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A review on the effectiveness of different cooling method in improving mechanical properties and mitigating heat-induced distortion of 3mm thick SS316L plate - GTAW single-pass buttwelds

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ABSTRACT The cooling method in welding has evolved from a post-weld heat treatment (PWHT) process to in-process cooling or continuous cooling during the welding procedure. The main reasons for this, in general, are to increase the cooling rate of the material to avoid the widespread area of heat input onto the base metal, which will lessen the wide heat-affected zone (HAZ) and prevent HAZ softening phenomena. These chain actions have proven effective in improving the mechanical properties and heat-induced distortion of various metals and welding process. However, from the literature study, the pinpoint study in-cooling method used in a 3mm thick SS316L plate welded using Gas Tungsten Arc Welding (GTAW) has yet to be explored by any literature. This review is essential as the specific thickness of SS316L plate is used in vast industry applications, more over the maximum penetration of GTAW is approximately at 3 mm. This article additionally offers a comprehensive survey of the literature on cooling methods for solving problems in fusion and non-fusion welding involving various metals. The significant findings are then summarized to identify critical solutions to related issues and interesting potential areas that require further investigation to overcome or to reduce those challenges and problems. The recommendation is also made based on the summary of how the cooling method procedure will be applied to 3mm thick SS316L GTAW welds.

KEYWORDS: Welding cooling method; GTAW; SS316L; HAZ softening; Distortion.
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Review Article

INTRODUCTION

Large amounts of heat energy are used during thermal welding process exceeding 3000 ^{0}C for specific types of welding. The heat generated during welding introduces challenges such as material distortions, residual stresses, and compromised mechanical properties (Aldalur *et al.*, 2020; Harinadh *et al.*, 2021). For instance, Sayed & Alanazi (2022) found that the mechanical properties of Shielded Metal Arc Welding (SMAW) welded of ASTM A370 low-carbon steel with were negatively impacted by air cooling after welding. Reduced yield and ultimate stress, modulus of elasticity, and increased elongation provided the evidence (Sayed & Alanazi, 2022). An effective thermal management through cooling method has become essential to ensure optimal weld quality and overall performance (Dash *et al.*, 2023). This paper will focus on comprehensive analysis of the current cooling innovations welding technology. By examining the latest trends, discussing their applications, and identifying potential future directions, this paper aims to contribute to the broader understanding of how cooling method shape modern welding process' landscape. The next sections examine the cooling approaches influences on welding microstructure and mechanical properties. These sections will investigate the range of cooling techniques currently utilised in various welding applications. Subsequently, the focus will be directed towards heat-affected zone (HAZ) related issues. In this paper, the impacts of cooling method on to HAZ are discussed in detailed. In addition, this paper will also address the existing challenges and provide an understanding into the implications of cooling innovations for industries and applications. The popularity of SS316L in the industry cannot be refutable as the wide application of this metal addressed in many studies (Chellaganesh *et al.*, 2021; Gustafson *et al.*, 2023; Ray *et al.*, 2019).

One of the most exciting and inspiring issues is related to HAZ softening phenomena, which happens to martensite steel after the welding process (Han *et al.*, 2023; Medvecká *et al.*, 2023; Medvecká *et al.*, 2022; Tuncel *et al.*, 2023). Does it have the same effect on Austenic steel (SS316L) welded with Gas Tungsten Arc Welding (GTAW)? Moreover, how will the chosen cooling method affect the HAZ? And how cooling method affect the overall performance of SS316L for its application. All these question marks are elaborated more in the following sections. The novelty for this work can be concluded as fixing puzzles of the optimized welding type and cooling methods in joining with butt-weld of two 3mm plates of SS316L.

