Selection of Optimal Filler Metal for Dissimilar Welding of SA335 Gr. P11 and Incoloy 800 in Primary Reformer Tube Catalyst Repairs

A Mechanical Property Analysis

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ABSTRACT

This investigation explores the effect of various filler metals on the mechanical performance of dissimilar weld joints between SA335 Gr. P11 and Incoloy 800, with particular relevance to repair operations in primary reformer tube catalysts used in petrochemical plants. The joining technique employed was Gas Tungsten Arc Welding (GTAW). Three different filler metals: ER-NiCr-3, ER-NiCrMo-3, and ER-NiCrCoMo-1, were evaluated, and their performance was assessed using tensile strength and hardness testing across the weld metal, the Heat-Affected Zone (HAZ), and the base materials. The findings demonstrate that ER-NiCrMo-3 achieved the highest tensile strength, reaching approximately 60 kgf/mm², which was superior to the values recorded for ER-NiCr-3 and ER-NiCrCoMo-1. With respect to hardness, the Vickers hardness of the base material (BM-1, SA335 Gr. P11) was found to be 234.7 HV when welded with ER-NiCr-3, 217.6 HV with ER-NiCrMo-3, and 223.8 HV with ER-NiCrCoMo-1. However, in the HAZ-1 region, ER-NiCrMo-3 again displayed the greatest hardness value, reaching 299.4 HV, thereby outperforming the alternative fillers. The study contributes to the optimization of filler metal selection for dissimilar welding in repair applications within the petrochemical sector. By demonstrating that the use of ER-NiCrMo-3 not only enhances mechanical performance but also has the potential to reduce repair time from 252 days to 90 days, the study highlights significant opportunities to improve plant reliability and achieve cost savings in large-scale industrial operations.

Keywords-dissimilar welding; SA335 Gr. P11; Incoloy 800; filler metal selection; mechanical properties

I. INTRODUCTION

In the petrochemical sector, the primary reformer represents a critical unit in the overall production chain, as it is responsible for converting hydrocarbons into synthesis gas through catalytic reforming [1-3]. The continuous and demanding operating conditions to which this equipment is exposed frequently result in progressive degradation, including the initiation and propagation of cracks in key components such as catalyst tubes. When such failures occur in high-temperature environments, they can severely compromise plant efficiency, ultimately causing extended downtime and significant production losses [2]. Addressing the repair and maintenance of these components remains a major challenge, particularly because the process often necessitates welding between dissimilar alloys, most notably Incoloy 800 and SA335 Gr. P11 [4].

The restoration of tube catalyst materials in reformers involves welding techniques, as these are essential for reinstating their operational performance. However, when dissimilar alloys such as Incoloy 800 and SA335 Gr. P11 are joined, several technical challenges arise, particularly regarding the selection of suitable filler metals that can provide sufficient mechanical integrity and long-term durability under demanding service conditions. Among the available joining methods, the GTAW is frequently employed due to its high level of precision and ability to produce welds of superior quality [5]. Nonetheless, the overall efficiency of welding dissimilar materials is based on the characteristics of the filler metal applied, which influence the key mechanical properties of the joint, including tensile strength and hardness [6-8].

Filler metals, such as ER-NiCr-3, ER-NiCrMo-3, and ER-NiCrCoMo-1, are employed for welding Incoloy 800 to SA335 Gr. P11, primarily because of their suitability for high-temperature service and their capacity to enhance the structural reliability of welded joints [5]. Alloying additions, particularly molybdenum and cobalt, contribute to improving the tensile strength of the weld metal and reducing its susceptibility to cracking. These characteristics render such filler metals highly applicable in industrial environments where components are continuously exposed to elevated operational temperatures [9-12].

Although the advantages of various filler metals have been widely acknowledged, a considerable research gap persists regarding the extent to which differences in their composition affect both the repair duration and the mechanical performance of dissimilar weld joints operating under high-temperature conditions. This gap is particularly relevant to the petrochemical industry, where equipment reliability is critical. The present study, therefore, investigates the effect of alternative filler metals on the mechanical behavior of welded joints between Incoloy 800 and SA335 Gr. P11, with a specific emphasis on improving repair strategies for primary reformers. By refining the welding procedure, the research seeks not only to enhance the strength and durability of the welds but also to reduce repair schedules from 252 days to 90 days, thereby improving plant efficiency and minimizing downtime within petrochemical operations.

