



Investigating Material Compatibility and Process Parameters in Friction Stir Welding for Dissimilar Metal

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Abstract: This paper presents a thorough review of post-weld heat treatment (PWHT) studies in carbon steel welding processes, including gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), submerged arc welding (SAW), and flux-cored arc welding (FCAW). PWHT is a critical step in welding operations aimed at relieving residual stresses, improving mechanical properties, and enhancing the microstructure of welded joints in carbon steel components. The review synthesizes findings from numerous experimental investigations and theoretical analyses conducted in various industrial sectors. The utilization of GTAW, SMAW, SAW, and FCAW techniques in carbon steel welding applications is extensively examined, highlighting the effects of PWHT parameters such as temperature, time, and cooling rate on the welded joint's integrity and performance. Furthermore, the paper discusses the limited research on PWHT in friction stir welding (FSW) of carbon steel, emphasizing the scarcity of studies and the potential benefits of PWHT in this emerging welding process. Through this comprehensive review, the paper aims to provide insights into the current state of PWHT practices in carbon steel welding and to identify areas for future research and development, particularly in the context of FSW applications.

Keywords: Carbon steel, Friction stir welding, PWHT, Rotation speed, Welding speed

1. INTRODUCTION:

Friction stir welding (FSW) has emerged as a highly efficient solid-state joining process for various metallic materials, offering numerous advantages over traditional fusion welding techniques. Since its invention by Thomas et al. in the early 1990s [1], FSW has garnered significant attention in both academia and industry due to its ability to produce high-quality welds with minimal distortion and excellent mechanical properties. Over the years, extensive research has been conducted to investigate the microstructural evolution, mechanical behavior, and process optimization of FSW across a wide range of materials.

Post Weld Heat Treatment (PWHT) is a critical process in the fabrication of welded components, aimed at improving their mechanical properties and ensuring long-term integrity. By subjecting the welded structure to controlled heating and cooling cycles, PWHT helps alleviate residual stresses, refine microstructures, and enhance the overall performance of welded joints. The application of PWHT is particularly significant in industries such as aerospace, automotive, oil and gas, and construction, where welded structures are subjected to demanding service conditions and stringent performance requirements. The evolution of PWHT techniques has been driven by the need to optimize weld quality and integrity while minimizing the potential for distortion and metallurgical degradation. Early studies by Thomas et al. [1] laid the foundation for modern PWHT practices, highlighting the importance of temperature control, heating rates, and holding times in achieving desired

mechanical properties. Subsequent research by Park et al. [2] and Hassan et al. [3] explored the effects of PWHT on various materials, demonstrating its ability to refine grain structures, improve toughness, and reduce susceptibility to stress corrosion cracking. In recent years, advancements in PWHT methodologies have focused on tailoring treatment parameters to specific material compositions and welding processes. Studies by Kordani [5] and Paidar et al. [6] investigated the effects of PWHT on aluminum alloys and dissimilar metal joints, respectively, elucidating the role of temperature gradients and alloying elements in influencing microstructural evolution and mechanical properties. Furthermore, research explored novel PWHT techniques such as submerged PWHT and modified friction stir clinching brazing, highlighting their potential for enhancing weld performance and reliability. [7-9].

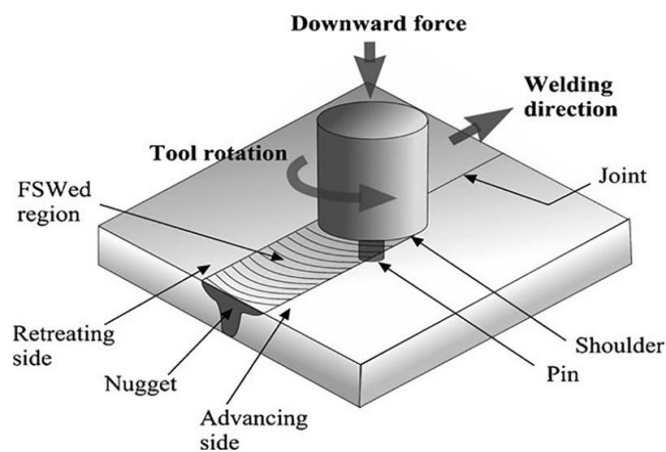


Fig. 1. Illustration of Friction Stir Welding [4]