WELDING METALLURGY OF SS316L WELDED WITH GTAW

316L stainless steel is classified as an Austenitic stainless steel, specifically a version with a reduced carbon content compared to standard 316 stainless steel. Both 316 and 316L stainless steels are characterized by the presence of molybdenum, with 316L stainless steel exhibiting a higher molybdenum content compared to 316 stainless steels. The inclusion of molybdenum in the composition of 316L steel results in enhanced performance characteristics compared to 310 and 304 stainless steels. The 316L stainless steel alloy is characterized by a carbon content that does not exceed 0.03%. This alloy is suitable for situations where it is not feasible to perform post-welding annealing and when optimal resistance against corrosion is of utmost importance. Due to its superior resistance to carbide precipitation, 316L stainless steel exhibits the capability to withstand continuous exposure to temperatures ranging from 427 °C to 857 °C, a range in which the use of 316 stainless steel is not recommended. According to CIVMATS (2023), whereas 316L exhibits superior corrosion resistance compared to 316, its mechanical qualities are comparatively inferior to those of 316. The chemical compositions of SS316L, as found in industrial supply, are as follows: carbon (C) content is less than or equal to 0.03%, silicon (Si) content is less than or equal to 0.75%, manganese (Mn) content is less than or equal to 2.00%, phosphorus (P) content is less than or equal to 0.045%, sulfur (S) content is less than or equal to 0.03%, nickel (Ni) content ranges from 10.0% to 14.0%, chromium (Cr) content ranges from 16.0% to 18.0%, molybdenum (Mo) content ranges from 2.0% to 3.0%, and nitrogen (N) content is less than or equal to 0.1%. SS316L exhibits exceptional corrosion resistance, rendering it well-suited for a wide range of harsh conditions. The presence of molybdenum into the material boosts its ability to withstand pitting and crevice corrosion, rendering it very suitable for many applications that include exposure to chloride solutions, such as marine conditions or seawater (CIVMATS, 2023)

Welding metallurgy is the basis for any new ideas in cooling innovation in welding. Welding metallurgy investigated how welding changed metals' physical, mechanical, and chemical properties. So, the purpose of learning welding metallurgy is to make good welds that keep the same properties as the base metals were before welding or even better. In fusion welding, particularly GTAW, it is necessary to consider various pre-, during-, and post-welding factors in producing a good weldment. The chemical composition of both base and filler metal should be recognized before the welding procedure, while heat input control and cooling procedure must be carefully selected before applied during the welding procedure. Heat input can be controlled by controlling volt, ampere and travel speed variables while cooling rate is controlled by choosing the cooling medium and technique. Finally, the grain size and mechanical properties of the weldment must be inspected by welders to ensure the weldment achieves the desired quality. Generally, the dissolving and solidifying of a metal during the welding process will eliminate its original microstructure (grain size) and modify its mechanical and corrosion properties. Usually, the temperature distribution in the fusion zone (FZ) and HAZ of welded metal can be interpreted from the thermal equilibrium phase diagram. However, the thermal equilibrium phase diagram constructed based on the normal cooling time of melting and solidifying process of metal, which is different in fusion welding process in this case GTAW when the metal is experiencing a high heating rate, short holding times at the peak temperature, and rapid cooling. This process behaviour resulting to the varies of thermal cycle along the weld zone leads to the HAZ formation, extending from FZ to the base metal (BM). The transition of weldment's microstructure varies from FZ to HAZ area, the size and geometry of HAZ can be control by heat-input adjustment. Besides that, cooling process of the weldment also been explored and applied by researcher to serve the same purposes. In turn, the thermal equilibrium cannot accurately represent the phase transition of weldment during welding (Khan *et al.*, 2023).

Annealed, normalised, quenched, hardened and tempered are the four mains process of heat treatment to achieve desired metal properties. In welding technology, these processes are applied to the welded part to adapt metal properties for its application. For instance, using a Union S 1 CrMo 2 V welding wire, Schönmaier *et al.* (2022) studied creep-resistant 2.25Cr–1Mo–0.25V steel multi-layer weld metal welded using single wire multi-layer Submerged-arc welding (SAW). The material has been used for several years as heavy wall pressure vessels, such as hydrocracking reactors in the petrochemical industry. To obtain the required material properties, the material is then subjected to a PWHT annealed process. One of the findings is that the 2.25Cr-1Mo-0.25V weld metal's creep strength and toughness behave in an opposite way, with a higher PWHT temperature decreasing the stress rupture time and concurrently increasing the Charpy impact energy. Second, significant coarsening of the MX carbonitrides promotes a quicker recovery of the dislocation structure, which is associated to a decrease in stress rupture time and strength with increased PWHT temperature (Schönmaier *et al.*, 2022).

