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SHORT COMMUNICATION

Experimental investigation on mechanical properties of post-weld heat-treated Inconel 718/316L dissimilar TIG weldments

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சுருக்கம்:
நிக்கல் அடிப்படையிலான சூப்பர் அலாய்கள் மற்றும் ஆஸ்டெனிட்டிக் ஸ்டெயின்லெஸ் ஸ்டீல்களுக்கிடையிலான வேறுபட்ட வெல்டிங் (Dissimilar Welding) அதிக வெப்பநிலை மற்றும் அதிக இயந்திர சுமை நிலைகளில் செயல்படும் மேம்பட்ட பொறியியல் அமைப்புகளை உருவாக்குவதில் மிகவும் முக்கியமானதாகும். இந்த ஆய்வில் Inconel 718 மற்றும் AISI 316L ஸ்டெயின்லெஸ் ஸ்டீல் ஆகியவற்றை தொடர்ந்து மின்சாரம் (continuous current) பயன்படுத்தும் டங்ஸ்டன் இனர்ட் கேஸ் (Tungsten Inert Gas) வெல்டிங் முறையின் மூலம் ERNiCrMo-4 என்ற நிரப்பு உலோகம் உதவியுடன் வெல்ட் செய்யப்பட்டது. வெல்டிங் செய்யப்பட்ட இணைப்பின் இயந்திர பண்புகளின் மீது போஸ்ட் வெல்ட் ஹீட் ட்ரீட்மெண்ட் (Post Weld Heat Treatment, PWHT) ஏற்படுத்தும் தாக்கம் ஆய்வு செய்யப்பட்டது. PWHT செயல்முறையில் மாதிரிகள் 450 °C, 650 °C மற்றும் 850 °C வெப்பநிலைகளில் கட்டுப்படுத்தப்பட்ட உலைவில் 2 மணி நேரம் சூடாக்கப்பட்டு, அதன் பின்னர் காற்றில் குளிர்விக்கச் செய்யப்பட்டன. அடிப்படை உலோகம் (Base Metal), வெப்பத்தால் பாதிக்கப்பட்ட பகுதி (Heat Affected Zone, HAZ) மற்றும் இணைப்பு பகுதி (Fusion Zone, FZ) ஆகிய பகுதிகளில் மைக்ரோஹார்ட்னஸ் மாற்றங்கள் மற்றும் ASTM தரநிலைகளுக்கு ஏற்ப அறை வெப்பநிலையில் டென்சைல் ப்ராபர்ட்டீஸ் ஆய்வு செய்யப்பட்டது. வெல்டிங் செய்யப்பட்ட இணைப்பில் ஃப்யூஷன் சோன் பகுதியில் சுமார் 220 HV என்ற அதிகபட்ச கடினத்தன்மை காணப்பட்டது; மேலும் மிகவும் குறைந்த 9.6% டக்டிலிட்டி பதிவாகியது. 650 °C இல் PWHT மேற்கொள்ளப்பட்டபோது Inconel 718 இல் பிரெசிபிடேஷன் ஸ்ட்ரெங்க்தனிங் ஏற்படுவதால் ஃப்யூஷன் சோன் சுமார் 23% அதிக கடினத்தன்மை பெற்றது. ஆனால் 850 °C இல் ஓவர்-ஏஜிங் மற்றும் கட்டமைப்பு துகள்களின் (Phases) பெரிதாக்கம் காரணமாக சாப்டனிங் ஏற்பட்டது. மேற்கண்ட மாற்றங்களால் டக்டிலிட்டி குறைந்தாலும், 850 °C PWHT செய்யப்பட்ட மாதிரி 416 MPa என்ற அதிகபட்ச டென்சைல் ஸ்ட்ரெங்க்த் மற்றும் 37.8% எலாங்கேஷன் பெற்றது. இது வெல்டிங் செய்யப்பட்ட நிலையை விட 300%-க்கும் அதிகமான மேம்பாட்டை காட்டுகிறது.

Abstract:
Dissimilar welding of nickel-based superalloys with austenitic stainless steels is crucial for the development of advanced engineering systems operating under extreme temperature and mechanical load conditions. This study reports the welding of Inconel 718 to AISI 316L stainless steel by means of continuous current Tungsten Inert Gas (TIG) welding and ERNiCrMo-4 as the filler metal. The influence of post-weld heat treatment (PWHT) on the mechanical properties of the joint has been investigated. PWHT was conducted by heating the samples to 450°C, 650°C, and 850°C for 2 h in a controlled furnace and then cooling them in the air. We examined the microhardness changes in the base metal, heat-affected zone, and fusion zone (FZ), and also the tensile properties at room temperature according to ASTM standards. The welded joint had a peak FZ hardness of nearly 220 HV and a very low ductility of 9.6%. The FZ was about 23% harder due to the strengthening of Inconel 718 by precipitation after PWHT at 650°C, but softening occurred at 850°C due to over-aging and coarser phases. Although the ductility dropped as a result of the above, the material after PWHT at 850°C exhibited the highest tensile strength (416 MPa) and elongation (37.8%), which are more than 300% higher than the welded state.