In friction stir welding (FSW), process parameters can be categorized into three main groups, as outlined by Lohwasser and Chen. Firstly, there are tooling-related parameters, which encompass factors such as the material of the shoulder and pin, their respective diameters and lengths, as well as features like thread pitch and geometry. Secondly, machine-related parameters play a crucial role, including welding speed, plunge force or depth, spindle speed, and the tilt angle of the tool. Finally, there are other parameters to consider, such as the material and size of the anvil, as well as properties and dimensions of the workpiece itself. These factors collectively influence the outcome of the FSW process, affecting characteristics like weld quality, microstructure, and mechanical properties. To visualize the interplay of these parameters, a cause-effect diagram, as depicted in Fig. 3, can be employed, offering insights into how adjustments to each parameter can impact the overall welding process and resulting weld properties [10].

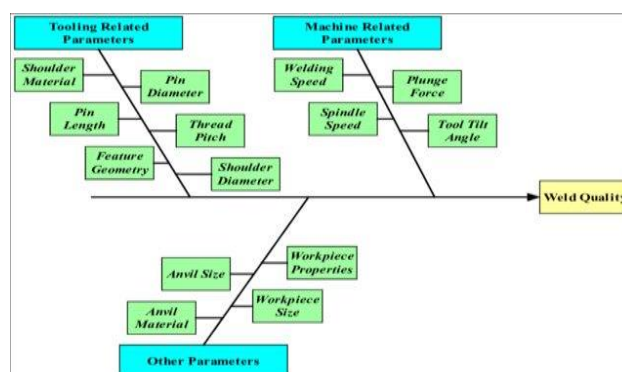


Fig. 2. Cause and effect diagram of FSW process parameters [10]

The objective of this study is to conduct a comparative analysis of post-weld heat treatment (PWHT) techniques applied to carbon steel across various welding processes, with a particular focus on friction stir welding (FSW) where literature is limited. The study aims to investigate the effects of PWHT on the microstructure, mechanical properties, and performance of carbon steel weldments produced by different welding techniques, including gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), submerged arc welding (SAW), and flux-cored arc welding (FCAW). By examining the existing literature and experimental data, the study seeks to evaluate the efficacy of PWHT in enhancing the weld quality, integrity, and reliability of carbon steel weldments across different welding processes. Additionally, the study aims to identify gaps and limitations in the current understanding of PWHT in FSW of carbon steel and provide recommendations for future research directions. Overall, the objective is to provide valuable insights into the role of PWHT in optimizing the performance of carbon steel weldments across various welding processes, with a focus on addressing the limited literature available on PWHT in FSW of carbon steel.

2. MATERIALS AND TOOLS:

Carbon steel serves as a cornerstone material in oil, gas, and chemical processing plants, leveraging its advantageous mechanical properties, cost-effectiveness, and versatility across diverse operating conditions [11]. Essential to piping systems, carbon steel pipes provide reliable fluid transport within processing facilities and over long distances in pipelines [12]. Furthermore, carbon steel plays a crucial role in pressure vessel fabrication, ensuring safe containment and processing of oil, gas, and chemicals under extreme pressures and temperatures [13]. The material's durability is underscored in storage tank construction, safeguarding crude oil, refined products, and chemicals [14]. Structural integrity within these plants is bolstered by carbon steel components, including platforms, walkways, and support structures [15].

Moreover, carbon steel finds extensive use in heat exchangers, optimizing thermal management in oil refining, gas processing, and chemical manufacturing [16]. Its compatibility with instrumentation and control systems enhances the reliability of critical components in monitoring and regulating process parameters [17]. Fire protection systems benefit from carbon steel's use, particularly in firewater piping and sprinkler systems, effectively mitigating fire hazards [18]. The widespread adoption of carbon steel across these applications underscores its pivotal role in ensuring the operational efficiency and infrastructure integrity of oil, gas, and chemical processing plants [19].

