

A Review on The Effect of Post-Weld Heat Treatment (PWHT) on Its Thermal Analysis and Mechanical Properties of Welded Metallic Pipe

Nurul Shahadah Roslan¹, Muzzahir Mohmad Hadzir², Iman Fitri Ismail¹,
Mohamad Nur Hidayat Mat³, Eliza M. Yusup^{1*}

¹ Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA

² PETRONAS Technical Services Sdn. Bhd.,
Kompleks Bersepadu Pengerang (PIC), 81600 Pengerang, Johor, MALAYSIA

³ Faculty of Mechanical Engineering,
Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, MALAYSIA

*Corresponding Author: elizay@uthm.edu.my

DOI: <https://doi.org/10.30880/ijie.2024.16.02.031>

Article Info

Received: 3 April 2024

Accepted: 12 June 2024

Available online: 17 August 2024

Keywords

PWHT, residual stress, temperature distribution, transient thermal, ansys software

Abstract

Welding is a commonly used process in manufacturing and engineering, and it may create residual stress in the welded region that can cause problems during service. Thermal expansion of the post-weld heat treatment (PWHT) of steel carbon induces residual stress. To relieve the internal stresses in the weld zone, PWHT is used to soften the hardening zone, improve microstructures, and lower hydrogen content in the welded region. The pipe size, heating width, insulation conditions, heating rates, soaking temperature, and holding time are factors that influence PWHT procedures. This paper will explain clearly about the PWHT process and the effect of PWHT on the metallic metal.

1. Introduction

PWHT is a process that is applied after welding and involves heating a welded material to a temperature below its critical transformation temperature and holding it for a predetermined period of time [1]. This process can be classified into three forms: annealing, normalizing, and quenching [2].

- i. Annealing – used to soften the metal for forming or machining. Annealing process can reduce the internal stress, remove defects, increase the ductility, increase toughness and decrease hardness.
- ii. Normalizing – used to provide uniformity in particle size. Normalizing improves the toughness of the steel and reduces its hardness, improve plasticity, and reduces cracking.
- iii. Quenching – used to harden iron-based metals. Quenching improves the hardness and brittleness of the metal, and improve the elastic limit. It also has high internal stress.

PWHT is used to alleviate welding-induced stresses in materials, as prescribed by the code of construction, and may also be required to relieve the stresses created during welding in certain service environments. If stress corrosion cracking, distortion, fatigue cracking, premature failure, and acceleration occur, it can be caused by locked-up stress [2].

1.1 Ferrous Metal in Piping

Ferrous materials, such as steel, are commonly used in manufacturing, construction, and building structures due to their widespread availability, low cost, high strength, and versatility. The production of steel is increasing globally as a result of industrialization, which reflects the growing demand for this material due to its versatility and ease of fabrication into various forms [3].

This is an open access article under the CC BY-NC-SA 4.0 license.



1.1.1 Stainless Steel Pipe

Stainless steel (SS) stands out for its resistance to corrosion and durability, primarily due to its chromium (Cr) content of at least 10.5%, which forms a protective oxide layer that prevents oxidation and corrosion [4]. The various types of SS, including austenitic, ferritic, and martensitic, each have distinct properties and applications. Austenitic stainless steel, with up to 0.15% carbon, at least 16% Cr, and often nickel (Ni) or manganese (Mn), excels in high-temperature strength, toughness, and formability, making it highly versatile from cryogenic to elevated temperatures [5]. Despite its many advantages, austenitic SS's high nickel content can drive up costs and may lead to price volatility due to market fluctuations.

Ferritic stainless steel, with 14-27% Cr and no nickel, offers a cost-effective alternative with decent corrosion resistance. However, its lower toughness and non-heat-treatable nature limit its use in demanding applications [6]. Being magnetic, ferritic SS also finds niche applications in household appliances and automotive parts where magnetic properties are advantageous.

Martensitic stainless steel, containing 11.5-18% Cr, combines corrosion resistance with heat-treatable properties, providing a wide range of hardness and strength levels [7]. This makes it suitable for applications requiring high strength and wear resistance, such as cutlery, surgical instruments, and valve components. However, its lower corrosion resistance compared to austenitic SS necessitates careful consideration in environments where corrosion is a significant concern.

In industrial applications like heat exchangers and furnaces, SS pipes are preferred to avoid iron dissolution, despite being three times more expensive than carbon steel (CS) pipes. The cost is mitigated by using thinner walls due to SS's superior strength and corrosion resistance, often omitting corrosion allowances [8]. This approach underscores the economic balance between material costs and performance requirements.

The ASTM A-403 standards for wrought austenitic SS piping fittings mandate solution heat treatment above 1000 °C followed by rapid cooling to ensure optimal mechanical properties and corrosion resistance [9]. For welded joints of AISI 321 SS and AISI 347 SS, stabilisation heat treatment at specific temperatures induces the precipitation of stabilising elements like Ti or Nb. These elements form carbides (TiC or NbC) that prevent chromium depletion and regulate sensitization, enhancing the durability and longevity of the stainless steel in high-temperature applications [10].

In summary, the choice among austenitic, ferritic, and martensitic SS depends on specific application needs, balancing cost, mechanical properties, and corrosion resistance. While austenitic SS offers superior performance in a wide range of environments, ferritic and martensitic SS provide cost-effective solutions with specific advantages in magnetic properties and heat-treatability, respectively. The careful application of heat treatments and material selection is crucial to optimizing the performance and longevity of stainless-steel components in various industrial contexts.

1.1.2 Cast Iron Pipe

Cast iron with a carbon content of 2-6.67% is a brittle metal with low ductility and malleability. It cannot be drawn, rolled or shaped due to its low ductility, but it can be easily melted and machined into complex shapes, making it a suitable material for various valve bodies because of its properties [4].

The journal article by Pouranvari et al. emphasized that cast iron is a difficult material to weld due to its inherent brittleness and the impact of the welding thermal cycle on its metallurgical composition, resulting in four distinct zones when welded [5]. These zones include:

- i. Fusion Zone (FZ), where melting occurs during the welding process and is resolidified upon cooling,
- ii. Partially Melted Zone (PMZ), which is the area immediately outside the FZ where liquation can occur during welding,
- iii. Heat Affected Zone (HAZ), which undergoes microstructural changes without melting, and the base metal (BM), whose structure remains unaffected during the weld thermal cycle.

Fig. 1 shows the correlation between the microstructural zone temperature and Fe-C phase diagram [6]. High-carbon cast iron produces hard brittle phases such as martensite and carbides in the FZ, PMZ, and HAZ, which can cause joint cracking and negatively impact weld ductility, toughness, and machineability owing to their hardness and brittleness [7], [8], [9], [10].

The factors that impact cast iron welding include the type of cast iron, its chemical composition, filler metal composition, original matrix structure, welding technique, and pre- and post-heat treatment [9], [10], [11], [12], [13], [14], [15], [16].

Grey cast iron is fragile and often unable to withstand cooling weld forces. However, the inclusion of graphite clusters in malleable iron and nodular graphite in ductile cast iron increases ductility and enhances weldability [17]. Martensite formation in HAZ is less likely in ductile cast irons and malleable irons, making them easier to weld, especially when the matrix consists of high ferrites. White cast iron, which is extremely hard and contains iron carbides, is typically considered unweldable [13], [17]. Cast iron welding techniques include oxyacetylene

and arc welding methods [16], [18], [19] with diffusion bonding, friction welding, and electron beam welding also being studied by researchers [20], [21], [22], [23], [24].

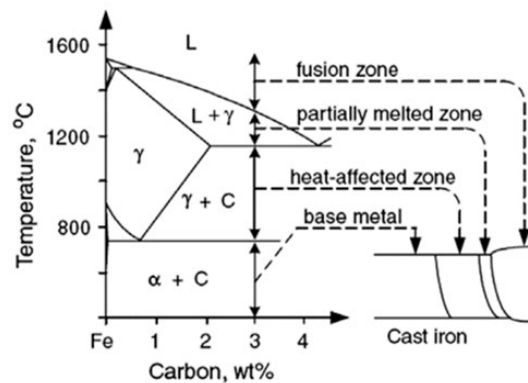


Fig. 1 Temperature experienced by various microstructural zones in a cast iron weld [6]

Welding cast iron involves three filler metals: nickel/nickel-iron-based, cast iron filler metal, and mild/low carbon steel filler metal. Mild steel electrodes are commonly used for gray cast iron welding because of their low price [25], but they also have metallurgical issues.

- i. Steel contracts more during solidification than grey cast iron, making the FZ more susceptible to shrinkage cracking due to tensile stresses [13], [18].
- ii. The use of a mild steel electrode mixed with high-carbon cast iron results in a hard and brittle weldment, reducing its impact characteristics and potentially causing a crack in the heat-affected zone. Steel electrodes should only be used when the joint is not under tension or bending forces.
- iii. High hardness in the FZ and HAZ requires preheating and post-weld heat treatment (PWHT). Preheating slows cooling, leaving a softer FZ and HAZ. The preheating temperatures ranged from 300 to 600 °C. Preheating is not possible because of the low heat usage [26]. According to Kumar's research [26], a 540 °C preheat temperature reduces hardness significantly, while PWHT improves machinability of welded cast iron. Preheating is not an option because of heat usage.