In the meantime, Lee *et al.* (2021) investigated how PWHT affected the microstructures and mechanical characteristics of SA-508 Gr.1a welds. They also suggested a new PWHT exemption criterion based on the assessment of nonductile fracture while taking welding residual stress into consideration. Five welding coupons were created using various heat treatment and welding techniques. Nuclear power plant steam generators employ SA-508 Gr.1a material and only one coupon that has been welded with SAW. It is noteworthy that the sample subjected to PWHT (tempering at 610 °C for 40 hours) experienced a decrease in strength. Based on this, it was determined that PWHT does not significantly affect the mechanical properties of SA508 Gr.1a welds. This strongly suggests that PWHT may be removed from the welding process for SA508 Gr.1a welds with thicknesses up to 120 mm in terms of mechanical properties (Lee *et al.*, 2021).

Garcia *et al.* (2022) investigated the rise in grade X70 pipe welds using cellulosic consumables that resulted in pipeline girth weld failures in the pipeline industry in North America. The researchers successfully established a correlation between the chemical composition of steel and the hardness of the HAZ in a typical production girth weld. This correlation was observed across a range of weld thermal simulations and real welds. The study consisted of two main stages. The first stage involved calibrating the influence of cooling rate and chemical compositions on the hardness of the material. The second stage focused on investigating the impact of Pcm, carbon content, Mo content, and cooling rate on the minimum and maximum hardness. The findings indicate that the ultimate hardness in the HAZ is directly influenced by the chemical composition of the steel, specifically in terms of Pcm, as well as the weld cooling rate (Garcia *et al.*, 2022).

In a recent study, Cheng *et al.* (2022a) investigate the impact of low-temperature cooling on the corrosion characteristics of laser-welded joints between Hastelloy C-276 and 304 stainless steel, utilising filler wire. The experimental setup involved the introduction of a low-temperature coolant, specifically a sodium chloride (NaCl) solution, to the side of the welded sheet, specifically the Hastelloy C-276 side. The cooling equipment utilised in this study is a HX-105 thermostatic circulating flume, which operates at low temperatures. It has a flow rate of 8 L/min. The coolant's temperature is recorded at -5 °C, 5 °C, and 20 °C, with the latter being considered room temperature. The findings suggest that the incorporation of low-temperature cooling has the potential to mitigate the formation of precipitated phases and the presence of unmixed zones. As the temperature of low-temperature cooling decreases, there is a steady increase in the fraction of the coherent relationship between μ phase and matrix is worse than that of *p* phase within the precipitated phase. This increase is observed in the ratio of grain boundaries with small angles and the contents of corrosion-resistant materials within the laser weld (Cheng *et al.*, 2022a).

In conclusion, the application of specific cooling process in welding can be used to achieve desirable mechanical properties in welded steels. The selection of cooling process is based on various factors, including the dimensions of the steel, chemical composition, grain size, and cooling rate (Lee *et al.*, 2021).

WELDING COOLING METHOD IN IMPROVING MECHANICAL PROPERTIES

As discussed earlier, the heat input supplied to the weldment while welding this material weakens the FZ by grain growth, widening the HAZ, reducing yield and tensile strength and introducing distortion (Cheng *et al.*, 2022; Hussain & Khushnood, 2023; Ma *et al.*, 2023; Sayed & Alanazi, 2022; Vemanaboina *et al.*, 2021). There are two distinct cooling processes employed in the field of welding, namely in-process cooling and post-weld process cooling. In-process cooling, often referred to as localized cooling, in-situ cooling, or continuous cooling, is a cooling technique implemented during the welding process. It is often useful for the purpose of restricting the heat affected zone during welding, particularly in steels containing 13% manganese and certain nickel alloys. In the latter scenario, the process of cooling serves to limit the development of carbides within the HAZ, hence resulting in improved corrosion resistance. Cooling is often achieved through the application of water spray or sprinkling over the underside of the plates near the joints, commonly employed during the welding process (Vora & Bandheka, 2019). The cooling medium in advanced technology has transitioned to several states, including ice, solid and gas forms of CO_2, liquid nitrogen, and helium. Advancements also have been achieved in the instrumentation of cooling procedures, including the introduction of a copper back and cooling chamber. These innovations aim to effectively dissipate excessive heat from the FZ and prevent its transfer to other sections of welded steels.