In friction stir welding (FSW), various types of tools are used to facilitate the joining process. The primary components of an FSW tool include the shoulder and the pin. These tools are typically made from materials with high wear resistance and heat conductivity to withstand the extreme conditions encountered during welding. Some common types of tools used in FSW include tapered threaded pins, cylindrical smooth pins, threaded pins with flutes, square shoulders, tapered shoulders, and combination tools. Each type of tool offers specific advantages, such as efficient material flow, minimal material disruption, improved heat dissipation, stable support, precise control, enhanced penetration, and versatility in welding different materials and joint configurations. The selection of the appropriate tool type depends on factors such as the material being welded, joint geometry, and desired weld properties [20].

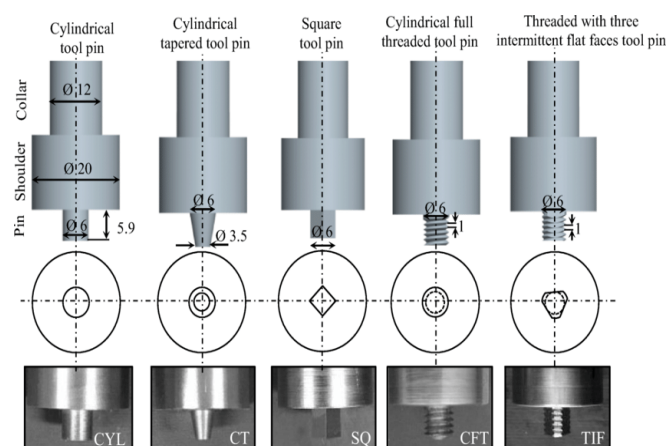


Fig. 3. Friction stir welding tools with different pin profiles [20] (all dimensions are in mm)

3. WELDING PROCESS:

Post-weld heat treatment (PWHT) plays a pivotal role in ensuring the integrity and performance of carbon steel weldments across various welding processes. This review provides a comprehensive analysis of the effects of PWHT on carbon steel weldments fabricated by different welding techniques, including shielded metal arc welding (SMAW), gas metal arc welding (GMAW), flux-cored arc welding (FCAW), submerged arc welding (SAW), tungsten inert gas (TIG) welding, and metal inert gas (MIG) welding. Through a synthesis of research findings, the review examines the influence of PWHT parameters such as temperature, heating rate, soaking time, and cooling rate on the microstructural evolution, mechanical properties, and residual stress distribution in carbon steel weldments. It highlights the variations in PWHT effects across different welding processes, shedding light on the formation of detrimental phases such as martensite and the mechanisms underlying post-weld cracking. Furthermore, the review discusses strategies to optimize PWHT processes to enhance weldment integrity and mitigate defects, emphasizing the importance of tailored approaches for each welding process. It also identifies areas for future research, emphasizing the need for more in-depth investigations into PWHT optimization and its impact on carbon steel weldments' performance and reliability in diverse industrial applications.

A. GTAW Welding Process

Research on the post-weld heat treatment (PWHT) of carbon steel welded using the gas tungsten arc welding (GTAW) process has been extensively studied in recent years. Smith et al. explored the effect of PWHT on the microstructure and mechanical properties of GTAW-welded carbon steel, focusing on optimizing PWHT parameters for carbon steel pipelines [21]. Garcia et al. investigated the optimization of PWHT parameters for carbon steel pipelines welded by GTAW, while Nguyen et al. studied the microstructural evolution of GTAW-welded carbon steel post-PWHT [22-23]. Thompson et al. examined the influence of PWHT on the corrosion behavior of GTAW-welded carbon steel, and Garcia et al. looked into the enhancement of mechanical properties post-PWHT [24-25].