II. METHODOLOGY

This research examines the influence of different filler metals on the mechanical performance of dissimilar weld joints between Incoloy 800 and SA335 Gr. P11, with a particular focus on their application in the repair of tube catalysts within primary reformers. The experimental procedure was structured into several stages, including material preparation, welding, and subsequent mechanical testing, each designed to evaluate the suitability of the welded joints under the demanding conditions of petrochemical operations.

The base materials selected, Incoloy 800 and SA335 Gr. P11 pipes are utilized in the fabrication of primary reformer tubes owing to their proven durability at elevated temperatures. For this study, pipes with a diameter of 6 inches and a thickness of 9 mm were sectioned into 200 mm length pieces and prepared with V-groove bevels to facilitate welding. The joining process employed three distinct filler metals: ER-NiCr-3, ER-NiCrMo-3, and ER-NiCrCoMo-1, each characterized by unique chemical compositions. These fillers were deliberately chosen to enable a comparative evaluation of their impact on the tensile strength and hardness of the resulting welds. The detailed chemical compositions of both the base alloys and the filler metals are presented in Table I.

TABLE I. CHEMICAL COMPOSITION OF MATERIALS AND FILLER METALS

Material	Min. UTS (MP.)	Chemical Composition (%)				
SA.335 Gr. P11	415	Fe	Ni	Cr	Si	Ti
		96.11	0.25	1.15	0.91	0.01
		Nb	Mn	Mo	Al	Cu
		0.01	0.47	0.53	0.56	0.08
		S	P	V		
		0.13	0.03	0.01		
Incoloy 800	515	Fe	Ni	Cr	Si	Ti
		36.77	32.93	27.01	1.41	
		Nb	Mn	Mo	W	Cu
		0.81	0.73	0.07	0.07	0.06
ERNiCr-3 (Inconel 82)	620	Fe	Ni	Cr	Si	Ti
		1.42	73.66	19.33	0.44	0.38
		Nb	Mn	V		
		2.28	2.72	0.07		
ERNiCrMo-3 (Inconel 625)	790	Fe	Ni	Cr	Si	Ti
		0.45	71.21	13.71	0.72	0.48
		Nb	Mn	Mo	Al	Pb
		2.95	-	9.67	0.51	0.29
ERNiCrCoMo-1 (Inconel 617)	700	Fe	Ni	Cr	Si	Co
		1.65	56.2	17.39	1.6	10.79
		Sn	Pd	Mo	Zr	Cu
		1.33	0.7	9.96	0.30	0.09

The welding was carried out using the GTAW technique, as summarized in Table II, owing to its precision and ability to deliver high-quality joints. To maintain consistency across all experimental samples, the principal welding parameters—namely current, voltage, and travel speed—were kept uniform for each of the selected filler metals. The process employed an AC/DC TIG welding power source, with a maximum current capacity of 500 A, an operating voltage of 40 V, and a duty cycle of 60%. Within this framework, the welding parameters were set to a current range of 100–120 A, a voltage of 13–15

V, and a travel speed of 56-70 mm/min. High-purity argon was utilized both as a shielding gas and as a backing gas, supplied at a flow rate of 12–15 L/min to ensure adequate protection of the molten pool. In addition, Post-Weld Heat Treatment (PWHT) was applied to relieve residual stresses and to improve the overall mechanical performance of the dissimilar weld joints.