The in-cooling process has been applied in various welding process, from fusion welding, friction stir welding (FSW) (Liu *et al.*, 2023; Shi *et al.*, 2022), laser beam welding (Cheng *et al.*, 2022a) and almost all types of welding since all welding process will involve heat-induced to parent metal. The heat-induced will create an FZ and a HAZ. The FZ usually brings no issues since it experiences a complete thermal cycle, melting and resolidifying. While HAZ only shares half of the process. Various welding cooling methods have been explored recently throughout different welding processes, including fusions, laser, and FSW. Welding has evolved from cooling via surrounding air, water-cooled, and ice cooled as cooling medium to cryogenic cooling, where dry ice, liquid CO_2 and liquid nitrogen were used. For example, in a recent study conducted by Barzegar-Mohammadi *et al.* (2023), the fatigue life of patch-welded joints was examined and quantified by an experimental method. The study focused on 516 GR.70 steel plates with thicknesses of 8 and 10mm, comparing joints with and without GTAW treatment. Several cooling conditions were also considered throughout the investigation. Three cooling methods were evaluated, with the initial panel being cooled using ambient air. In the second and third operations, a cooling water system was employed, consisting of a schematic arrangement of water, a pump, and piping. This system facilitated the passage of water to a cooling chamber located at the rear of the weldment. Notably, two distinct flow rates were utilized during these procedures. The cooling procedure was implemented concurrently with the welding operation (Barzegar-Mohammadi *et al.*, 2023).

Studies have shown cooling techniques can mitigate defects and enhance mechanical properties of welds. Lee *et al.* (2020) demonstrated water cooling during gas tungsten arc welding (GTAW) of stainless steel prevented solidification cracking by reducing thermal strain below the threshold for cracking. The cooled welds also exhibited increased yield strength. Wegrzyn *et al.* (2019) analyzed micro-jet helium cooling during gas metal arc welding, finding 40-50 μm nozzles at 0.5 MPa improved impact toughness. Snyder and Strauss (2021) showed multiple cooling methods (compressed air, water, dry ice, liquid nitrogen) applied during friction stir extrusion of aluminum-to-steel joints increased joint strength regardless of medium.

Looking at recent research trends, cooling mediums range from surrounding air, water, liquid CO_2, solid CO_2, liquid nitrogen, and helium gas. The different cooling mediums produced different results in each study, for they have unique temperatures such as liquid nitrogen (LN_2) with (-195^0C) at boiling point, (−78.5 °C) for dry ice CO_2, (−29 °C) for liquid CO_2, 25^0C for water at room temperature depends on surrounding air and (−271 °C) for helium. In addition to the stated fact, the application of low-temperature cooling has the potential to boost both the cooling and solidification rate of the weld. Furthermore, the cooling effect of the weld is intensified as the temperature of the low temperature cooling medium decreases. Nevertheless, the procedural strategy employed in the cooling process exerts a substantial influence on the determination of cooling rates (Cheng *et al.*, 2022a).

HEAT AFFECTED ZONE (HAZ) RELATED ISSUES

The HAZ frequently appears to be the location of hot cracks, cold cracks, and brittle phases, making it the most fragile section of welded joints (Geng *et al.*, 2022). HAZ is formed from several subregions with different grain sizes depending on its locations from the FZ (weldment) and the base metal. The HAZ frequently appears to be the location of hot cracks, cold cracks, and brittle phases, making it the most fragile section of welded joints (Dikić & Simon, 2023). Some researchers divide the HAZ into three sub-zones (Khan *et al.*, 2023; Rios *et al.*, 2022) and some of them into four sub-zones (Medvecká *et al.*, 2022) with different mechanical properties and microstructures. The sub-zone can be classified as sub-critical HAZ (SCHAZ) also known as the tempered zone, refers to the region in which the temperature experienced during welding reaches a level that is sufficiently enough to temper martensite, inter-critical HAZ (ICHAZ) is characterized by a partially altered region and upper- or super-critical HAZ (UCHAZ) or coarse grain HAZ (CGHAZ) refers to a region in welding where the temperature reaches a higher level.