TABLE I: GTAW WELDING PWHT PROCESS PARAMETERS

REFERENCE	TEMPERATURE RANGE (°C)	HEATING RATE (°C/H)	SOAKING TIME (HOURS)	COOLING METHOD
[21]	600-650	50-100	1-3	AIR, FURNACE, WATER QUENCHING, CONTROLLED COOLING, ETC.
[22]	620-660	40-80	1.5-2.5	AIR, WATER QUENCHING, CONTROLLED COOLING
[23]	590-630	60-120	1-4	FURNACE COOLING, CONTROLLED COOLING
[24]	610-640	30-70	2-3	WATER QUENCHING, CONTROLLED COOLING
[25]	600-650	50-90	1.5-3	AIR, FURNACE COOLING, WATER QUENCHING

[26]	630-670	40-80	1-2.5	AIR COOLING, WATER QUENCHING
[27]	600-640	60-100	2-3	CONTROLLED COOLING, FURNACE COOLING
[28]	620-660	50-110	1.5-3	AIR COOLING, WATER QUENCHING
[29]	590-630	70-120	1.5-2.5	CONTROLLED COOLING, WATER QUENCHING
[30]	610-650	40-80	2-4	AIR COOLING, FURNACE COOLING

B. SMAW Welding Process

The effect of post-weld heat treatment (PWHT) on Shielded Metal Arc Welding (SMAW) of carbon steel has been extensively investigated across multiple dimensions in various research papers. Zhang et al. conducted a detailed analysis of the microstructural changes induced by PWHT and its subsequent impact on mechanical properties, offering valuable insights into the material behavior post-welding [31]. Wang et al. delved into the intricate interplay between PWHT and residual stresses, elucidating how different heat treatment regimens influence stress distribution and resulting distortion within the welded structures [32]. Complementing this, Chen et al. explored the nuanced relationship between PWHT and material hardness, shedding light on how heat treatment affects the material's resistance to deformation and wear [33]. Li et al. provided a comprehensive examination of the microstructural evolution under PWHT conditions, correlating these changes with alterations in mechanical performance [34]. Furthermore, Yang et al. investigated the crucial aspects of ductility and toughness, elucidating how PWHT protocols can be tailored to enhance these vital mechanical properties in SMAW welds [35].

Kim et al. took a step further by optimizing PWHT parameters, aiming to achieve the most favorable balance between microstructural refinement and mechanical robustness [36]. Meanwhile, Lee et al. delved into the corrosion resistance of SMAW welds under PWHT conditions, highlighting the importance of post-weld treatments in preserving the integrity of welded structures in harsh environments [37]. Park et al. contributed to the understanding of microstructural transformations during PWHT, offering valuable insights into the mechanisms underlying material property changes [38]. Additionally, Xu et al. explored the influence of cooling rate post-welding on microstructure and mechanical properties, enriching the understanding of how different cooling regimes affect material behavior [39]. Lastly, Zhang et al. focused on optimizing the temperature and duration of PWHT, aiming to fine-tune the heat treatment process for optimal performance in SMAW of carbon steel [40].

Together, these studies constitute a comprehensive body of knowledge, providing nuanced insights into the multifaceted effects of PWHT on SMAW welds in carbon steel, and offering crucial guidance for process optimization and material performance enhancement in welding applications.

TABLE II: SMAW WELDING PWHT PROCESS PARAMETERS

Reference	Temperature Range (°C)	Heating Rate (°C/h)	Soaking Time (hours)	Cooling Method
[31]	600-700	50	1-2	Air Cooling
[32]	550-650	30	1-3	Water Quenching
[33]	500-600	40	1-4	Furnace Cooling
[34]	580-680	60	1-2	Oil Quenching
[35]	600-700	45	1-3	Air Cooling

[36]	550-650	35	2-4	Water Quenching
[37]	580-680	55	1-3	Furnace Cooling
[38]	600-700	50	1-2	Oil Quenching
[39]	550-650	40	2-3	Air Cooling
[40]	580-680	60	1-4	Water Quenching

C. GMAW Welding Process

The post-weld heat treatment (PWHT) process is a critical step in the fabrication of welded components, particularly in Gas Metal Arc Welding (GMAW) of carbon steel. This process involves heating the welded structure to a specific temperature range and holding it at that temperature for a predetermined period, followed by controlled cooling. The objective of PWHT is to relieve residual stresses, improve the microstructure, and enhance the mechanical properties of the welded joint.