El Banna et al. studied the restoration of pearlitic cast iron using shielded metal arc welding (SMAW) with specific filler materials. Their findings indicated that preheating the cast iron to 300°C effectively minimized the 20-melt region and heat-affected zone (HAZ), which contained discontinuous carbides and bainites. Furthermore, they noted that multipass welding decreased the width of the melt area and the microhardness of the HAZ [34]. This suggests that careful preheating and welding techniques can significantly improve the weld quality of pearlitic cast iron, reducing the risk of defects and enhancing mechanical properties.

Pouranvari et al. explored the impact of SMAW, nickel-based electrodes, and post-weld heat treatment (PWHT) on welded sections of cast iron. Their study underscored the importance of electrode composition and heat treatment in achieving optimal weld characteristics [12]. The use of nickel-based electrodes was particularly effective in improving the ductility and toughness of the welds, which are critical for the integrity of cast iron structures.

Voigt et al. examined the HAZ structures in ductile cast irons using SMAW with Eni-CI filler material and preheating at 300°C. Their research highlighted that preheating plays a crucial role in controlling the HAZ microstructure, which is vital for maintaining the mechanical properties of ductile cast iron welds [35]. Preheating helps in reducing thermal stresses and preventing the formation of brittle phases in the HAZ.

Hatate et al. compared electron beam welding (EBW) and metal active gas (MAG) welding of spheroidal graphite cast iron to mild steel. Their findings provided insights into the suitability of different welding techniques for joining dissimilar materials. EBW produced narrower HAZs and fewer defects compared to MAG welding, suggesting that it might be a better choice for applications requiring high precision and minimal thermal distortion [27].

Sanghoon et al. investigated the welding of ferritic stainless steel to high silicon nodular cast iron using metal active gas (MAG) welding with a Ni-Cr alloy filler material. They discovered the presence of an unmixed zone (UMZ) at the fusion boundary, which exhibited the highest hardness values. Their study also identified various metallurgical zones, including martensitic phases and carbides in the UMZ, transition zone (PMZ), and HAZ, each characterized by distinct microstructures and properties [36][37]. The high hardness in the UMZ could pose challenges for the joint's ductility and toughness, necessitating further optimization of welding parameters and post-weld treatments.

In summary, these studies collectively emphasize the critical role of preheating, filler material selection, and welding techniques in restoring and joining cast irons and dissimilar materials. Preheating effectively reduces thermal stresses and prevents brittle phase formation, while the choice of filler material influences the mechanical properties of the weld. Advanced techniques like EBW offer advantages in precision and reduced thermal distortion, whereas multipass welding can improve weld quality by minimizing melt area width and HAZ microhardness. Understanding these factors is essential for optimizing welding processes and ensuring the integrity and performance of welded components in various industrial applications.

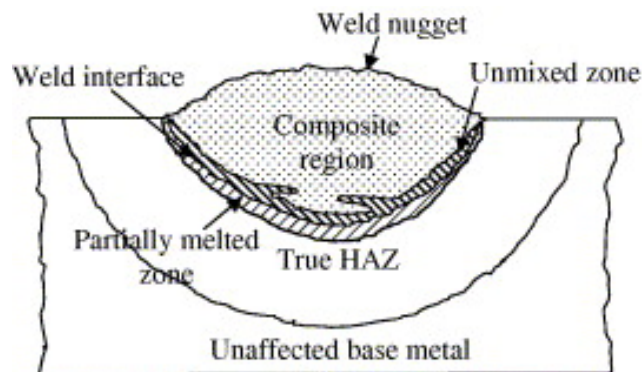


Fig. 2 Metallurgical zones of the weld [27]

Tadashi Kasuya et al conducted a study to determine the maximum hardness of HAZ and the appropriate preheat temperature for steel welding. Their findings indicated that HAZ's hard microstructure can lead to degradation of weld properties and increased susceptibility to cold cracking [28]. Additionally, Takamura et al found that TIG welding between specific compositions can eliminate technical issues with conventional steel materials welding without the need for preheating or post-heating treatment [29].

According to research conducted by Hisaki O and Ryochi K. et al. [30], to avoid HAZ cracking in 9Cr-1Mo-Nb-V (P91) steel, the preheating and post-heating must be:

- i. The lowest preheating temperature to avoid cracking is around 200 °C, which is lower than the values (300 °C) predicted from the chemistry mentioned above.
- ii. When a mild steel electrode with a 58 kg/mm² tensile steel content is used to make the weld, the preheating temperature rises.
- iii. Utilising a martensitic weld metal minimises residual stress and produces a weld that is less susceptible to cracking.

1.1.3 Carbon Steel Pipe

Carbon steel (CS) pipes are prevalent in piping systems due to their robustness, adaptability, and range of connection types, including screwed, socket-welded, and butt-welded options. Selecting the appropriate CS pipe involves considering the application's requirements for strength, durability, and machinability. These pipes must endure pressure, temperature variations, and potential corrosion, with relevant ASTM or API standards ensuring these demands are met [8].

CS is an iron-carbon alloy with less than 0.8% carbon, widely used in the petroleum industry for its balance of strength and ductility. Compared to other alloys, CS contains lower levels of manganese and microelements, which can impact its performance in different environments [20]. During production, deoxidants like silicon or aluminum are added to remove oxygen, enhancing the steel's quality and performance.

High-energy CS pipes, designed for high-temperature and high-pressure applications, resist wall thinning better than standard CS pipes. This resistance is crucial for their use in both aboveground and underground services transporting liquids, gases, and steam. However, CS pipes are generally not recommended for highly corrosive environments [11]. The material's limitations in such conditions can lead to increased maintenance costs and potential system failures, suggesting the need for alternative materials like stainless steel in corrosive applications [8]. The variety in wall thickness and grades of CS pipes is determined by the allowable stress influenced by the material's metallurgy and manufacturing process. This variety allows engineers to choose the appropriate pipe for specific pressure and temperature conditions. Wall thickness requirements are particularly critical, as they directly impact the pipe's ability to withstand operational stresses [11]. The chemical composition and properties of CS pipes for various temperature ranges are documented in standard references, providing essential data for material selection and engineering calculations [63].

Critically, while CS pipes offer a cost-effective solution for many applications, their susceptibility to corrosion in certain environments necessitates careful consideration. The decision to use CS over more corrosion-resistant

materials like stainless steel or specialized alloys should factor in the total lifecycle cost, including potential maintenance and replacement expenses. Furthermore, advances in protective coatings and treatments can extend the service life of CS pipes, but these solutions may not fully mitigate the inherent limitations of the material in highly corrosive conditions.

In conclusion, CS pipes are a versatile and economical choice for many piping applications, particularly where high strength and ease of fabrication are paramount. However, their application in corrosive environments requires additional protective measures or consideration of alternative materials to ensure long-term performance and reliability. The balance between cost, performance, and maintenance is essential in the selection of CS pipes for any given application. The CS pipe is chosen in this study due to its exceptional mechanical strength, resistance to corrosion, ease of welding, user-friendliness, and safety, making it a widely used material in the transmission of chemicals, petroleum products, and water [31]. These characteristics have made the CS pipe a popular choice in the industry [32].

Table 1 Chemical composition of the CS pipe [4]

Material	C	Mn	P	S	Si	Cr	Mo	V	Nb	N	Al	Ni
Carbon Steel	0.15	0.30	0.03	0.03	0.50	1.90	0.87	-	-	-	-	-

Table 2 Metal design temperature for piping [4]

Design Temperature (°F)	Specification
650 to 60	API 5L
50 to -20	A-53
-21 to -51	A-106
-51 to -150	API 5L
-151 to -325	A-106
	A-333 Grade 1 or 6
	A-333 Grade 304
	A-312 Grade 304
	A-358 Grade 304
	A-312 Grade 304
	A-358 Grade 308

1.2 Welding for Ferrous Metal

Welding is crucial in various industries, including shipbuilding, bridge construction, pressure vessel manufacturing, heavy machinery, automotive, and rolling stock. However, welding introduces several issues, particularly concerning the heat-affected zone (HAZ), a distinct microstructure formed in the base metal adjacent to the weld [43], [44]. The nonuniform heating and cooling during welding can harden the HAZ, increasing susceptibility to cold cracking and residual stress. To mitigate these issues, it is essential to control the heating and cooling rates in the base metal and the weld HAZ. Employing pre- and/or post-heating techniques can significantly alleviate these effects [45].

The rapid thermal cycles near the weld line due to welding cause uneven heating and cooling, which heightens the risk of cold cracking, a tougher HAZ, and residual stress [38], [46], [47], [48]. The differential heating and cooling introduce harmful stresses within the welded material [49]. Weld contraction, due to metal cooling along the weld's length, can generate residual tensile stresses, affecting the overall performance and integrity of the structure more than the base metal alone [38]. Addressing these challenges involves implementing preheating and post-heat treatments to ensure the HAZ has acceptable properties and to minimize hydrogen-induced cracking. These treatments help to slow the heating and cooling rates, reducing the formation of detrimental microstructures and residual stresses. Preheating the base metal before welding ensures a more gradual temperature gradient, minimizing thermal shock and stress concentrations.