Keywords: dissimilar TIG welding, Inconel 718, AISI 316L stainless steel, post-weld heat treatment, microhardness, tensile properties

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Introduction

AISI 316L austenitic stainless steel has been a material of choice for nuclear, petrochemical, and thermal power sectors, as it exhibits outstanding corrosion resistance, excellent weldability, and high fracture toughness (1). However, due to the steel's relatively low strength at elevated temperatures, its use has been limited in areas where severe thermal and mechanical stresses are expected. Inconel 718, on the other hand, is a nickel-based superalloy that is precipitation hardened and thus offers better strength, creep resistance, and oxidation stability in high-temperature environments (2). Consequently, various combinations of Inconel 718 and 316L stainless steel are becoming more frequent in advanced engineering components for the achievement of both operational performance and cost effectiveness (3).

Despite their industrial importance, welding Inconel 718–316L stainless steel still presents great challenges due to the presence of large differences in the chemical composition, thermal expansion coefficients, and solidification characteristics of the two metals (4, 5). These differences often result in the formation of residual stress, elemental segregation, and the development of brittle phase in the fusion and heat-affected zones (HAZs), thus weakening the joint integrity (6). Gas Tungsten Arc Welding is generally preferred for dissimilar combinations owing to its superior control over heat input and weld pool stability. However, TIG-welded dissimilar junctions are sometimes characterized by nonuniform microstructures and lower ductility in the as-welded condition (7).

Post-weld heat treatment (PWHT) is a method that is very widely used, among other purposes, to reduce residual stresses, to make microstructures uniform, and to enable good phase transitions (8, 9). Inconel 718 is an alloy system where the effect of PWHT on the change in precipitation phases is very marked (10). However, in 316L stainless steel, the principal effect of PWHT is on stress relaxation rather than on the change in the phase. Although a number of researchers have studied the effects of PWHT on nickel-based welds, either similar or different, there is hardly anyone who has undertaken this for the case of Inconel 718/316L TIG weldments (10, 11). Besides, the existing information often does not provide quantitative relationships of the PWHT temperature vs. the variation of hardness vs. tensile ductility.

This paper experimentally investigates the changes in mechanical properties of Inconel 718/316L dissimilar TIG weldments subjected to PWHT at different temperatures to fill the gap in the literature. The aim is to understand the strength, ductility trade-off and identify a suitable PWHT condition for nuclear and high-temperature structural applications.

Materials and methods

Base and filler materials

The main materials used in this work were wrought Inconel 718 and stainless steel AISI 316L plates, with dimensions of 150 mm × 100 mm × 5 mm. 1.6 mm diameter ERNiCrMo 4 nickel-based filler wire was selected to run a weld with less elemental difference between the layers and reduce the possibility of the formation of brittle intermetallic at the weld interface. The chemical compositions of the base metals and filler wire were determined by optical emission spectroscopy and are given in **Table 1**.

Joint configuration and welding parameters

A single V butt joint configuration with a 45° groove angle and 1.5 mm root face was machined on both plates. The root gap was regularly kept at 2 mm with the help of tack welds. We used a continuous current TIG welding machine to weld in the flat (1G) position. The argon shielding gas was supplied at a constant flow rate of 10 L/min. Welding by two passes ensured that the welds were fully penetrated and well fused. The exact welding parameters are given in **Table 2**.

Post-weld heat treatment

The specimens after welding were permitted to cool gradually to room temperature in air. PWHT was done in a calibrated muffle furnace with a regulated heating rate of 10°C/min. The welded joints were held at 450°C, 650°C, and 850°C for 2 h and then cooled in air to the ambient temperature (**Figure 1**). These temperatures were chosen to demonstrate the stress relief, precipitation strengthening, and over-aging effects, respectively.

Microhardness testing

Microhardness testing was performed using the method outlined in ASTM E92 17. Samples were cut perpendicular to the weld, polished, and tested. Vickers microhardness tests were performed using a 500 gf load and a dwell time of 10 s around the base metal, HAZ, and fusion zone (FZ) areas.

Tensile testing

Sub-size tensile samples were made according to ASTM E8/E8M 16a standards. The tests were carried out at room temperature using a universal testing machine with a constant crosshead speed of 1 mm/min. Three specimens

TABLE 1 | Composition of main alloying elements (wt.%) present in base/filler metals.