There has been a significant number of research-contributing findings in HAZ-related investigations recently. For instance, a study conducted by Lu *et al.* (2022a) examined the softening behavior and mechanism of the HAZ in a spray-formed 7055 aluminum alloy following T76 heat treatment during single-pass GTAW. Based on the observed findings, it was determined that the microstructures and mechanical characteristics exhibited significant non-uniformities. Consequently, the HAZ was classified into two distinct regions, namely the solid solution zone and the over ageing zone (Lu *et al.*, 2022a). According to Medvecká *et al.* (2022), The present study examined the microstructural alterations occurring in the HAZ of thermo-mechanically controlled processed (TMCP) production grade S960 MC advanced high-strength steels (AHSSs). The investigation revealed that the welding process induces noteworthy modifications in the HAZ due to the presence of a heat gradient. The use of heat induces alterations in the microstructure of the material, leading to corresponding modifications in its hardness (Medvecká *et al.*, 2023).

Moreover, in a recent study conducted by Lu *et al.* (2022b), the researchers examined the impact of a subsequent thermal cycle induced by heat treatment on the softening behavior and underlying mechanism of the HAZ in GTAW spray-formed 7055 aluminum alloy. The findings indicated a deterioration in the mechanical characteristics of the solid solution zone after the second heat cycle. After undergoing the second thermal cycle, it was seen that the solid solution zone saw a decrease in hardness from 180HV to 103HV. Additionally, the tensile strength of the material decreased from 570 MPa to 346 MPa. The primary factors contributing to the decline in mechanical characteristics inside the solid solution zone following the second heat cycle were the attenuation of the solid solution strengthening phenomenon and the occurrence of over-ageing. Following the completion of the second thermal cycle within the over-aging zone, it was observed that the mechanical properties exhibited a decline, followed by a subsequent increase as the temperature of the thermal cycle was elevated. In general, it was seen that the width of the HAZ exhibited an increase after the secondary thermal cycle. Additionally, it was noted that the region experiencing the most significant softening expanded in the direction of the fusing line (Lu *et al.*, 2022).

WELDING PROCESS OF 3MM THICK OF SS316L WITH GTAW PROCESS

In most recent studies, it has been learned that the viable option welding process to join 3mm thick of SS316L is GTAW for the heat input concentrated in small FZ, and the maximum penetration reaches up to 3mm (Advaith *et al.*, 2019; Lu *et al.*, 2022a; Sahu *et al.*, 2021). According to Hussain & Khushnood (2023), the attainment of a satisfactory joint for SS316 poses difficulties due to the presence of a protective film on its surface. This film not only imparts stainless properties to the material but also shields it from corrosion. The film under consideration possesses properties characteristic of a resistant material, requiring the consumption of a substantial amount of concentrated heat to facilitate its removal. This is due to its greater melting point, which might end up resulting in weld burn-through and limit the achievement of full joint penetration (Hussain & Khushnood, 2023). A few more advantages for promoting GTAW to be used in this joining procedure are the HAZ formation is relatively tiny compared to other joint fusion welding processes like GMAW and SMAW. They were followed by the finer effective grain size of the martensitic microstructure and fewer oxide inclusions of 10 wt% Ni steel (Barrick & DuPont, 2020).

Heat-input in GTAW

The metallurgical control of welding bead properties is determined by the heat input, which is subject to the welding parameters. However, some welding experts believe that obtaining precise measurements of current, voltage, and welding speed is sufficient to ensure clear process specifications (Fei *et al.*, 2019). The heat-input calculation commonly employed in fusion welding is typically written

$$E_{weld} = \frac{U \times I}{TS_{weld}} \qquad (1)$$

Table 1. Summary of recent research work on welding cooling method.