Post-heat treatment helps to relieve residual stresses and reduce hardness in the HAZ, thereby enhancing the welded structure's performance and longevity [47]. Despite these mitigation strategies, the inherent issues of welding, such as cold cracking and residual stress, demand continuous advancements in welding techniques and materials. Innovations in welding technology, such as controlled heat input methods and advanced filler materials, are crucial to overcoming these persistent challenges. Moreover, ongoing research and development in welding metallurgy are essential to understand better and control the microstructural changes during welding, ensuring the production of robust and reliable welded structures.

In conclusion, welding remains indispensable across various industries, but it comes with significant challenges related to the heat-affected zone. Effective management of heating and cooling rates through pre- and post-heating techniques, along with continuous advancements in welding technology, are vital to mitigating these issues and ensuring the structural integrity and performance of welded components.



Fig. 4 Welding of CS pipe [33]

1.2.1 The Preheat of Ferrous Metal

Preheating is the process of heating metal to a predetermined temperature before welding [34], with the aim of reducing shrinkage stresses and enhancing the cooling rate. The specifics and mode of preheating vary depending on the situation [35]. The metal is ready for welding when preheated, especially when the base metal thickness increases, as it has a higher self-quenching capacity and increased weld structure rigidity. A higher preheat temperature and lower heat input are more favorable for limiting martensite formation and hardness, resulting in better welds, particularly when the heat input is lower [36]. Hardenable steels should be preheated to reduce the cooling rate after welding, and the amount of carbon present determines the preheating requirements and the critical preheating temperature.

The following factors determine the minimum preheating temperature required to prevent cracking:

- i. Carbon equivalent expressing carbon and alloy content
- ii. Condition of base metal prior to welding
- iii. Thickness of base material
- iv. Constraint level
- v. Hydrogen available risk

The Heat-Affected Zone (HAZ) in welding often develops a hard microstructure due to rapid heating and cooling, which can degrade weld properties and lead to failure in welded joints [38], [49]. The variability in cooling rates across different microstructure regions within the HAZ contributes to this issue, making it a critical factor in weld integrity [43].

Preheating the workpiece before welding is a recognized method to mitigate these issues. Preheating reduces atmospheric water vapor condensation, which can prevent hydrogen-induced cracking and improve weld quality. Benjamin King's study from the University of Wollongong underscores the importance of preheating, aligning with Australian and international standards that mandate this practice [53]. For instance, AD4458-1997 requires preheating 2.25Cr-1Mo steel sections thicker than 12 mm to 200 °C and thinner sections to 150 °C [54]. The ASME Boiler and Pressure Vessel Code specifies a higher preheating temperature of 232 °C [55], while a survey by Viswanathan and Gandy indicates a range of 149–316 °C in American industry practices [56].

Preheating is particularly effective in managing the challenges posed by the low heat conductivity of thin sections during welding. According to Lant et al., this low conductivity can result in low cooling rates, which permits safe preheating without negatively impacting performance, even with the additional heat generated during the welding process [57]. The British Standard BS 2633: 1973 mandates a modest preheating of 50 °C for thin tubes made of 2.25Cr-1Mo during C-steel root runs, emphasizing that thinner materials can benefit from lower preheating temperatures [58].

For thicker plates welded using the hydrogen-controlled gas tungsten arc welding (GTAW) technique, preheating requirements can be adjusted based on procedural tests. This adaptability ensures that weld integrity is maintained without unnecessary thermal stress on the material. The ability to reduce preheating temperatures for certain welding procedures, as supported by procedural tests, highlights the balance between ensuring adequate preheating and preventing excessive heat input that could lead to other welding defects.

In conclusion, preheating is a critical process in welding that addresses the hard microstructure development in the HAZ and enhances the overall quality of welds. Adhering to preheating standards and adjusting practices

based on material thickness and welding techniques can prevent weld failures and extend the service life of welded components. The variation in preheating requirements across different standards and industry practices underscores the need for careful consideration of specific welding conditions to optimize outcomes.

1.2.2 The Post-Heat of Ferrous Metal

Post-weld heat treatment (PWHT) is crucial for enhancing the mechanical properties and microstructure of welded materials. It aims to improve toughness, achieve a uniform grain structure, and minimize residual stress through controlled heating after welding [59]. This treatment is essential for pressure vessel and piping components, where residual stresses can lead to failure under operational pressures and temperatures. McEnerney and Dong highlight that PWHT is often mandated for pressure vessel and piping components to alleviate residual stresses and enhance the properties of weldments [60]. Design codes and standards, such as ASME Division 2, API 579 RP, and EN 13445, specify PWHT requirements, including ramp-up heating rates, hold temperatures, and hold times. These requirements are tailored based on the type of steel and the wall thickness, ensuring that the treatment is effective and appropriate for the specific material and application [61][62][63].

G. Rajamurugan et al.'s study on using resistance heating for localized PWHT provides valuable insights into the practical application of this technique [64]. Resistance heating, which involves running an electric current through a component to generate heat, is particularly useful for localized PWHT of small parts or repairs. In their experiment, a heating coil was used to perform PWHT on a thick-walled carbon steel (CS) pipe. This method allowed for controlled and localized heating, effectively relaxing residual stresses, softening the hardened zone, improving the microstructure, and reducing hydrogen content in the welded region [64]. The study found that the width of the heating coil significantly affects the temperature gradient between the outer and inner diameters of the pipe. A wider coil reduces the temperature gradient, thereby decreasing residual stresses and enhancing the microstructure and mechanical properties of thick-walled CS pipes. This finding underscores the importance of optimizing heating coil dimensions to achieve uniform temperature distribution and effective PWHT [64].

Despite the benefits, PWHT has its challenges. The process can be time-consuming and costly, particularly for large structures or components with complex geometries. Additionally, improper PWHT can lead to detrimental effects, such as overheating or thermal embrittlement, which can compromise the integrity of the material. Therefore, precise control over the heating parameters and adherence to established standards are critical to the success of PWHT.

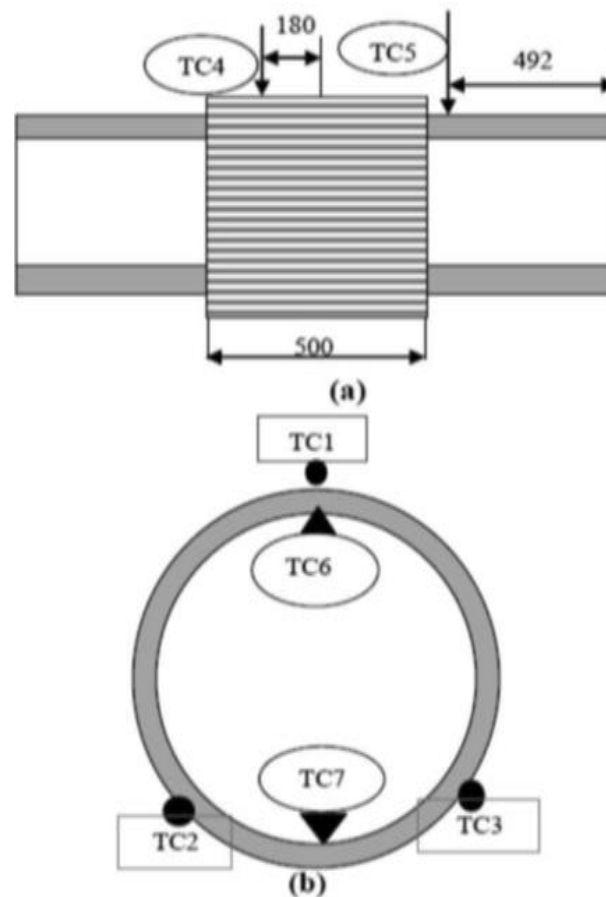


Fig. 3 Coil and thermocouple location at (a) Longitudinal; (b) Cross-section for trials 1, 2, and 3 [37]

1.3 The Effect of PWHT on Ferrous Metal

The post-weld heat treatment (PWHT) of ferrous metals has a crucial impact on their properties. It is possible to enhance the mechanical strength, structural stability, and performance of ferrous alloys through controlled thermal processing. This study thoroughly examines the key effects of PWHT on these metals, underscoring their importance in various industries [33]. According to Byeong et al [38], he conducted a study about the effect of PWHT on the fatigue behaviour of medium-strength carbon steel weldments. The researchers used a few methods to analyse the mechanical properties of the CS weldments. The detail properties can be seen in Table 3.

Heat treatment of the entire vessel in a furnace is often more time-consuming and expensive than performing PWHT during field fabrication. To achieve PWHT, heat sources are placed over the weld zone and a section of the base metal next to the weld zone, and heated to a predetermined temperature [96]. The use of flexible ceramic pad (FCP) heaters is common for PWHT. As shown in Fig. 4, the two heating pad layers (outer and inner) are positioned appropriately [39].