TABLE II. WELDING PARAMETERS

Material	3” Pipe SA.335 Gr. P11 / 3” Pipe Incoloy 800		
Welding process	GTAW	GTAW	GTAW
Filler metal	ERNiCr-3	ERNiCrMo-3	ERNiCrCoMo-1
Filler trade name	NIN-82R	NIN-625R	DAIKO SF 617
Filler diameter (mm)	2.4	2.4	2.4
Arus (Ampere)	100-120	100-120	100-120
Polatity	DCEN	DCEN	DCEN
Voltage (volt)	13-15	13-15	13-15
Length of weld (mm)	280	280	280
Duration time /pass (min)	10-15	10-15	10-15
Travel speed (mm/min)	56 – 70	56 -70	56 -70
Heat input (kJ/mm)	1.4 -1.5	1.4 -1.5	1.4 -1.5
Shielding gas	Argon 99.999%		
Backing gas	Argon 99.999%		
Shielding gas flow	12-15 L/m		
Backing gas	12-15 L/m		
Tungsten electrode	EWTh-2, 2.4mm		
Welding position	2G-Horizontal		
Interpass temperature	150 max.		

Two mechanical tests were conducted to evaluate the performance of the welded joints, namely tensile testing and hardness testing. For the tensile tests, specimens were carefully sectioned from the welded joints in accordance with the ASME BPVC IX standard. These specimens were then subjected to uniaxial loading using a Galdabini 2007 testing machine with a maximum load capacity of 100 kN, and the tests were continued until fracture occurred. The resulting data provided a direct measure of the tensile strength of the welds.

In addition, hardness testing was carried out using a Proceq portable Equotip 550 LEEB hardness tester, which measured Vickers hardness at predetermined locations along the welded joint, as illustrated in Figure 2. Measurements were recorded at four critical points: the BM-1, the HAZ-1, the WM, and the HAZ-2. The hardness values obtained at these locations were essential for assessing the resistance to plastic deformation and for determining the overall structural integrity of the welded joints. Collectively, the tensile and hardness tests offered a comprehensive characterization of the mechanical behavior of the welds, thereby providing assurance of their reliability and durability in high-temperature service conditions.

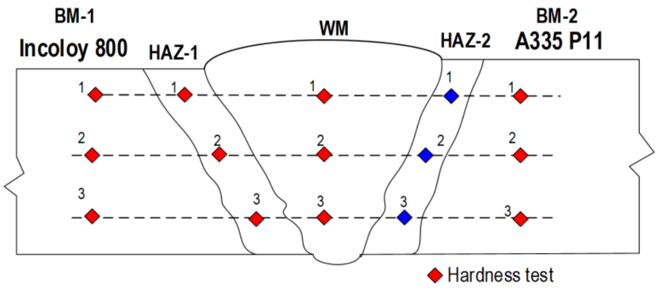


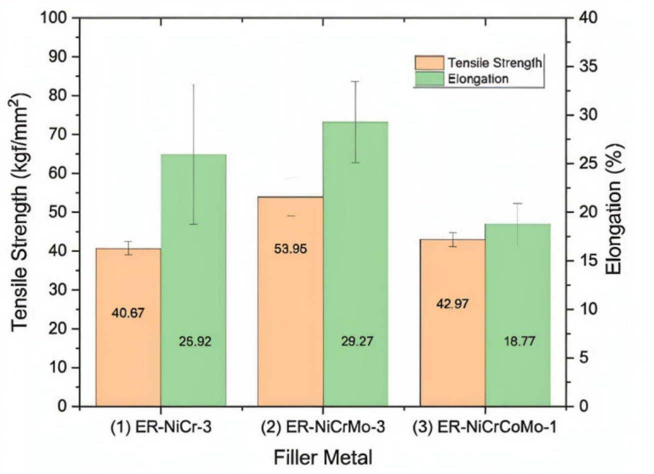
Fig. 1. Hardness testing locations on welded joints.

III. RESULTS AND DISCUSSION

The mechanical performance of the welded joints was systematically assessed using two principal tests: tensile testing and Vickers hardness measurement. These evaluations were conducted to determine the behavior of dissimilar joints between Incoloy 800 and SA335 Gr. P11, produced using the GTAW process with three alternative filler metals: ER-NiCr-3, ER-NiCrMo-3, and ER-NiCrCoMo-1. The tensile test results, presented in Figure 3, illustrate the comparative tensile strength and elongation achieved with each filler metal, providing insights into their relative effectiveness in enhancing joint performance.

