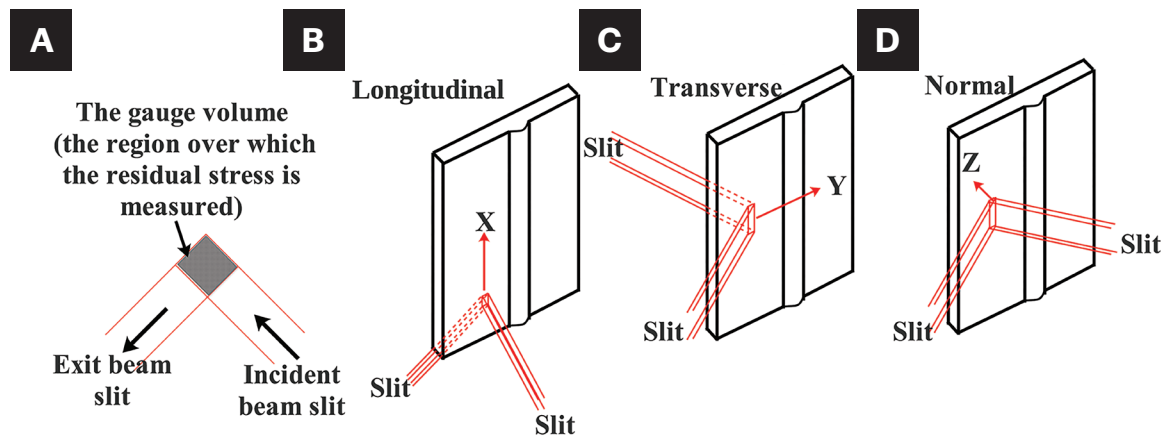


Fig. 8 — A — Gauge volume definition; B, C, and D — scattering vectors used in this study.

Table 3 — Diffraction Elastic Constants Used in This Study (Ref. 27)

Material	hkl	E^{hkl}	ν^{hkl}
1018 Steel	Fe (211)	225.5 GPa	0.28
304 Stainless Steel	Fe (311)	183.5 GPa	0.31

At each measurement point, lattice strains were calculated from the corresponding d-spacing changes in three orthogonal directions, allowing the stress fields to be calculated. The lattice strain can be determined from the measured lattice spacing according to (Ref. 27):

$$\varepsilon_{ii} = \frac{d - d_o}{d_o} = -\cot\theta(\theta - \theta_o) \quad i = 1, 2, 3 \quad (1)$$

where the d and d_o are the interplanar spacing under the stressed and stress-free state, respectively. θ and θ_o are the diffraction angles for the stressed and stress-free specimens at each location, respectively. Since d_o is required as a reference in ND strain calculation, it was determined using a macroscopic “stress-free” comb-like coupon. Each comb-like coupon was cut from a nominally identical weld at the same locations as the ND measurements using electric discharge machining. The coupon was sliced to a 3 mm width and 3 mm thickness along the transverse direction to effectively release macroscopic stress from the bulk of the weldment. With the assumption that the three orthogonal components of measured strain correspond to the principal directions, i.e., that shear stresses are zero in these directions, the analysis to determine RS is simplified.

The macroscopic stress components, where the numerical superscripts refer to the lattice plane family, are related to the elastic strains in analogy with Hooke’s Law (Ref. 27):

$$\sigma_{ij} = \frac{E^{hkl}}{(1 + \nu^{hkl})} \left[\varepsilon_{ij} + \delta_{ij} \frac{\nu^{hkl}}{(1 - 2\nu^{hkl})} \varepsilon_{kk} \right] \quad (2)$$

where E^{hkl} and ν^{hkl} are the diffraction elastic constants relating strain in the (311) and (211) lattice planes to the macroscopic stress. Additionally, ε_{ij} and ε_{kk} in the above equations are the elastic bulk strains. These elastic constants may be either measured or calculated with good accuracy based on the self-consistent Kröner model and using single-crystal elastic constants for austenitic stainless steel and low carbon steel (Ref. 27). The values used in this study are shown in Table 3.