1.3.1 Influence on Temperature Profile

The role of temperature control in post weld heat treatment (PWHT) is pivotal for its success in ensuring structural integrity and mitigating the detrimental effects of heating [96]. Finite element (FE) models have been instrumental in simulating the temperature profiles required for PWHT, aiding in the optimization of heat treatment processes. These models, validated extensively through ANSYS Workbench simulations of Transient Thermal behavior, provide a robust framework for understanding the thermal behavior of welded structures [96].

Traditionally, PWHT involves heating the entire vessel in a furnace, a process that can be both time-consuming and expensive, particularly during field fabrication [96]. To address this challenge, localized PWHT techniques have been developed, wherein heat sources are strategically positioned over the weld zone and adjacent base metal sections, allowing for targeted heating to predetermined temperatures [96]. Flexible Ceramic Pad (FCP) heaters are commonly employed for such localized PWHT applications, offering flexibility and precise temperature control [66].

Table 3 Properties with and without PWHT

	With PWHT	Without PWHT
Tests	<ul style="list-style-type: none"> Tensile test: Used to understand the deformation and failure mechanism Charpy Impact Absorption Energy Test: Used to evaluate their energy absorption capacity, both with and without PWHT at different temperatures Fatigue test: To study the impact of residual stresses on fatigue behaviour Microstructural analysis: To observed any changes induced PWHT Hardness Testing: To understand the effects on strength, ductility, toughness, and fatigue resistance. 	
Results		
Tensile and Yield Strength	PWHT at temperatures of 590 °C and 800 °C for a duration of 1 hour led to a reduction in both yield strength and tensile strength, while the elongation increased.	The welded specimens may exhibit increases yield strength and tensile strength compared to specimens that undergone PWHT.
Impact Absorption Energy	PWHT at temperature of 590 °C resulted in a little enhancement of the Charpy impact absorption energy. However, at 800 °C, PWHT led to the homogenization of the weldment structure and a slight improvement in shock absorption energy.	The Charpy impact absorption energy may vary, with specimens that did not undergo PWHT potentially showing variable impact resistance compared to those that did not undergo heat treatment.
Fatigue Strength	PWHT demonstrated a little enhancement in fatigue strength for certain butt-welded specimens. However, it did not consistently	The fatigue strength of weldments without PWHT may be affected by the residual stresses produced during welding, which might have

	improve the fatigue strength of weldments in other cases.	an impact on the fatigue characteristics of the structure.
Microstructure	The microstructure of the weldments was potentially altered by PWHT at various temperatures, which could have an impact on characteristics like hardness and toughness.	The absence of PWHT can lead to a different microstructure in the weldments, which may have an impact on characteristics like hardness, toughness, and ductility.
Residual Stresses	PWHT influenced the residual stresses in the welded structures, thereby impacting the fatigue characteristics.	The structure may retain the residual stresses from the welding process, which might have an impact on its mechanical properties and fatigue performance.

In the context of PWHT, the use of FCP heaters presents several advantages, including their ability to conform to irregular surfaces and provide uniform heating [66]. Fig. 4 illustrates the arrangement of two layers of heating pads (outer and inner), ensuring efficient and controlled heating of the weld zone and surrounding areas [66]. This localized approach not only reduces overall energy consumption but also minimizes thermal distortion and residual stresses in the welded structure [96].

However, despite the benefits of localized PWHT, challenges remain, particularly regarding temperature uniformity and control [96]. Variations in material properties, geometry, and heat transfer characteristics can impact the effectiveness of PWHT, potentially leading to inadequate or uneven heating, which may compromise the integrity of the weld and surrounding material [96]. Therefore, ongoing research is focused on refining FE models, optimizing heating strategies, and developing advanced heating technologies to address these challenges and enhance the reliability and efficiency of PWHT processes [96].

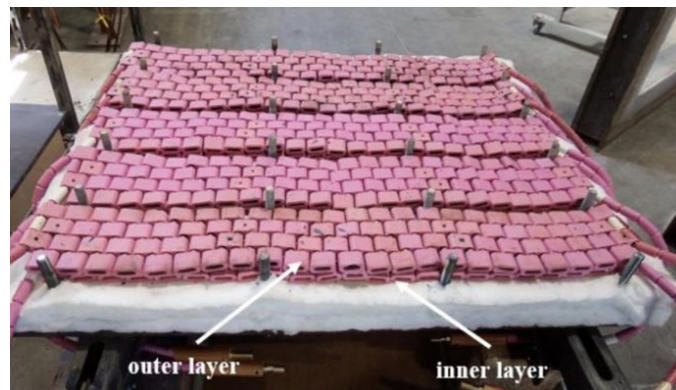


Fig. 4 Positioning of two heating pads layers (outer layer and inner layer) [39]

The impact of PWHT on weld properties is contingent upon the temperature field distribution. Elevated or reduced temperatures can have adverse effects on the properties [40], [41]. Lei Hu et al. studied the temperature profile during local PWHT of 9% Cr heat-resistant steel pipes [42]. They discovered that the temperature gradient across the thickness of the pipe increased with an expansion of the pipe diameter and wall thickness. This can result in inadequate tempering of the weld close to the interior surface of the pipe.

To mitigate the through-thickness temperature gradient, this study suggests enlarging the heated band (HB) width, which is an efficient way to reduce the gradient. Additionally, increasing the gradient control band (GCB) width effectively relieves the axial temperature gradient [42]. Fig. 5 shows a schematic of the temperature field in the local PWHT [42].

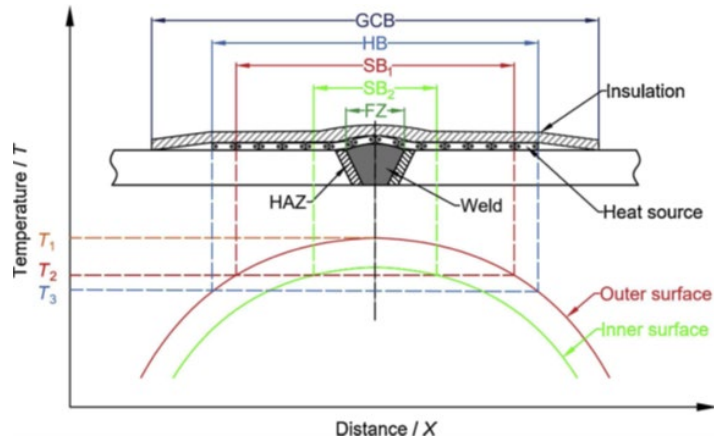


Fig. 5 The schematic description of temperature field in local PWHT [42]

The researchers found that the temperature inside the pipe decreased linearly from the outer to the inner surface of the pipe wall, with a slight decrease in the rate of temperature reduction as the pipe wall thickness increased. This was due to the smaller inner space in heavy wall pipes, resulting in reduced heat loss through radiation on the inside surface [42]. As shown in Fig. 6, the pipe wall thickness affects the temperature distribution in the through-thickness direction [42]. Therefore, it is crucial to optimize the process parameters, such as the HB and GCB widths, to achieve the desired weld properties and prevent the negative effects of local heating during the post-weld heat treatment of 9% Cr heat-resistant steel pipes.

1.3.2 Influence on Metal Expansion

PWHT is mostly used for ferrous metals, such as carbon steel metal and low alloy steel, to relieve the residual stress and improve the mechanical properties of the material after the welding process. PWHT can affect the expansion and dimensional stability of a metal, and it depends on several factors such as the way the material is being treated, the specific PWHT process parameters, and the temperature of the metal heated during the treatment process.

When the metal is heated during PWHT, it undergoes thermal expansion. Therefore, it increases in size as it absorbs heat. Conversely, when the metal is cooled after the heat treatment, it contracts. These expansions and contractions can lead to dimensional changes in metals. It can also relieve residual stresses in welded components. Residual stresses can cause distortions and dimensional changes in the metals. The important reason for performing PWHT is to reduce these stresses which can have a positive effect on the dimensional stability of the welded structure.

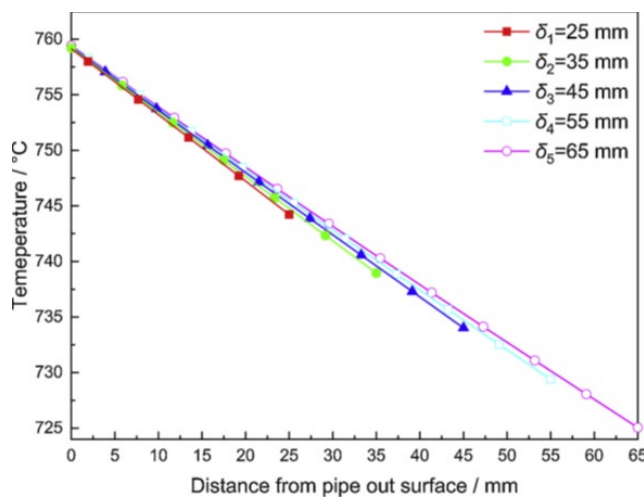


Fig. 6 Effect of pipe wall thickness on temperature distribution in through thickness direction [42]

Pandey et al. revealed that 9% Cr heat-resistant steel welds experienced thermal expansion due to increased temperature, causing the crystal lattice structure of the material to expand [43]. The magnitude of expansion was determined by the coefficient of thermal expansion. Hu et al. conducted finite element simulations to examine the

temperature field during local PWHT of 9% Cr heat-resistant steel pipes [42]. This reveals that the thermal expansion and contraction can be influenced by the temperature gradient along the thickness of the pipe.