Metal/wire	Ni	Fe	Cr	Mo	Mn	Si	C	P	Cu	Others
AISI 430	-	Bal	16.19	-	0.32	0.37	0.04	0.025	-	S-0.005
Inconel 718	Bal	20.08	17.26	2.8	0.20	0.10	0.03	0.09	0.12	Nb- 4.9, Ti-0.73, Co-0.38, Al-0.28, S-0.012
ERNiCrMo-4	Bal	5.50	15.84	16.26	0.51	0.04	0.02	0.007	-	-

TABLE 2 | Welding parameters used for joining dissimilar plates.

No. of pass	Current, I (A)	Voltage (V)	Time taken for welding (s)
First pass	140	12	36
Second pass	140	12	34

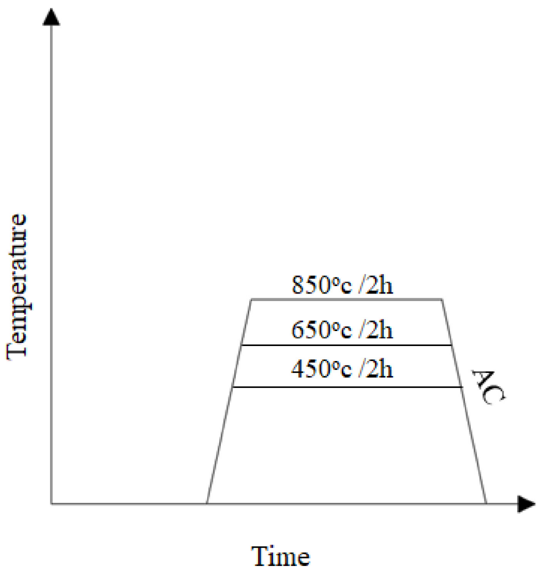

FIGURE 1 | Process of post-weld heat treatment (PWHT).

were tested for each condition at a minimum to guarantee the results, and the average values are presented.

Results and discussion

Microhardness distribution

Figure 2a–d shows the microhardness profiles of the Inconel 718/316L dissimilar welds in as-welded and PWHT conditions. In the as-welded condition, the FZ showed a hardness level (~220 HV) that was between the 316L base metal (~185 HV) and the Inconel 718 base metal (~406 HV), thus indicating compositional dilution and rapid solidification effects.

Post-weld heat treatment (PWHT) at 450°C brought about a slight increase in the hardness of the FZ, which was mainly due to stress relaxation and minimal precipitation in the Inconel-rich regions. A considerable rise in hardness was demonstrated after PWHT at 650°C, with the FZ hardness going up to ~271 HV, implying that precipitation strengthening caused by phase formation in Inconel 718 was responsible. On the other hand, PWHT at 850°C resulted in the decrease of hardness (~243 HV), which has been explained by precipitate coarsening and overaging phenomena. Thus, the obtained results indicate that the PWHT temperature is a parameter of utmost importance in controlling the hardness changes of dissimilar weldments.

Tensile properties

The engineering stress/strain curves for all conditions are presented in Figure 3a–d, and the corresponding tensile properties are listed in Table 3. The as-welded joint showed very limited ductility (9.6%) with a ultimate tensile strength (UTS) of 355 MPa, thus demonstrating a rather brittle behavior mainly due to the presence of residual stresses and microstructural heterogeneity.

Post-weld heat treatment (PWHT) at 450°C and 650°C has led to significant increases in elongation (29.7% and 32.8%, respectively), whereas the tensile strength only varied slightly. The greatest upgrade was found at 850°C, where the joint had a UTS of 416 MPa and an elongation of 37.8%. The joint became stronger and more ductile at the same time, as the hardness decreased; this indicates that the weld interface had fewer stresses and was able to undergo more plastic deformation. The study underlines the role of PWHT in adjusting mechanical properties to meet the specific needs of the service.