Reseacher, Years, Country	Method	Welding process	Material/ Filler	Joint design	Test sample (mm/″)	Cooling method/medium	Distortion analysis	Impact/ Findings
(Liu *et al.*, 2023), China	Exp./ pure	FSW	AA1050-H24	Butt	200×60×3	Liquid CO_2	NA	Increase tensile strength, Decrease elongation
(Dash *et al.*, 2023) United States	Exp.	GMAW	Industrial Mild steel	WAAM	Cylinder	Active cooling heat exchanger with 20.5 ◦C coolant flow.	NA	Microhardness is increase with adaption of active cooling.
(Hussain & Khushnood, 2023) Pakistan	Exp.	Plasma	SS316	ь Butt automatic	300×150×2	Surroundings, LN_2, Thermo gel	Reduced	Improves mechanical properties of welded joint.
(Han *et al.*, 2023) *Republic* of Korea	Exp./	FSW	DP780	Butt automatic	150×80×1.4	550 ◦C for 1 h followed by furnace cooling (PWHT–FC), water quenching (PWHT–WQ), liquid N2 quenching (PWHT–LNQ)	NA	FC- decrease, WQ- improves LNQ – Improves mechanical properties
(Barzegar-Mohammadi *et al.*, 2023) Iran	Exp., FEA. /	GTAW	Normalized A516 GR.70 steel plates	Fillet weld	400×500×8 400×500×10	Surroundings air, fluid motion (cooling chamber with 25 ◦C water flowing at 0.5 & 1.5 ms^{-1})	NA	Higher cooling rate reduced HAZ size and improve fatigue life of normalized A516 GR.70 steel plates
(Shi *et al.*, 2022), China	Exp./	FSW	AA2195-T6	Butt	200×100×2	Cooled -10^0 Water + ethanol (5:1) splat at the back of weldment.	-	Improves microhardness, Increase tensile strength, Decrease elongation
(Cheng *et al.*, 2022a), China	Exp., Numerical simulation	Laser	Hastelloy C-276/SS304	Lap	40 x 30 x 0.5 20 x 30 x 2	Cooling block with coolant is at −5 ◦C, 5 ◦C, 20 ◦C	-	corrosion properties of welded joints are improved
(Cheng *et al.*, 2022b), China, Canada	Exp	GTAW	AA5083-O AA6061-T6	Butt	220 × 85 × 1	Water cooled-copper backing & cover plate	-	Increase hardness due to reduced HAZ softened zone.
(Snyder & Strauss, 2021), USA	Exp./	FSE	AA6061 to mild steel	Butt	3″ × 8″ × 0.25″	compressed air, water, granulated dry ice, LN_2	-	hardness performance increased
(Lee *et al.*, 2020), Japan	Exp., FEA/	GTAW	SS310S	Bead formation	100x50x2	Water cooling	-	Increase in the yield strength, Prevent cracking.
(Wegrzyn *et al.*, 2019), Poland	Exp., Numerical simulation	GMAW	Weld Metal Deposit	Bead formation	NA	Micro-jet/Helium	-	Obtain weldment with demanded mechanical characteristics.

Equation (1) represents the relationship between $\boldsymbol{E}_{weld}$, U, I for arc welding process in this context, the variable E_{weld} represents the energy input measured in joules per millimeter, U represents the represents the unit of Volts, and I represent the unit of Amperes and TS_{weld} represents the travel speed of the heat source measured in millimeters per second. The welding speed is the main controlling factor for porosity defect formation (Mondal *et al*., 2016).

Optimization of the Process Parameter.

The optimizing process is one of the steps in controlling heat input. The parameter optimization is based on calculation no. 1, followed by preliminary experiments. This optimization step is crucial to ensure the results of the cooling experiment were not influenced by inappropriately selected parameters. The design of experiments for SS316L welded with GTAW should involves the consideration of three primary objectives. These objectives included the optimization of heat input use during welding process, achieving complete weld bead joint penetration with the use of filler metal, and improving the microstructure as well as the mechanical properties of the welded samples. As in the welding industry, Welding Procedure Specification (WPS) according to American Welding Society (AWS) is applied to achieve industrial standard practice.