As depicted in Figure 3, the filler metal ER-NiCrMo-3 demonstrated superior performance compared with the other candidates, achieving the highest tensile strength of approximately 60 kgf/mm², which was markedly higher than that of ER-NiCr-3 (45 kgf/mm²) and ER-NiCrCoMo-1 (40 kgf/mm²). This enhanced performance can be attributed to the presence of molybdenum in ER-NiCrMo-3, which improves the resistance to thermal stresses and reduces susceptibility to crack formation, thereby making it more suitable for high-strength applications. In contrast, ER-NiCr-3, although providing acceptable weldability, displayed lower tensile strength and reduced durability under load. A closer examination of the detailed results further highlights these differences. ER-NiCr-3 exhibited the lowest tensile strength at 40.67 kgf/mm², accompanied by an elongation of 25.92%. These results suggest that, while it offers moderate ductility, its overall strength is insufficient when compared with the other fillers. ER-NiCrMo-3, in contrast, achieved a tensile strength of 53.95 kgf/mm² and the highest elongation at 29.27%, reflecting a favorable balance between strength and ductility. Meanwhile, ER-NiCrCoMo-1 recorded a tensile strength of 42.97 kgf/mm², which was greater than that of ER-NiCr-3, yet its elongation was considerably lower at 18.77%. This indicates that although ER-NiCrCoMo-1 provides reasonable strength, its limited flexibility makes it less suitable for applications involving substantial mechanical stresses.

In addition to the tensile tests, Vickers hardness measurements were conducted at critical regions of the welded joints in order to evaluate the resistance of the material to plastic deformation. As portrayed in Figure 4, hardness values were recorded at four distinct locations: the BM-1, the HAZ-1, the WM, and the HAZ-2. The data obtained from these measurements provided further insights into the mechanical behavior of the joints and enabled a comparative assessment of the effectiveness of each filler metal under varying service conditions.



Filler 1

Filler 2

Filler 3

Fig. 2. Comparison of tensile strength and elongation for different filler metals.

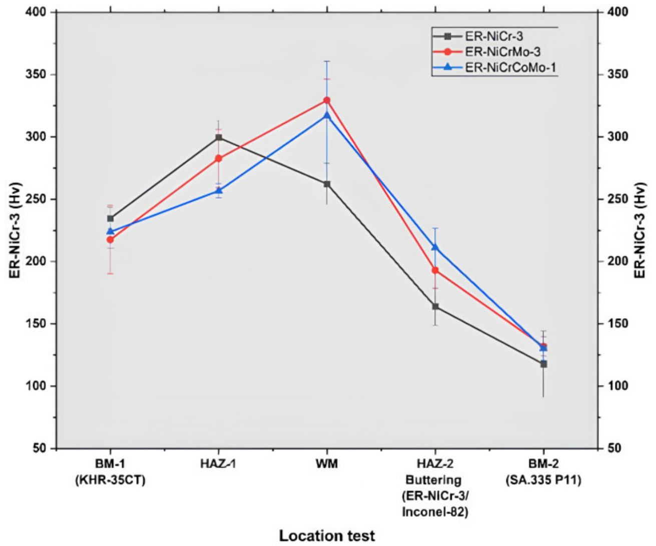


Fig. 3. Vickers hardness values at different testing locations for various filler metals.

As displayed in Figure 4, the hardness measurements revealed distinct variations among the filler metals. At the BM-1 location (Incoloy 800), the highest Vickers hardness was recorded for ER-NiCr-3 at 234.7 HV, indicating that it offers superior surface hardness in the base material compared to ER-NiCrMo-3 (217.6 HV) and ER-NiCrCoMo-1 (223.8 HV). In contrast, within the HAZ-1 and HAZ-2 as well as the WM, ER-NiCrMo-3 exhibited significantly higher hardness values, reaching 299.4 HV and 329.4 HV, respectively. These elevated values suggest that ER-NiCrMo-3 provides enhanced resistance to plastic deformation, particularly in regions exposed to severe thermal gradients, such as the HAZ and WM.