According to Alipooramirabad et al., the yield strength of the weld metal (642.24 MPa) was achieved in the as-welded joints of Bisalloy 80 steel. It also exhibits high levels of tensile residual stress [44]. The residual stresses significantly decreased to 145 ± 21 MPa or approximately 23% of the weld metal yield strength after the PWHT process. Additionally, PWHT was tested by Choi et al. to determine whether it could reduce the residual stress in the HAZ and welded joint of the A516 carbon steel pipe [45]. PWHT can influence the extent of metal expansion based on the control of cooling rates. This control of cooling rates is implemented in various PWHT processes to minimize distortions and dimensional changes. Gradual and controlled cooling can reduce the risk of dimensional instability by managing thermal loads.

Research on the influence of welding heat input and cooling rate on the mechanical properties of 1.25Cr-0.5Mo steel for pressure vessels was performed by Hwan et al. [46]. The study showed that the impact toughness and microstructure were not significantly affected by the welding heat input up to 30.9 kJ/cm. However, the increase in ferrite production and coarsening of the coarse-grained heat-affected zone (HAZ) led to a decrease in toughness at 44.8 kJ/cm. The microstructure and properties did not change with the cooling rates during the PWHT.

1.3.3 Influence on Residual Stress

According to a thorough analysis by McEnerney and Dong [47], PWHT is frequently required for pressure vessels and piping components to relieve residual stresses and/or improve weldment properties. The steel was heated during the welding process. HAZ is the term for the heated part, which has a microstructure distinct from that of the base metal [48], [49]. Repeated heating and cooling during welding leads to a severe thermal cycle near the weld line region, resulting in a tougher HAZ, residual stress, and susceptibility to cold cracking in the base and weld metal. Nonuniform heating and cooling also occur often [28], [33], [50], [51], and differential heating and cooling cause detrimental residual stress [52]. The detail finding can be seen in Table 4.

1.3.4 Influence on HAZ

The heat-affected zone (HAZ) refers to a region within the material that does not reach the temperature required for melting; however, it undergoes changes in its microstructure owing to the thermal changes experienced during the welding process [58]. The detail finding can be seen in Table 5.

Table 4 Findings of residual stress

No.	Researcher	Topic	Summary
1.	Sadeghi et al. [53]	Effects of post-weld heat treatment on residual stress and mechanical properties of GTAW: The case of joining A537CL1 pressure vessel steel and A321 austenitic stainless steel	PWHT did not have major effects on the microstructure of various regions in the welded joints. However, it resulted in a drop in the tensile strength, hardness, and residual stress.
2.	Huang et al. [54]	Effect of post-weld heat treatment on the residual stress and deformation of 20/0Cr18Ni9 dissimilar metal welded joint by experiments and simulations	The initial residual stress is significantly higher than the stress in cases 1- 9. This suggests that the residual stress reduces after heat treatment, but the reduction is not huge.
3.	Yaghi et al. [55]	Comparison of measured and modelled residual stresses in a welded P91 steel pipe undergoing post weld heat treatment	<ul style="list-style-type: none"> The residual stress predicted by the Finite Element (FE) method has significantly decreased in magnitude compared to the values determined prior to PWHT The XRD measurements of residual stresses also decreased in magnitude because of PWHT, falling within the range of ± 50 MPa.
4.	Banglong Yu et al. [56]	The residual stress relief of post-weld heat treatment in SMA490BW welded joints: Simulation and experiment	<p>PWHT without creep: The longitudinal residual stress decreases by around 18.6% and the transverse residual stress is around 63 MPa.</p> <p>PWHT with creep: Results in a decrease of the maximum longitudinal residual stress to 150 MPa.</p>

The transverse residual stress drops from 63 MPa to 22 MPa, resulting in a reduction of approximately 65%.

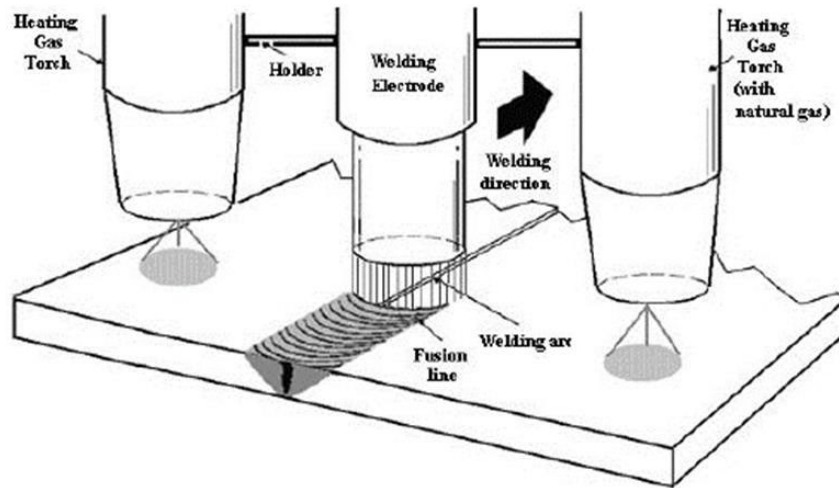


Fig. 7 The parallel heat welding (PHW) process according to C.P Chow et al. [57]

1.4 Finite Element Analysis for PWHT on Ferrous Metal

Strength design for machines and structures has traditionally relied on formula or rule approaches. However, analyzing design can remove conservatism [61]. ANSYS Workbench is a powerful platform software that supports an integrated simulation system [22]. This part explains how to use ANSYS Transient Thermal to correlate thermal profiles for piping systems and visualize thermal expansion effects and temperature reduction length over relative length.

ANSYS is a versatile software tool used by engineers for various simulations, including stress analysis, fluid dynamics, and heat transfer, aiding researchers in design optimization, cost reduction, and performance improvement. ANSYS is recognized as a globally recognized FEA software program, used in industries like automotive, aerospace, manufacturing attracting a large user base [22].

In the field of engineering, it is common to use Finite Element Analysis (FEA) software like ANSYS for simulating and analysing thermal and structural behaviour. This software allows for the modelling and simulation of complex geometries and boundary conditions, making it a valuable tool for studying the effects of thermal analysis in pipes and welds. As per India's leading CAE and CAD Training Academy and Service, users can analyse heat transfer, temperature distribution, and thermal stress in components and systems, optimize cooling solutions, and ensure safe operating conditions [59].

Table 5 Findings of HAZ

No.	Researcher	Topic	Summary
1.	R.N.S Fassani et al. [59]	The analytical modelling of multipass welding process with distributed heat compares between thermal cycles.	The analysis reveals that the thermal cycles can be attributed to the concentrated heat source model. The analytical solution generated from the point source model is considered dependable and suitable for predicting temperature distributions in areas that are far from both the FZ and the HAZ.
2.	M. Pouranvari et al. [5]	The welding of grey cast iron by shielded metal arc welding process using nickel-based filler metal.	Welding of grey cast iron with nickel-based filler metal and applying PWHT can serve as a solution for cast iron welding problems.
3.	Dunder et al. [60]	Effect of post-weld heat treatment on the toughness of heat-	<ul style="list-style-type: none"> A 760 °C for 2 hours PWHT can significantly increase the cross-weld toughness of the HAZ. The highest toughness and lowest hardness across all HAZ regions have been achieved by conducting a

	affected zone for grade 91 steel	<p>PWHT at a temperature of 20 °C below the A_{c1} temperature for a duration of 2 hours.</p> <ul style="list-style-type: none"> • PWHT above the A_{c1} temperature for 2 hours will result in the formation of fresh martensite, which decreases the toughness and increases the hardness of all HAZ regions.
4.	Jeong et al. [58] Phase transformation and the mechanical characteristics of heat-affected zones in austenitic Fe-Mn-Al-Cr-C lightweight steel during post-weld heat treatment	<ul style="list-style-type: none"> • PWHT at 400 °C had minimal impact on the microstructural and mechanical properties of the HAZ. However, at 500 °C, an increase κ-carbide precipitation was found based on hardness data and TEM observations. • At a temperature of 600 °C, PWHT facilitated the formation of Cr-enriched M_7C_3 carbide and increased the amount of ferrite in the HAZ. This was due to the destabilization of austenite, leading to the expansion of existing ferrite and the formation of new allotriomorphic α-ferrite at the boundaries of the austenite grains. As a result, the hardness in the HAZ exhibited irregular fluctuations.