Results

Figures 9 and 10 illustrate the significant distortions observed in both 1018 similar and 304-1018 dissimilar welds before applying UIT. These distortions are primarily attributed to residual plastic strain around the welded joints. However, following the UIT application, there was a notable reduction in these distortions. Displacement measurements were obtained using a dial gauge with an accuracy of $\pm 50 \mu\text{m}$ at 5 mm intervals from -150 mm to $+150 \text{ mm}$ relative to the weld centerline, and the plotted lines represent connections between discrete measurement points.

To better illustrate the strain redistribution behavior induced by UIT, a comparative strain analysis was conducted prior to RS evaluation. Although a complete through-thickness strain map would require combined XRD and ND measurements, the present study focuses on the strain evolution within a $\pm 50 \text{ mm}$ region from the weld centerline, where the effects of UIT were most pronounced. The strongest influence was observed within the $\pm 20 \text{ mm}$ zone, corresponding to the directly peened region.

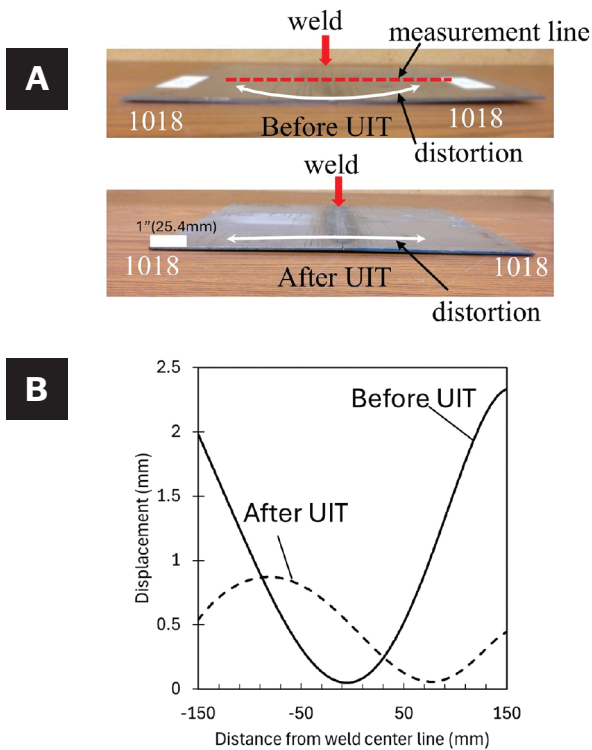


Fig. 9 — Distortion observed in 1018 similar samples before and after UIT: A — Specimens; B — measured displacement profiles.