The hardness test outcomes, therefore, complement the tensile test findings, collectively reinforcing the superior performance of ER-NiCrMo-3 in critical regions where thermal stability and deformation resistance are required. This highlights the suitability of ER-NiCrMo-3 for demanding service environments, such as primary reformers, where welded joints are continuously subjected to high operating temperatures and substantial mechanical stresses.

The combined outcomes of the tensile and Vickers hardness tests demonstrate the considerable effect of the filler metal composition on the mechanical performance of welded joints, particularly when joining dissimilar alloys, such as Incoloy 800 and SA335 Gr. P11. Among the consumables examined, ER-NiCrMo-3 emerged as the most appropriate option for applications that demand both high tensile strength and long-term durability. This superiority is reflected in its enhanced tensile strength and hardness across critical regions of the joint. The inclusion of molybdenum within ER-NiCrMo-3 is especially significant, as it contributes to improved resistance against thermal stresses and supports the retention of structural integrity under elevated loading conditions. ER-NiCr-3, although exhibiting relatively good surface hardness in the base material, displayed inferior performance in terms of both tensile strength and hardness when compared with ER-

NiCrMo-3. This suggests that ER-NiCr-3 could be advantageous in situations where surface hardness in the base material is a primary requirement, yet it is less effective in zones exposed to substantial stress. Similarly, ER-NiCrCoMo-1, while providing a moderate level of strength, revealed lower elongation and reduced hardness relative to ER-NiCrMo-3, which limits its suitability for repair applications that demand both flexibility and mechanical robustness.

The weld-zone temperature gradient during the welding, cooling, and post-weld stages is a key factor in distortion. Experiments on ASTM A36 (EN S275) steel welded through the MAG process, using AWS A5.18 ER70S-6 electrode and cooled in air, water, and ice, showed a maximum distortion of 3.13 mm in the air-cooled specimen [13]. For TMCP-grade EH-36 steel, the FEM analysis of hybrid GTAW-SMAW welding demonstrated that ultrasonic stress relief reduced residual stress from 193.4 MPa to 39.1 MPa, with deformation predictions closely matching the experiments [14].

Copper welding is challenging due to its high thermal conductivity; studies on copper-to-copper GTAW with ERCuNi 90/10 filler showed that a higher heat input (1.2 kJ/mm) improved penetration, yielding 180 MPa tensile strength and 132.12 HV hardness through dendritic refinement, while a lower input (1.09 kJ/mm) preserved thermal conductivity (206.72 W/mK) by limiting nickel dilution [15]. The applied computation simulation modeling of St-37 steel fishing boats predicted 340 MPa maximum stress under 4200 N at 6 mm hull thickness [16], and the SMAW welding of API 5L X42 pipelines revealed weld hardening and reduced elongation, highlighting metallurgical issues in hydrocarbon transport systems [17].

Previous studies on dissimilar metal welding have explored various material combinations and welding processes. For instance, research on SA335 P11 and SA312 TP304 employed the GTAW method with ER309L filler metal. It was concluded that the mechanical properties and microstructure of the weldment—including carbon migration and carbide formation—were significantly influenced by the compositional differences between the base metals, underscoring the importance of appropriate filler metal selection (ER309L) [18].

Further investigations explored the interfaces of high-temperature alloys. An examination of Incoloy 800H and 321 Stainless Steel using microstructural analysis (Optical Microscopy and SEM) with Inconel 82 and Inconel 617 fillers found that Inconel 617 was superior. This superiority stemmed from its tendency to promote epitaxial growth, which enhanced the weld's strength and ductility, whereas Inconel 82 resulted in more extensive grain boundary migration and the formation of an unmixed zone [19]. Similarly, a study on dissimilar welds between HP heat-resistant steel and Incoloy 800 with various fillers (309 SS, Inconel 82, Inconel 182, Inconel 617) stressed that the Inconel 617 weld exhibited favorable precipitates and epitaxial growth. In contrast, Inconel 82 showed excessive grain boundary migration, and 309 SS posed a risk of cracking [20].