In order to accurately assess the thermal properties of the CS pipe, it is crucial to determine the relevant physical quantities such as temperature, thermal gradient, and heat flow distribution. There are two primary types of thermal analysis: steady-state thermal analysis and transient thermal analysis. Equilibrium thermal analysis aims to determine the temperature or heat flux distribution when thermal stability is achieved. Conversely, transient thermal analysis seeks to investigate how the temperature profile and other thermal quantities change over time [62].

Before investigating the thermal profiles and thermal expansion of the pipe, a meshing convergence study of finite element analysis using a different size of meshing has been conducted. Meshing convergence study is conducted to obtain the accurate data before comparing it with analytical result [63]. A numerical Finite Element Analysis (FEA) model was created using the ANSYS/Mechanical FEA software [64] to study the edge effect of a legacy host pipe with a circumferential crack on the PIP repair system. A mesh convergence study was conducted on the PIP system to compare the accuracy of the numerical results with the analytical solution [65]. Figure 8 shows the circumferential crack that was assumed to be 90-degree sharp [65].

To reduce computational complexity, a quarter-symmetry model was employed, leveraging symmetry boundary conditions along the longitudinal and transverse directions. The surface discretization adopted a mesh size of 4×4 mm for the legacy pipe and a finer mesh size of 2×2 mm for the internal Pipe-in-Pipe (PIP) liner. Through the thickness direction, both the legacy pipe and the PIP liner were discretized using three elements, as depicted in Figure 9 [65]. This modelling approach aimed to strike a balance between computational efficiency and accurate representation of the geometric features, particularly for the critical PIP liner region [65].

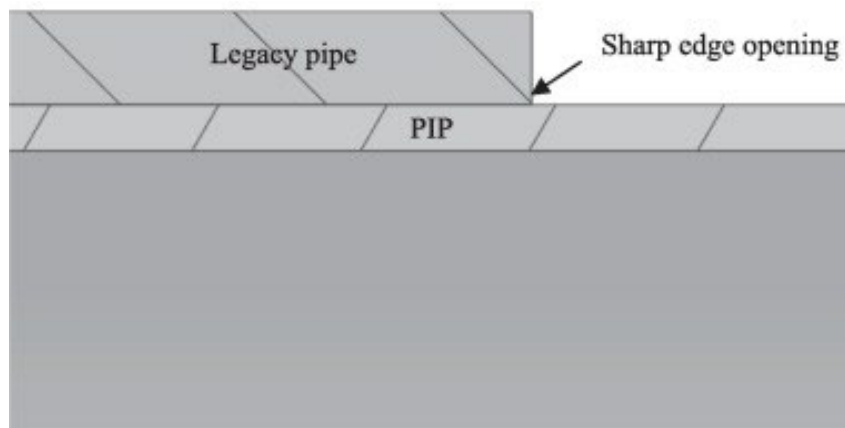


Fig. 8 An enlarged view on the sharp edge opening of the legacy pipe [65]

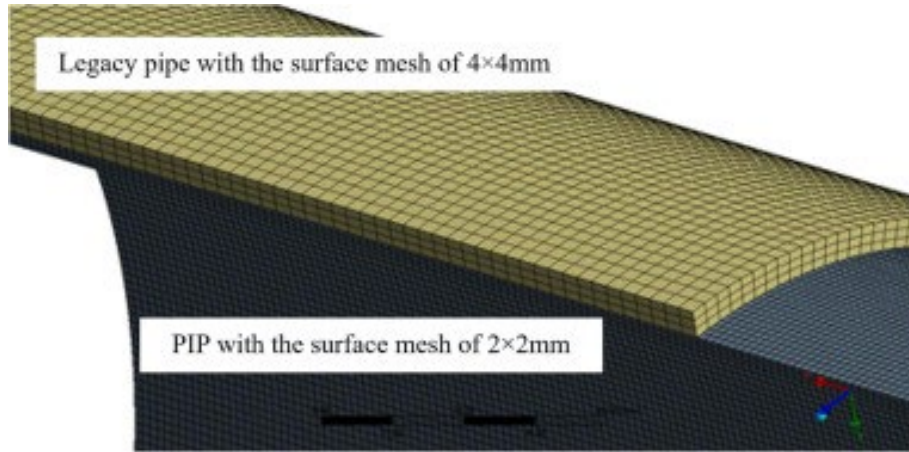


Fig. 9 An enlarged view on the sharp edge opening of the legacy pipe [65]

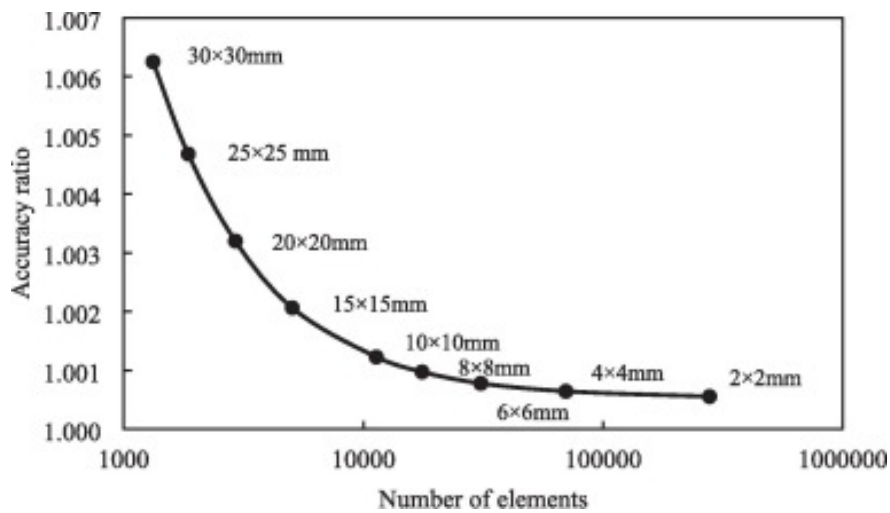


Fig. 10 Mesh convergence study: accuracy ratios versus the number of elements [65]

Figure 10 presents a graphical representation of the accuracy ratio, obtained by comparing the numerical results from the finite element analysis with the corresponding theoretical predictions, as a function of mesh refinement [65]. The accuracy ratio serves as a quantitative measure of the solution convergence and reliability. It is evident from the plot that as the mesh size is progressively refined to 8 × 8 mm or finer, the solution exhibits convergence, with the accuracy ratio attaining a value of at least 1.001 [65]. This convergence behaviour indicates that the numerical solution is in close agreement with the theoretical expectations, thus instilling confidence in the modelling approach [65].

To achieve highly accurate solutions, a judicious mesh discretization strategy was adopted. Specifically, for the critical PIP (Pipe-in-Pipe) liner region, a relatively fine surface mesh size of 2 × 2 mm was employed, ensuring adequate resolution of the geometric features and stress gradients. Concurrently, for the host pipe, a surface mesh size of 4 × 4 mm was deemed sufficient, striking a balance between accuracy and computational efficiency in the less critical regions of the model [65].

A team of researchers led by Prayoga Wira Adie et al. [66] conducted a study to determine the appropriate mesh for further research on ocean thermal energy conversion (OTEC). They carried out a mesh convergence study using a step buckle in ABAQUS software. The study found that as the number of elements increased, the critical moment decreased, and the results became more convergent.

In this study, transient thermal analysis will be employed to analyse the thermal expansion of the CS pipe over a period of 8 hours of heating. A mesh convergence study will be explained thoroughly by using ANSYS Transient Thermal. CS alloy grade A106 Grade B is designed by using Solidworks software before importing it to the ANSYS Transient Thermal. The thermal profiles can be obtained from the ANSYS Transient Thermal while the thermal expansion can be obtained from the ANSYS Transient Structural.

In the realm of post-welding analysis, a critical area for future exploration lies in examining the effects of welding processes on the thermal behavior and structural integrity of carbon steel (CS) pipes. While the focus of the current study is primarily on transient thermal analysis, extending the investigation to post-welding scenarios

can provide valuable insights into the thermal response of welded joints and their susceptibility to thermal expansion and residual stresses. Post-welding, the material properties and microstructure of CS pipes can be altered, leading to variations in thermal conductivity, expansion coefficients, and mechanical properties. Therefore, incorporating post-welding effects into transient thermal analysis can offer a more comprehensive understanding of the thermal behavior of CS pipes in real-world applications. Additionally, exploring advanced material models that account for the heterogeneous nature of welded joints and the presence of weld-induced defects can enhance the accuracy of simulations and enable more precise predictions of thermal expansion and stress distribution. Moreover, integrating transient thermal analysis with structural integrity assessments can provide insights into the long-term performance and durability of welded CS pipe systems under thermal loading conditions. By addressing these aspects in future research endeavors, the reliability and applicability of transient thermal analysis for CS pipes in post-welding scenarios can be significantly enhanced, ultimately contributing to improved design practices and operational efficiency in various industrial applications.