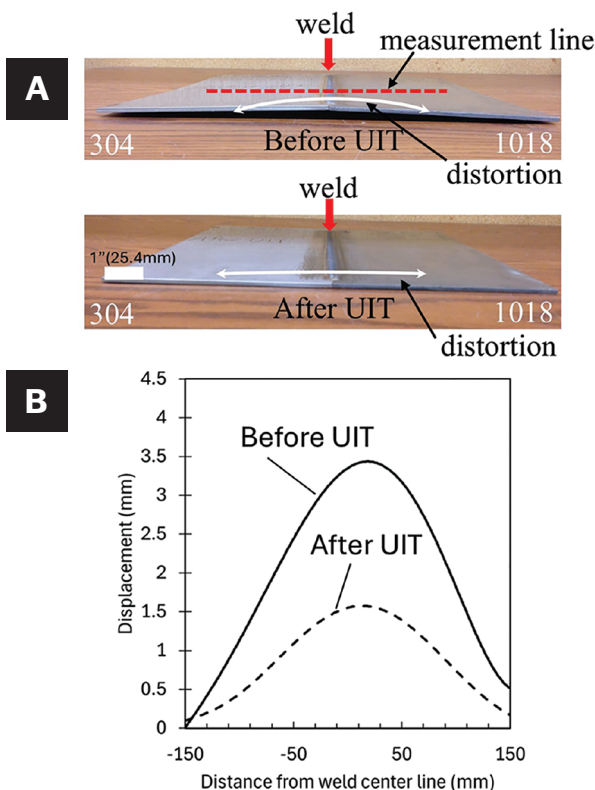


Fig. 10 — Distortion observed in dissimilar metal weld samples before and after UIT: A — Specimens; B — measured displacement profiles.

The average strain components within this region for both similar and dissimilar welds, with and without UIT, are summarized in Table 4. The results show that UIT significantly reduced longitudinal tensile strain and introduced localized compressive strain, while moderate tensile strain redistribution occurred in the transverse and normal directions. For example, in a similar weld, the longitudinal strain changed from + 373.9 $\mu\epsilon$ in the untreated condition to - 108.5 $\mu\epsilon$ after UIT, whereas in the dissimilar weld, it decreased from + 432.9 $\mu\epsilon$ to + 26.3 $\mu\epsilon$, approaching a nearly neutral state.

Figures 11 and 12 further present the longitudinal, transverse, and normal strain profiles for both similar and dissimilar welds, which illustrate the localized strain relaxation and compressive zones induced by UIT near the weld region. It is worth noting that based on a lattice-spacing uncertainty of $\pm 1 \times 10^{-4}$ Å, the strain and stress uncertainties are approximately ± 100 $\mu\epsilon$ and ± 20 MPa, respectively, and are represented as error bars in Figs. 11 and 12.

The RS profiles along longitudinal, transverse, and normal directions for welds without UIT and with UIT are presented in Fig. 13. The similar weld of 1018 steel shows RS of 430 MPa, 200 MPa, and 150 MPa in the longitudinal, transverse, and normal directions, respectively. The results in Fig. 13B show that the UIT technique significantly affected the RS distribution in similar weld. The maximum stress in the longitudinal direction dropped by nearly 280 MPa. Although the UIT method used was relatively simple, it introduced enough compressive stress into the weld area to counteract the tensile stress near the FZ. However, the RS distribution in the UIT-treated sample is not symmetrical. This is likely due to uncontrolled variables during the UIT application, such as inconsistent tool movement or uneven pressure. It was also observed that RS increased in the transverse and normal directions after applying UIT. This is likely due to stress redistribution, as the stress components must rebalance to maintain mechanical equilibrium within the material. When the longitudinal RS is reduced, some of that stress may shift into the other directions to maintain mechanical equilibrium. As a result, both transverse and normal stresses increased to some extent. However, these increases were moderate and did not reach the high levels originally seen in the longitudinal direction before UIT. Therefore, despite the rise in other stress components, the overall effect of UIT is still beneficial in reducing the most critical tensile RS in the weld.

The RS profiles along longitudinal, transverse, and normal directions for DMW without UIT and with UIT are presented in Figs. 14A and B, respectively. UIT demonstrated its capability to reduce longitudinal RS. However, the induced compressive stresses from UIT led to significant tensile RS in the transverse and normal directions.

Discussion

Welding of thin-sheet structures produces severe distortions, primarily due to residual plastic strain around the weld joints, as shown in Figs. 9 and 10. These distortions can vary depending on several factors, including material properties, and welding parameters. A common observation is that RS in the longitudinal direction tends to be larger than that in the transverse or normal directions, as depicted in Figs. 11A