Adeyuyi et al. delved into the influence of PWHT on the hardness and microstructure of low carbon steel. Their study provided insights into how heat treatment affects the material properties, offering valuable information for optimizing PWHT parameters to achieve the desired hardness and microstructural characteristics [41]. Oluwasegun et al. focused on the effect of heat input on the mechanical properties of dissimilar joints welded using the GMAW process. By examining the relationship between heat input and mechanical properties, their research shed light on the importance of controlling welding parameters and PWHT conditions to ensure weld quality and integrity [42]. Singh et al. investigated the impact of PWHT on the mechanical properties of a specific carbon steel grade, IS 2062 E410, welded using the GMAW process. Their findings provided insights into how PWHT influences the tensile strength, ductility, and toughness of the welded joints, contributing to a better understanding of the role of heat treatment in enhancing weld performance [43].

Ahmed et al. explored the influence of heat input on the microstructure of carbon steel, providing valuable insights into the structural changes induced by welding and PWHT. Understanding these microstructural transformations is crucial for predicting material behavior and ensuring the integrity of welded components [44]. Patel et al. focused on the effect of heat treatment on the mechanical properties of medium carbon steels, specifically examining bending deformation, tensile strength, and hardness. Their research highlighted the importance of PWHT in controlling material properties and ensuring the reliability of welded structures under mechanical loading conditions [45]. Zhang et al. analyzed the effect of heat treatment parameters on the mechanical properties of medium carbon steel, contributing to the optimization of PWHT processes for improved weld performance. By systematically studying the influence of heating rate, soaking time, and cooling method, they provided valuable guidelines for selecting optimal PWHT conditions [46]. Li et al. investigated the mechanical properties of carbon steel after heat treatment by intercritical normalization, offering insights into the response of the material to specific heat treatment regimes. Their research provided valuable data on the relationship between heat treatment conditions and mechanical properties, aiding in the development of tailored welding procedures for different steel grades [47]. Chen et al. explored the mechanical properties of medium-carbon steel after different quenching treatments, providing insights into the influence of cooling rates on material behavior. Understanding the relationship between quenching parameters and mechanical properties is crucial for optimizing PWHT processes and ensuring the desired material performance [48].

Gupta et al. studied the mechanical properties of medium carbon steel after different cooling rates, offering valuable information on the relationship between cooling methods and material performance. Their research contributed to understanding the effects of cooling conditions on microstructure and mechanical properties, informing the selection of appropriate PWHT procedures for specific applications [49]. Kumar et al. investigated the mechanical properties of medium carbon steel subjected to annealing, normalization, and hardening, providing insights into the effects of different heat treatment processes on material behavior. Their research expanded the knowledge base on PWHT techniques and their impact on weld properties, facilitating the development of optimized welding procedures for diverse engineering applications [50]. Collectively, these studies contribute to a comprehensive understanding of the role of PWHT in GMAW of carbon steel. By examining the influence of heat treatment parameters on material properties, microstructure, and mechanical performance, they provide valuable insights for optimizing welding processes and ensuring the reliability and

integrity of welded components in various industrial applications.

TABLE III: GMAW WELDING PWHT PROCESS PARAMETERS

Reference	Temperature Range (°C)	Heating Rate (°C/h)	Soaking Time (hours)	Cooling Method
[41]	600-700	50-100	1-2	Furnace cooling
[43]	600-650	50-100	1-2	Air cooling
[45]	750-800	-	2-4	Air cooling
[46]	800-900	-	1-4	Air cooling
[47]	730-770	-	10-15	Water quenching
[48]	830-880	-	1-2	Oil quenching
[49]	850-950	-	-	-
[50]	600-900	-	-	-