1.5 Conclusion

In conclusion, PWHT is crucial due to the residual stresses and microstructural changes that occur after welding. The high-temperature gradient experienced during the welding process can lead to these changes. PWHT is particularly important in various industries, including construction of piping and pipelines, pressure vessels, storage tanks, offshore and onshore platforms, power plants, oil and gas refineries, and petrochemical plants, as it can effectively reduce residual stresses and improve resistance to brittle fracture. PWHT is regularly carried out to restore some of the properties of the part after welding. PWHT also can improve the mechanical strength, structural stability, and performance of metallic pipes. However, it may reduce the yield strength and tensile strength, and also affect the residual stress and fatigue characteristics of the welded structure. Additionally, the temperature gradient across the pipe's thickness increases with larger diameter and thickness, potentially leading to insufficient tempering of the weld near the interior surface of the pipe.

Acknowledgement

The authors would like to thank Universiti Tun Hussein Onn Malaysia (UTHM) for supporting this research through internal grant "Geran Penyelidikan Pascasiswazah (GPPS)" with vot number Q603. Also to the faculty, Faculty of Mechanical and Manufacturing Engineering (FKMP) for providing the facility. The appreciation also dedicated to Petroliaam Nasional Berhad (PETRONAS) for the guidance of expertise in the project.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contribution

*The authors confirm contributions to the paper as follows: **study conception and design:** Nurul Shahadah Roslan, Eliza M. Yusup; **data collection:** Nurul Shahadah Roslan, Muzzahir Mohmad Hadzir; **analysis and interpretation of results:** Nurul Shahadah Roslan, Iman Fitri Ismail, Eliza M. Yusup; **draft manuscript preparation:** Nurul Shahadah Roslan. All authors reviewed the results and approved the final version of the manuscript.*

Recommendation and Suggestion for the Future Works

Future research should focus on refining mesh convergence studies, validating numerical results with experimental data, exploring advanced material models within ANSYS software, optimizing heating parameters, integrating transient thermal analysis with structural integrity studies, exploring alternative simulation software, extending analysis to different pipe materials and geometries, and investigating environmental factors such as ambient temperature variations and fluid flow conditions. These endeavors will enhance the accuracy and applicability of transient thermal analysis for carbon steel pipes, contributing to improved design practices and operational efficiency in various industrial applications.

References

- [1] K. Sotoodeh, "Cryogenic valve design features," in *Cryogenic Valves for Liquefied Natural Gas Plants*, Elsevier, 2022, pp. 111–174. doi: 10.1016/B978-0-323-99584-9.00003-3.
- [2] M. Stewart, *Surface Production Operations*. Elsevier, 2021. doi: 10.1016/C2014-0-03881-6.
- [3] S. Mridha, "Metallic Materials," in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2016. doi: 10.1016/B978-0-12-803581-8.04097-2.
- [4] M. Stewart, "Material requirements," in *Surface Production Operations*, vol. 3, Elsevier, 2016, pp. 159–192. doi: 10.1016/B978-1-85617-808-2.00003-1.

- [5] M. Pouranvari, "On the weldability of grey cast iron using nickel based filler metal," *Materials & Design - MATER DESIGN*, vol. 31, pp. 3253–3258, Aug. 2010, doi: 10.1016/j.matdes.2010.02.034.
- [6] S. Kou, *Welding Metallurgy*, 2nd ed. Wiley, 2002. doi: 10.1002/0471434027.
- [7] E. E. Huke and H. Udin, "Welding Metallurgy of Nodular Cast iron," *Weld. J.*, vol. 32, no. 8, 1953.
- [8] Nippes. E.F., "The Heat Affected Zone of Arc Welded Ductile Iron," *Weld. J.*, vol. 39, pp. 72–465, 1960.
- [9] G. R. Pease, "The Welding of Ductile Iron," *Weld. J.*, vol. 39, pp. 1–9, 1960.
- [10] S. D. Kiser, "Production Welding of Cast Iron," *AFS Trans*, vol. 85, pp. 37–42, 1977.
- [11] S. D. Kiser and B. Irving, "Unraveling the Mysteries of Welding Cast Iron," *Weld. J.*, vol. 72, pp. 39–44, 1993.
- [12] N. FUJII, H. HONDA, A. FUKASE, and K. YASUDA, "Comparison of Strength Characteristic of Nodular Graphite Cast Iron Welded Joints by Various Welding Process," *Quarterly Journal of The Japan Welding Society*, vol. 25, pp. 261–267, May 2007, doi: 10.2207/qjws.25.261.
- [13] R. C. Voight, "Welding Metallurgy of Grey and Ductile Cast Irons," *AFS Trans*, vol. 94, pp. 46–133, 1986.
- [14] R. A. Martinez and J. K. Sikora, "Pearlitic Nodular Cast Iron: Can it be Welded," *Weld. J.*, pp. 65–70, 1995.
- [15] E. M. El-Banna, "Effect of preheat on welding of ductile cast iron," *Mater Lett*, vol. 41, no. 1, pp. 20–26, Oct. 1999, doi: 10.1016/S0167-577X(99)00098-1.
- [16] D. J. Kotecki, N. R. Braton, and N. R. Loper, "Preheat Effects on Gas Metal-Arc Welded Ductile Cast Iron," *Weld J*, no. 48, pp. 161–166, 1969.
- [17] The Welding Institute, "Weldability of Materials - Cast Irons," TWI Ltd.
- [18] A. G. Hogaboom, "Welding of Gray Cast Iron," *Weld J*, vol. 56, no. 2, pp. 17–21, 1977.
- [19] J. Klimek and A. V. Morrison, "Gray Cast Iron Welding," *Weld J*, vol. 56, no. 3, pp. 29–33, 1977.
- [20] M. Hatate, T. Shiota, N. Abe, M. Amano, and T. Tanaka, "Bonding characteristics of spheroidal graphite cast iron and mild steel using electron beam welding process," *Vacuum*, vol. 73, no. 3–4, pp. 667–671, Apr. 2004, doi: 10.1016/j.vacuum.2003.12.097.
- [21] S. Kolukisa, "The effect of the welding temperature on the weldability in diffusion welding of martensitic (AISI 420) stainless steel with ductile (spheroidal graphite-nodular) cast iron," *J Mater Process Technol*, vol. 186, no. 1–3, pp. 33–36, May 2007, doi: 10.1016/j.jmatprotec.2006.11.148.
- [22] M. Eroğlu, M. Aksoy, and N. Orhan, "Effect of coarse initial grain size on microstructure and mechanical properties of weld metal and HAZ of a low carbon steel," *Materials Science and Engineering: A*, vol. 269, no. 1–2, pp. 59–66, Aug. 1999, doi: 10.1016/S0921-5093(99)00137-9.
- [23] G. Ciszewski, "New experimental concept for the fabrication of cast iron to cast iron and cast iron to steel joints by means of friction welding and the mechanical and plastic properties of these joints," vol. 6, pp. 288–297, Jan. 2007.
- [24] Y. SAWADA and M. NAKAMURA, "Lapped Friction Stir Welding between Ductile Cast Irons and Stainless Steels," *Quarterly Journal of The Japan Welding Society*, vol. 27, pp. 176–182, Aug. 2009, doi: 10.2207/qjws.27.176.
- [25] R. A. Bishel, J. G. Bielenberg, R. J. Dybas, K. L. Johnson, and A. B. Malizio, "Cast Irons," *Welding Handbook*, vol. 4, no. 7, 1982.
- [26] R. L. Kumar, "Welding Grey Iron with Mild Steel Electrodes," *Foundry Journal*, vol. 96, no. 1, p. 64, 1968.
- [27] Y. CUI, C. XU, and Q. HAN, "Effect of ultrasonic vibration on unmixed zone formation," *Scr Mater*, vol. 55, no. 11, pp. 975–978, Dec. 2006, doi: 10.1016/j.scriptamat.2006.08.035.
- [28] T. Kasuya, M. Okumura, and N. Yurioka, "Methods for predicting maximum hardness of heat-affected zone and selecting necessary preheat temperature for steel welding," pp. 7–14, Apr. 1995.
- [29] T. Takamura, N. Yukio, K. Teraoka, M. Oyama, K. Akiyama, and T. Arima, "Method for TIG welding 1.25 Cr-0.5Mo steel pipe for which preheating and postheating treatments can be effectively omitted," *JFE Steel Corp*, Jul. 1995.
- [30] H. Ryochi, "Effects of Pre-and Post- Heating on weld cracking of 9Cr-1 Mo- Nb-V Steel," *Transaction of the Japan Welding Society*, vol. 19, pp. 67–83, 1988.
- [31] W. Renu, *Advanced Well Completion Engineering*, 3rd ed. Elsevier, 2011. doi: 10.1016/C2010-0-66820-9.
- [32] K. M. Usher, A. H. Kaksonen, I. Cole, and D. Marney, "Critical review: Microbially influenced corrosion of buried carbon steel pipes," *Int Biodeterior Biodegradation*, vol. 93, pp. 84–106, Sep. 2014, doi: 10.1016/j.ibiod.2014.05.007.
- [33] S. Lee, B. Kim, and D. Kwon, "Correlation of microstructure and fracture properties in weld heat- affected zones of thermomechanically controlled processed steels," *Metallurgical Transactions A*, vol. 23, pp. 2803–2816, Oct. 1992, doi: 10.1007/BF02651759.
- [34] R. Scott Funderbuck, "Key Concepts in Welding Engineering - Fundamentals of Preheat," *Welding Innovation*, vol. XIV, no. 2, pp. 1–2, 1997.
- [35] R. Scott Funderbuck, "Key Concepts in Welding Engineering - Postweld Heat Treatment," *Welding Innovation*, vol. XV, no. 2, 1998.
- [36] *The Procedure Handbook of Arc Welding*, 14th ed. The James F. Lincoln Arc Welding Foundation, 1993.