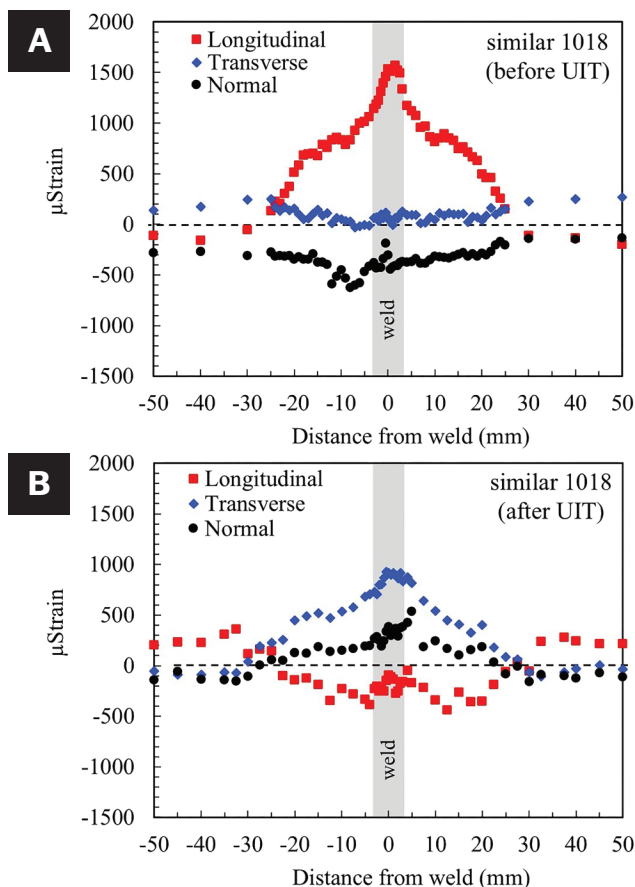


Fig. 11 — Strain distribution in a similar 1018 weldment: A — without UIT; B — with UIT. The error of strain calculation is $\pm 100 \mu\epsilon$.

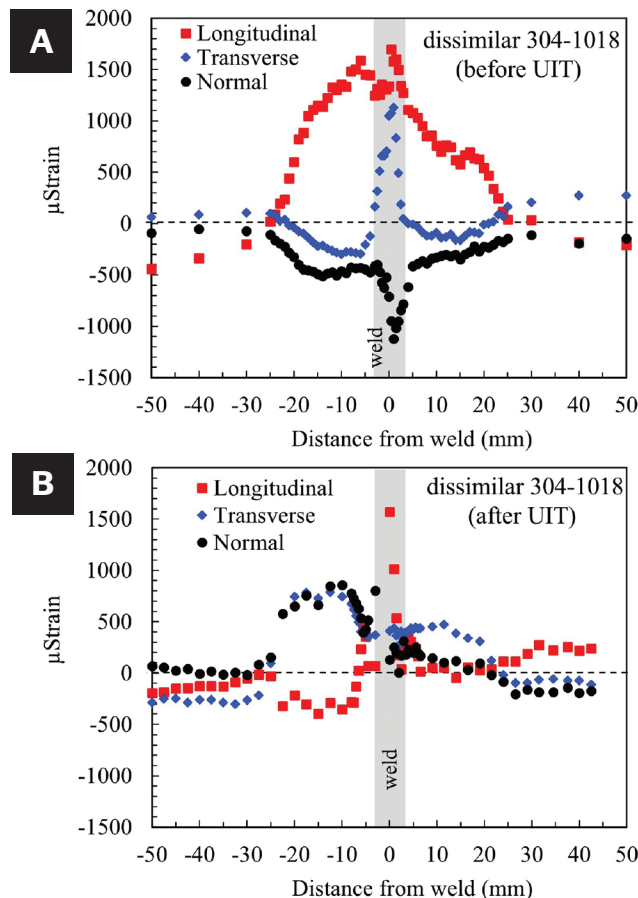


Fig. 12 — Strain distribution in a dissimilar 304-1018 weldment: A — without UIT; B — with UIT. The error of strain calculation is $\pm 100 \mu\epsilon$.