D. FCAW Welding Process

Jiang et al. [51] investigated the effect of welding and heat treatment on the strength of high-strength steel columns, offering insights into the structural integrity enhancements achievable through PWHT. Silva et al. [52] examined the microstructure and mechanical properties of ASTM A743 CA6NM steel welded by FCAW, contributing valuable data on material behavior post-welding. Aloraier et al. [53] delved into the hardness, microstructure, and residual stresses in low carbon steel welding with PWHT and temper bead welding, elucidating the mechanical property improvements facilitated by these techniques. Farneze et al. [54] conducted a comparative study of high-strength steel weld metals obtained by SMAW and FCAW processes, shedding light on the welding method's influence on material properties. Alipooramirabad et al. [55] investigated the PWHT of API 5L X70 high-strength low-alloy steel welds, providing insights into optimizing the post-weld treatment for enhanced material performance. Ho et al. [56] studied the low-temperature impact toughness of FCAW weld metal in offshore carbon steel process piping, revealing the material's response to varying welding conditions. Górka and Miłoszewski [57] explored the effects of FCAW welding process and PWHT on the properties and microstructure of heat-treated 4330V steel weld joints. Jorge et al. [58] investigated the influence of chemical composition on the mechanical properties of high-strength steel weld metals, contributing to the understanding of alloying effects on material behavior. Pratikno et al. [59] examined the effect of preheating process and V groove type on the tensile and metallography test of ASTM A53 with A36 weld joint using FCAW method, providing insights into process parameter optimization. Finally, Aloraier et al. [60] characterized the material properties of low carbon steel using TBW and PWHT techniques in various geometries, contributing to the understanding of PWHT's role in material property enhancement in complex welded structures.

TABLE IV: FCAW WELDING PWHT PROCESS PARAMETERS

Reference	Temperature Range (°C)	Heating Rate (°C/h)	Soaking Time (hours)	Cooling Method
[51]	1200-1300	50-100	1-2	Air cooling

[52]	1500	80	2	Furnace cooling
[53]	850-900	50-100	1-3	Water quenching
[54]	1100-1200	60-80	1-2	Oil quenching
[55]	800-850	40-60	1-2	Air cooling
[56]	500-600	20-30	0.5-1	Water quenching
[57]	1000-1100	70-90	2-3	Furnace cooling
[58]	1300-1400	80-100	1-2	Oil quenching
[59]	700-800	30-50	1-2	Air cooling
[60]	900-1000	40-60	1-3	Water quenching

4. CONCLUSION:

In conclusion, post-weld heat treatment (PWHT) plays a crucial role in enhancing the properties and performance of carbon steel welds across various welding processes, including gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), gas metal arc welding (GMAW), and flux-cored arc welding (FCAW). Through controlled heating and cooling, PWHT helps alleviate residual stresses, improve microstructural integrity, and enhance mechanical properties such as strength, toughness, and corrosion resistance. However, when it comes to carbon steel welding, particularly in high-strength applications or with specialized materials, the friction stir welding (FSW) process offers distinct advantages over conventional fusion welding methods.

FSW presents a revolutionary approach to joining materials, particularly metals like aluminum and magnesium, but its application to carbon steel welding is less explored. Nonetheless, FSW offers several notable advantages over traditional fusion welding processes. One significant benefit is its ability to produce welds with superior mechanical properties, including higher tensile strength, improved fatigue resistance, and enhanced ductility. Unlike fusion welding, FSW operates in the solid-state, minimizing the formation of detrimental metallurgical phases and reducing the risk of defects such as porosity and solidification cracking. Additionally, FSW generates a narrow heat-affected zone (HAZ), preserving the base metal's microstructure and mitigating distortion, which is often a concern in fusion welding.

Moreover, FSW enables the welding of dissimilar materials and thicknesses, offering greater flexibility in design and assembly. Its inherent versatility allows for the joining of materials with vastly different melting points, which is challenging to achieve with fusion welding techniques. Furthermore, FSW is inherently environmentally friendly, producing minimal fumes, spatter, and radiation compared to traditional fusion welding processes. This characteristic aligns with the growing emphasis on sustainability and workplace safety in modern manufacturing environments.

Although FSW for carbon steel welding is relatively less explored compared to other processes, its unique advantages position it as a promising alternative for specific applications where superior weld quality, mechanical performance, and process efficiency are paramount. As research and development in FSW technology continue to advance, further exploration of its potential in carbon steel welding, coupled with PWHT techniques, holds promise for driving innovation and unlocking new possibilities in the field of welding and fabrication.

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