- [37] G. Rajamurugan, S. Suresh, and P. Krishnasamy, "Influence of local post-weld heat treatment and its thermal analysis on thick wall carbon steel pipe," *Mater Today Proc*, vol. 46, pp. 7076–7081, 2021, doi: 10.1016/j.matpr.2020.10.067.
- [38] B.-C. Goo, "Effect of Post-Weld Heat Treatment on the Fatigue Behavior of Medium-Strength Carbon Steel Weldments," *Metals (Basel)*, vol. 11, no. 11, p. 1700, Oct. 2021, doi: 10.3390/met11111700.
- [39] A. Seweryn, A. Lucherini, and J.-M. Franssen, *An apparatus for applying fire-like heat flux to bench-scale samples*. 2022.
- [40] C. Pandey, A. Giri, and M. M. Mahapatra, "Effect of normalizing temperature on microstructural stability and mechanical properties of creep strength enhanced ferritic P91 steel," *Materials Science and Engineering: A*, vol. 657, pp. 173–184, Mar. 2016, doi: 10.1016/j.msea.2016.01.066.
- [41] C. Pandey, A. Giri, and M. M. Mahapatra, "Evolution of phases in P91 steel in various heat treatment conditions and their effect on microstructure stability and mechanical properties," *Materials Science and Engineering: A*, vol. 664, pp. 58–74, May 2016, doi: 10.1016/j.msea.2016.03.132.
- [42] L. Hu, X. Wang, Q. Ma, W. Meng, and S. Chen, "Numerical and experimental investigations on the temperature field in local post weld heat treatment of 9 % Cr heat resistant steel welded pipes," *J Mater Process Technol*, vol. 297, p. 117232, Nov. 2021, doi: 10.1016/j.jmatprotec.2021.117232.
- [43] C. Pandey, M. M. Mahapatra, P. Kumar, F. Daniel, and B. Adhithan, "Softening mechanism of P91 steel weldments using heat treatments," *Archives of Civil and Mechanical Engineering*, vol. 19, no. 2, pp. 297–310, Mar. 2019, doi: 10.1016/j.acme.2018.10.005.
- [44] H. Alipooramirabad, A. Paradowska, M. Reid, and R. Ghomashchi, "Effects of PWHT on the Residual Stress and Microstructure of Bisalloy 80 Steel Welds," *Metals (Basel)*, vol. 12, no. 10, p. 1569, Sep. 2022, doi: 10.3390/met12101569.
- [45] S.-W. Lee, S.-I. Lee, and B. Hwang, "Effect of Bainitic Microstructure on Low-Temperature Toughness of High-Strength API Pipeline Steels," *Korean Journal of Metals and Materials*, vol. 58, pp. 293–303, May 2020, doi: 10.3365/KJMM.2020.58.5.293.
- [46] L. Dong-Hwan and P. Jong-Jin, "Effect of Welding Heat Input and PWHT Cooling Rate on Mechanical Properties of Welded Region at SAW of 1.25Cr-0.5Mo Steel for Pressure Vessel," *Journal of the Korean Welding and Joining Society*, vol. 22, Jan. 2004.
- [47] J. W. McEnerney and P. Dong, "Recommended practices for local heating of welds in pressure vessels," pp. 1–63, Jun. 2000.
- [48] Q. Xue, D. Benson, V. Nesterenko, and E. A. Olevsky, "Constitutive response of welded HSLA 100 steel," *Materials Science and Engineering: A*, vol. 354, pp. 166–179, Aug. 2003, doi: 10.1016/S0921-5093(03)00007-8.
- [49] J. E. Ramirez, S. Mishael, and R. Shockley, "Properties and sulfide stress cracking resistance of coarse-grained heat-affected zones in V-microalloyed X60 steel pipe," *Welding Journal (Miami, Fla)*, vol. 84, pp. 113–123, Jul. 2005.
- [50] T. Teng and P.-H. Chang, "A study of residual stresses in multi-pass girth-butt welded pipes," *International Journal of Pressure Vessels and Piping - INT J PRESSURE VESSELS PIPING*, vol. 74, pp. 59–70, Nov. 1997, doi: 10.1016/S0308-0161(97)00091-4.
- [51] B. Eigenmann, V. Schulze, and O. Vohringer, "Surface Residual Stress Relaxation in Steels by Thermal or Mechanical Treatment," *In Proceedings of the Fourth International Conference on Residual Stresses*, pp. 598–607, 1994.
- [52] Y.-C. Lin and K. Lee, "Effect of preheating on the residual stress in type 304 stainless steel weldment," *Journal of Materials Processing Technology - J MATER PROCESS TECHNOL*, vol. 63, pp. 797–801, Jan. 1997, doi: 10.1016/S0924-0136(96)02727-6.
- [53] B. Sadeghi, H. Sharifi, M. Rafiei, and M. Tayebi, "Effects of post weld heat treatment on residual stress and mechanical properties of GTAW: The case of joining A537CL1 pressure vessel steel and A321 austenitic stainless steel," *Eng Fail Anal*, vol. 94, pp. 396–406, Dec. 2018, doi: 10.1016/j.engfailanal.2018.08.007.
- [54] B. Huang, J. Liu, S. Zhang, Q. Chen, and L. Chen, "Effect of post-weld heat treatment on the residual stress and deformation of 20/0Cr18Ni9 dissimilar metal welded joint by experiments and simulations," *Journal of Materials Research and Technology*, vol. 9, no. 3, pp. 6186–6200, May 2020, doi: 10.1016/j.jmrt.2020.04.022.
- [55] A. H. Yaghi *et al.*, "Comparison of measured and modelled residual stresses in a welded P91 steel pipe undergoing post weld heat treatment," *International Journal of Pressure Vessels and Piping*, vol. 181, p. 104076, Mar. 2020, doi: 10.1016/j.ijpvp.2020.104076.
- [56] B. Yu, P. Wang, X. Song, and S. Huo, "The residual stress relief of post weld heat treatment in SMA490BW welded joints: Simulation and experiment," *International Journal of Pressure Vessels and Piping*, vol. 200, p. 104852, Dec. 2022, doi: 10.1016/j.ijpvp.2022.104852.
- [57] P. Barsanescu, B. Leitoiu, V. Goanta, D. Cantemir, and S. Gherasim, "Reduction Of Residual Stresses Induced By Welding In Monel Alloy, Using Parallel Heat Welding Itm Suceava Iasi (ROMANIA)," vol. 3, Feb. 2011.

- [58] S. Jeong *et al.*, "Phase transformation and the mechanical characteristics of heat-affected zones in austenitic Fe-Mn-Al-Cr-C lightweight steel during post-weld heat treatment," *Mater Charact*, vol. 177, p. 111150, Jul. 2021, doi: 10.1016/j.matchar.2021.111150.
- [59] F. S and O. Trevisan, "Analytical modeling of multipass welding process with distributed heat source," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 25, Jul. 2003, doi: 10.1590/S1678-58782003000300013.
- [60] M. Dunder, T. Vuherer, I. Samardžić, and D. Marić, "Analysis of heat-affected zone microstructures of steel P92 after welding and after post-weld heat treatment," *The International Journal of Advanced Manufacturing Technology*, vol. 102, pp. 3801–3812, 2019.
- [61] H. Okabayasi and R. Kume, "Effects of Pre- and Post-Heating on Weld Cracking of 9Cr-1Mo-Nb-V Steel," *Transaction of the Japan Welding Society*, vol. 19, no. 2, 1988.
- [62] S. Z. Jia, J. S. Gunasekera, and J. Glancey, "Computer integrated sustainable manufacturing," in *Sustainable Manufacturing Processes*, Elsevier, 2023, pp. 313–334. doi: 10.1016/B978-0-323-99990-8.00001-1.
- [63] A. Rashid, "How to estimate mesh convergence just by looking at stress contour plot," LinkedIn.
- [64] Z. Zhang, "Application of finite element analysis in structural analysis and computer simulation," *Applied Mathematics and Nonlinear Sciences*, vol. 0, no. 0, May 2023, doi: 10.2478/amns.2023.1.00273.
- [65] C. M. T. Tien *et al.*, "Effects of the legacy pipe ends on the behaviour of pipe-in-pipe repair systems under internal pressure," *Eng Fail Anal*, vol. 144, p. 106957, Feb. 2023, doi: 10.1016/j.engfailanal.2022.106957.
- [66] P. W. Adie *et al.*, "Non-linear assessment of cold water pipe (CWP) on the ocean thermal energy conversion (OTEC) installation under bending load," *Procedia Structural Integrity*, vol. 47, pp. 142–149, 2023, doi: 10.1016/j.prostr.2023.07.005.