Table 4 — Average Strain Components ($\mu\epsilon$) within ± 20 mm of the Weld Centerline for Similar and Dissimilar Welds with and without UIT

Condition	Longitudinal Strain	Transverse Strain	Normal Strain
Similar Weld – No UIT	373	28	-158
Similar Weld – With UIT	-108	235	84
Dissimilar Weld – No UIT	432	-10	-182
Dissimilar Weld – With UIT	26	209	162

and 12A. This is primarily due to high thermal gradients and contraction during welding. As the weld cools, the material contracts, but the surrounding cooler base material resists this contraction, especially along the weld's length (longitudinal direction). This resistance contributes to the higher RS observed in the longitudinal direction, which is influenced by two key factors. First, the cooling rate along the weld's length is generally slower than in the transverse or normal directions (Refs. 30, 31). This occurs because heat dissipation is more uniform along the length of the weld, resulting in slower

cooling and greater retention of RS. Second, the mechanical constraints and geometry of the weldment play a significant role (Refs. 32, 33). The transverse and normal directions experience less constraint which allows easier deformation and, consequently, reduces reducing the retained RS.

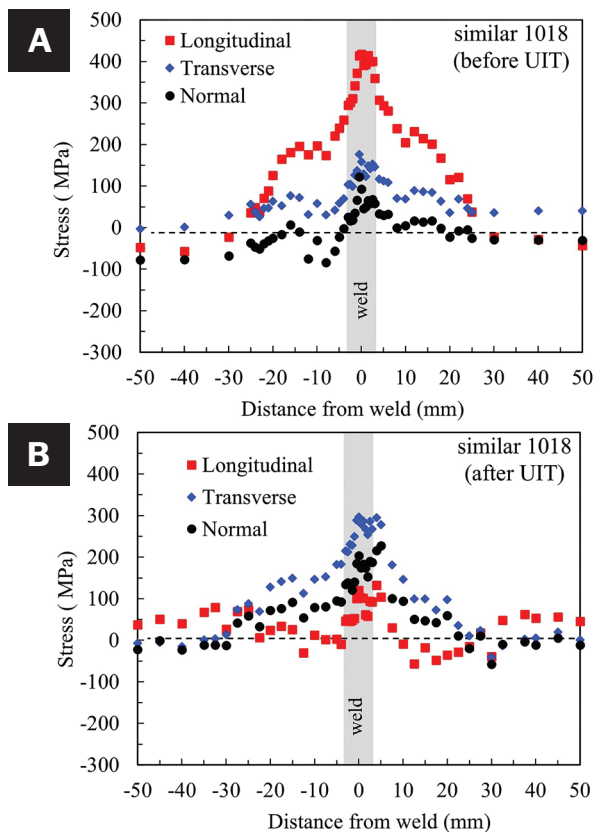


Fig. 13 — Longitudinal, transverse, and normal residual stress in a similar 1018 weld: A — Without UIT; B — with UIT. The error of stress calculation is ± 20 MPa.

Effect of UIT on Distortions

UIT is effective in reducing distortions in welded structures, as demonstrated in Figs. 9B and 10B. However, its influence on RS is not always uniform, as shown in Fig. 12B. Variability in applications, such as inconsistent tool movement or uneven pressure, can result in an asymmetrical distribution of RS across the treated surface. Previous studies (Ref. 16) have similarly noted UIT's potential to redistribute RS through the introduction of compressive stresses. Yet they also emphasize that excessive treatment can counteract these benefits. These findings highlight the need to carefully fine-tune UIT parameters to achieve effective stress relief without introducing new complications.