Conclusion

This research clearly shows that the mechanical properties of Inconel 718/AISI 316L dissimilar TIG weldments can be effectively controlled through PWHT. The microstructure-related hardness led to the microcrack formation and brittle failure of the weld metal. The tensile strength of the weld at 450°C heat treatment was greater than that of the welds at 650°C and 850°C heat treatment because the different microstructures have different strength levels. The strength of the weld metal at 450°C heat treatment was higher than that of those at 650°C and 850°C heat treatment because the nanostructures in the microstructures have different strength

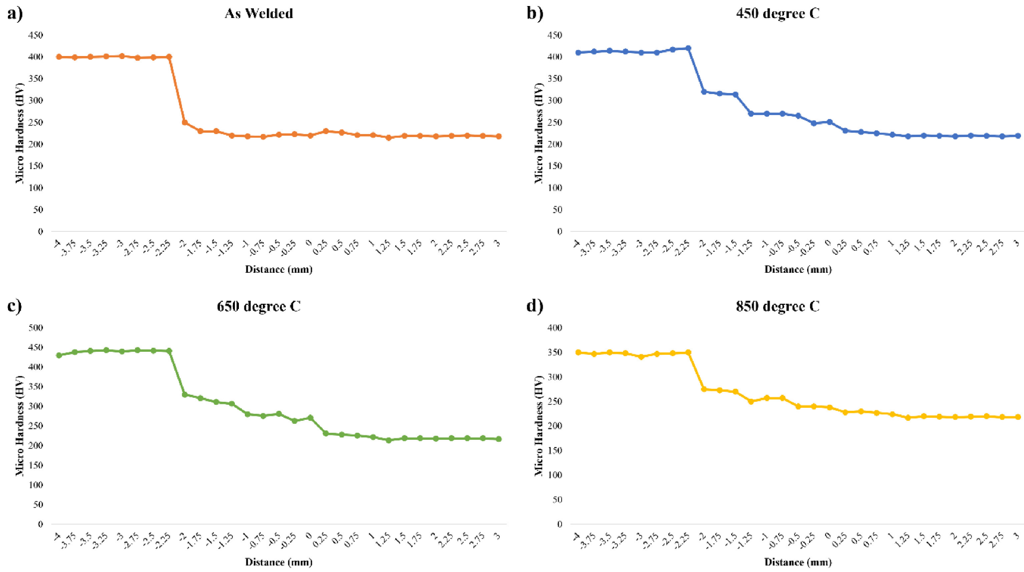

FIGURE 2 | Microhardness distribution at welded condition (a), at 450°C (b), 650°C (c), and 850°C (d).

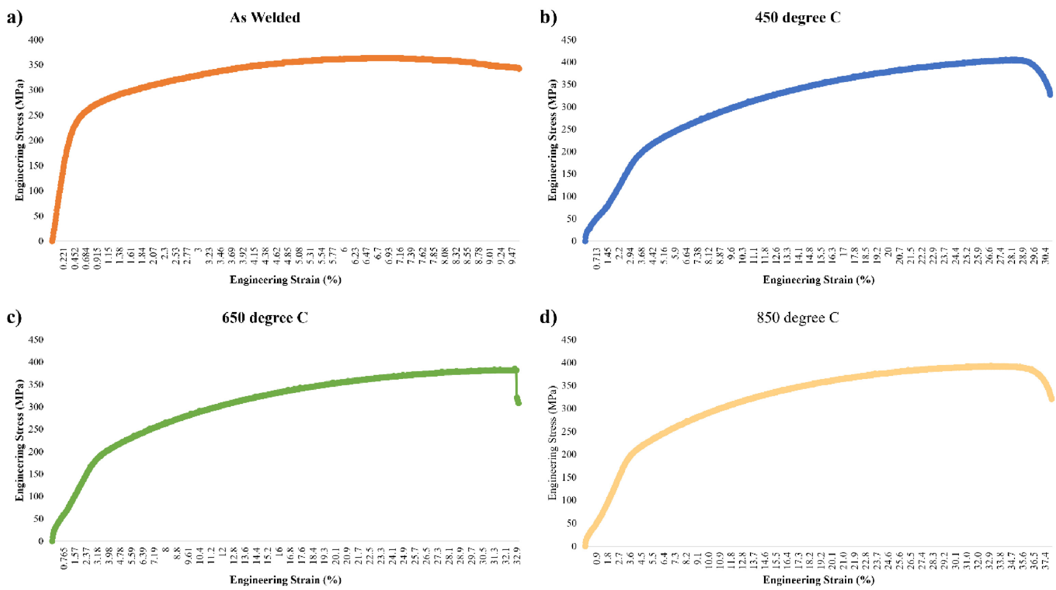

FIGURE 3 | Engineering stress vs engineering strain curve at welded condition (a), at 450°C (b), 650°C (c), and 850°C (d).

levels. The results of the tests suggest that 850°C PWHT will be the right decision to make if your nuclear, high-temperature service, and other structural applications need to have toughness and mechanical reliability enhanced.

TABLE 3 | Tensile properties of Inconel 718/316L joints at different PWHT.

Specimens	Ultimate tensile strength (MPa)	Fracture elongation (%)
As Welded	355	9.6
450°C	398	29.7
650°C	375	32.8
850°C	416	37.8

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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