Research has also focused on ferrite/martensitic steels. Single-pass Activated TIG (A-TIG) welding of P91 and AISI 316L utilized Incoloy 800 and Inconel 600 interlayers, demonstrating that Inconel 600 produced an optimal fully austenitic structure and that the interlayers significantly reduced carbon migration while boosting the weld's impact toughness and ductility [21]. However, studies involving the laser welding of P91 and Incoloy 800HT revealed that although full penetration was achieved, the joints were susceptible to solidification cracking in the Incoloy 800HT fusion zone, leading to unsatisfactory impact toughness, especially after PWHT, and indicating difficulties in achieving a reliable joint [22, 23]. The application of multi-pass GTAW on P91 and Incoloy 800HT using AWSER90S-B9 filler confirmed the necessity of PWHT to enhance tensile strength and mitigate excessive hardness and mechanical non-linearity, albeit at a slight sacrifice in impact toughness [24].

Alternative material pairings and techniques have also been explored, such as TIG welding of 304L and Incoloy 800HT with S Ni 6082 filler, which yielded joints with satisfactory tensile strength and no defects, displaying desirable epitaxial growth on the Incoloy 800HT side [25]. Additionally, studies on thinner gauge materials, like the filler-less TIG welding of Inconel 625 and Incoloy 800, identified that higher welding currents (60 A) maximized tensile strength and resulted in the highest residual stresses [26]. Finally, investigations into 316LN and Alloy 800 joints using various nickel-based fillers found that Inconel 182 exhibited superior long-term metallurgical stability against brittle sigma phase precipitation after high-temperature aging, unlike the 316 stainless steel filler [27]. Similar research on SMAW joints between P91 (with IN82 buttering) and Alloy 800 using IN182 filler showed that high-temperature tensile failure consistently occurred in the P91 base metal, with peak hardness recorded in the P91 HAZ [28].

Despite the extensive body of work reviewed, a clear research gap remains, as the literature has not specifically investigated the dissimilar weld joint between the low-alloy steel SA335 Gr. P11 and the nickel alloy Incoloy 800. Furthermore, existing studies primarily focused on different filler metal groups (e.g., ER309L, Inconel 82, AWSER90S-B9). Consequently, no preceding work has systematically applied the GTAW method to the P11/Incoloy 800 pairing while evaluating the specific nickel-based fillers: ER-NiCr-3, ER-NiCrMo-3, and ER-NiCrCoMo-1. The current study directly addresses this void, offering a novel contribution by demonstrating that, for this precise dissimilar joint, the ER-NiCrMo-3 filler yields the highest tensile strength and hardness within the HAZ, thus establishing it as the most effective choice among the three nickel-based fillers tested.

IV. CONCLUSION

This study examined the influence of three different filler metals: ER-NiCr-3, ER-NiCrMo-3, and ER-NiCrCoMo-1, on the mechanical performance of dissimilar joints between SA335 Gr. P11 and Incoloy 800, produced by Gas Tungsten Arc Welding (GTAW). The assessment was conducted through tensile testing and hardness measurements across the weld metal, Heat-Affected Zone (HAZ), and base materials. The findings indicate that the choice of filler metal significantly affects the mechanical properties of the welded joints. Among the three fillers tested, ER-NiCrMo-3 demonstrated the most superior performance, achieving a tensile strength of approximately 60 kgf/mm² and hardness values of up to 329.4 HV within the HAZ and weld metal. This highlights the ability of ER-NiCrMo-3 to produce welds with enhanced mechanical resistance compared with ER-NiCr-3 and ER-NiCrCoMo-1. Such improved performance is particularly crucial for ensuring the reliability of joints operating under extreme service conditions in petrochemical environments. Furthermore, the application of ER-NiCrMo-3 was shown to have a significant impact on operational efficiency, potentially reducing repair duration from 252 days to only 90 days. This reduction is highly relevant to the repair of primary reformer tubes in the petrochemical industry, as it minimizes downtime while improving overall productivity. Therefore, the adoption of ER-NiCrMo-3 as the primary filler metal may be regarded as the optimal solution, offering both technical and economic advantages.

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