Residual Stress in DMWs

When dissimilar metals are welded, the RS distribution becomes more complex, particularly near the FZ. This arises from differences in CTE and yield strengths between the two base metals. For example, in a 304-1018 dissimilar weld, the 304 stainless steel, with a higher CTE, expands and contracts more than the 1018 steel during the welding thermal cycle. As 304 cools and contracts, it pulls on the 1018 side, creating tensile load on the 1018 steel while placing itself

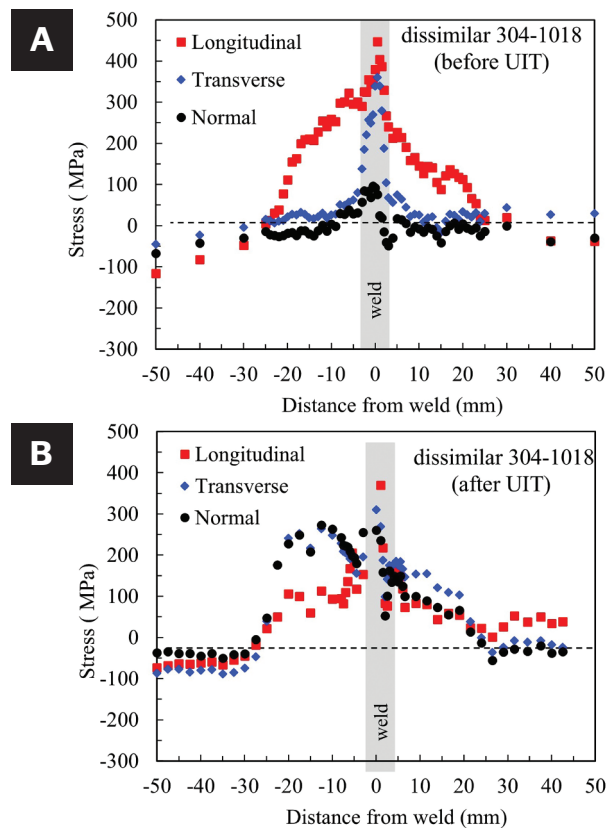


Fig. 14 — Longitudinal, transverse, and normal stress in a 304-1018 DMW: A — Without UIT; B — with UIT. The error of stress calculation is ± 20 MPa.

in compression. This behavior has been shown to reduce longitudinal tensile RS in welds (Ref. 25).

The microstructure in the FZ plays a critical role in RS development. In the 304-1018 DMW, the FZ primarily consists of martensite, formed by the rapid cooling rate and the chemical composition of the base metals, as shown in Table 1. Martensite formation generates compressive stress within the FZ but exerts tensile stress on surrounding areas. A previous study found that the martensitic transformation significantly affects RS distributions in welded joints, particularly in the FZ and heat-affected zone (Ref. 34).

UIT's Effectiveness and Limitations in DMWs

The sensitivity of UIT in DMWs derives from differences in mechanical properties between the base metals and the FZ. These variations can lead to uneven stress redistribution when UIT is applied. In this study, the FZ in DMW was not treated by UIT due to pre-existing compressive stresses from martensite formation; only the orange areas shown in Fig. 5B were treated. These surrounding areas experienced UIT-induced stress redistribution, which influenced the overall RS state of the weld, as shown in Fig. 14B. Therefore, even localized UIT applications can significantly affect the RS state in heterogeneous joints. A similar effect was observed in the

study by Song et al. (Ref. 23). They utilized UIT on electron beam-welded TA15/BTi-6431S dissimilar titanium alloys and found that x-ray diffraction revealed a significant reduction in RS near the FZ after three treatments. This process improved stress uniformity without affecting the material's tensile strength or microhardness.

While UIT can effectively mitigate welding distortions and reduce RS, its application in DMW must be carefully controlled. Variations in thermal expansion, material properties, and microstructure contribute to complex RS distributions, which can be influenced by UIT. Future research should focus on refining UIT techniques and on exploring advanced measurement methods, such as ND, to fully capture RS contributions across all phases in DMW.

Comparison with Prior Studies

The residual-stress modification observed in the present study is consistent with trends reported in earlier investigations of UIT. In similar welds, UIT reduced the peak longitudinal strain from $+373\ \mu\epsilon$ to $-108\ \mu\epsilon$. This indicates a strong relaxation of tensile stress. This behavior aligns with the findings of Cheng et al. (Ref. 14) and Turski et al. (Ref. 13), who also reported formation of a shallow compressive layer ($< 1\ \text{mm}$) at the weld toe and a corresponding reduction in subsurface tensile stresses measured using XRD. For thicker welded sections, Ahmad et al. (Ref. 15) and Gao et al. (Ref. 9) demonstrated that UIT can influence stresses to depths of 4–8 mm. Although the plates in the present study were only 3 mm thick, similar redistribution behavior was observed, confirming that ultrasonic mechanical impacts effectively transport strain energy and relieve tensile RS, even in thin-sheet welds.

In the dissimilar 304–1018 welds, the present results showed that longitudinal strain decreased from $+432\ \mu\epsilon$ to $+26\ \mu\epsilon$ after UIT. This trend is consistent with the observations of Song et al. (Ref. 23), who reported that UIT effectively reduced tensile RS in dissimilar titanium welds without significantly altering microhardness or tensile strength. However, the accompanying increase in transverse and normal strain observed here is attributed to stress redistribution within the thin plate — an effect similarly noted by Gao et al. (Ref. 9). They reported that compressive stress introduction in one direction must be balanced by increases in other components to satisfy mechanical equilibrium.

A comparison with mechanical surface treatments, such as shot peening, further highlights the effectiveness of UIT. Shot peening typically generates a compressive layer only 0.1–0.5 mm deep (Ref. 13), whereas the UIT-induced strain redistribution observed in this work extended across much of the 3 mm plate thickness. This deeper influence helps explain the stronger reduction in longitudinal RS measured through ND. Overall, the present results agree with established UIT behavior reported in the literature while providing new insight into strain and stress redistribution in thin dissimilar welds, where asymmetric phase transformation and constrained geometry lead to unique post-UIT stress patterns.

Conclusions

In this study, UIT was applied to the top and bottom surfaces of similar and DMWs. RS in three orthogonal directions — longitudinal, transverse, and normal — was measured to evaluate the effect of UIT on stress distribution. The following conclusions can be drawn:

- UIT significantly reduced longitudinal RS in similar 1018 steel welds. The peak stress in this direction dropped by nearly 280 MPa. This demonstrates the technique's effectiveness in mitigating large tensile stresses.

- Despite the reduction in longitudinal stress, UIT caused increases in RS in the transverse and normal directions. This is attributed to stress redistribution, where a reduction in one direction leads to compensatory increases in others due to equilibrium constraints. However, these increases were moderate and did not offset the overall benefit of longitudinal stress reduction.

- In DMW, RS behavior was more complex due to differences in CTE and mechanical properties between the 1018 steel and 304 stainless steel. These mismatches influenced how stress developed and was redistributed during both the welding and the UIT processes.

- The FZ in the DMW consisted primarily of martensite, which introduced compressive stress internally but led to tensile stress in the surrounding regions due to volumetric expansion during phase transformation. Because FZ already exhibited compressive RS, it was not directly treated with UIT.

- UIT applications to the surrounding regions still altered the RS distribution significantly. While it reduced longitudinal RS, it increased transverse and normal RS, particularly on the 304 side. This shows the sensitivity of DMWs to UIT and the potential for unintended stress concentrations arising from mismatched material behavior.

Precise control of UIT process parameters is essential to ensure uniform stress relief and avoid introducing undesirable tensile stresses in other directions. Future work should focus on optimizing UIT conditions specifically for the different mechanical and thermal responses of materials like 304 stainless steel and 1018 carbon steel, which can lead to uneven stress redistribution in dissimilar metal welds.

Acknowledgments

This research used resources at the High Flux Isotope Reactor, a Department of Energy Office of Science User Facility operated by the Oak Ridge National Laboratory. The beam time was allocated to HIDRA on proposal number IPTS-15602.

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