DISTORTION

The extreme thermal concentration involved in the Gas Tungsten Arc Welding (GTAW) process enables effective joint penetration by eliminating the passive oxide coating and other contaminants present on the surface, therefore facilitating the production of a strong weld (Houldcroft & John, 2001) Nevertheless, the substantial heat energy produced during the welding process leads the cause of undesirable residual stresses, which can have negative impact on the structural integrity of various components. These effects include compromised corrosion resistance, reduced fatigue strength, and undesired distortion. The appearance of distortion in weldments can be linked to the thermal cycles experienced during the welding procedure, defined by fast heating and rapid cooling. The distortion in the weldment causes inaccuracy and affects the assemblies of structures (Barat *et al*., 2023; Li *et al*., 2022; Sun & Yu, 2022).

CONCLUSION

This study provides a comprehensive overview of the historical development of cooling technologies and their various applications in the context of welding process. Moreover, the present study focuses its attention on the seamless integration of the field of welding metallurgy and recent developments in welding techniques, which are further elaborated upon in a comprehensive manner. As summarized in Table 1, cooling procedures do improve mechanical properties of weldment for various metals. Material thickness has been left out from discussion because the penetration of GTAW is only up to 3mm, thus 3 mm plate is good enough to monitor the penetration or weldment. Furthermore, the focus of this work is on multiple cooling methods employed for different types of metal and welding processes. This includes an examination of the changes in mechanical properties and distortion defects resulting from heat-induced effects, as well as the intriguing phenomenon of HAZ softening caused by similar factors. Several major findings have been derived from the comprehensive research conducted on this topic. These results can be clearly stated as follows.

1. The cooling method has been applied to improve the mechanical properties of metal in the welding process depending on the type of metal, metal thickness and type of welding process.
2. The existence of HAZ softening phenomena in the sub-critical HAZ can be attributed to the tempering process of martensite. This tempering process causes the decomposition of martensite, allowing previously trapped carbon to diffuse out of the martensitic lath. Consequently, this diffusion leads to a deterioration in the mechanical properties of the joint. In the context of the tensile test, it is consistently observed that failure consistently occurs within the HAZ.
3. There are three factors for changes in the material's mechanical properties after weldment: martensite phase volume, chemical composition and heat input.
4. The in-process cooling applied in recent studies minimizes the tempering time in the thermal cycle of welded material; cooling is applied as soon as the weldment occurs, ensuring the supplied heat is contained in a small area and not distributed far away from the FZ. The benefits include a small area of HAZ, low distortion and improved mechanical properties.
5. Finally, the type of cooling medium and method used in the in-cooling process affected the cooling rates of weld material, heat distribution, HAZ area size, and tempering time, further affecting mechanical properties and distortion.

RECOMMENDATION

Despite encountering numerous challenges in the implementation of this procedure, current study has provided evidence to support its success. Based on the outcomes of this review project, several recommendations were proposed to provide direction for future efforts towards mitigating these concerns:

1. The focus of future experiments to be conducted on the cooling method of the GTAW process of SS316L should focus on the formation of HAZ. The smaller the HAZ, the better.
2. In addition, conducting an examination of the compressive and tensile stress experienced by the HAZ could be significant, since the lack of any existing research on this investigation.
3. The influence of the cooling technique on the transformation of δ ferrite to γ austenite and the presence of residual δ ferrite at the grain boundaries were elements which contribute to the enhanced ductility of the welded structure.
4. Most of the material pertaining to the in-process cooling operation is focused on its application in semi-automated or fully automatic welding techniques. The application of the in-cooling process during manual Gas Tungsten Arc Welding (GTAW) poses an important challenge.
5. The choice of cooling mediums could differ according to the available literature. Nevertheless, solid carbon dioxide (CO_2) exhibits more significant potential for exploration due to several advantages. Firstly, it leaves no residue on the weldment, unlike water. Additionally, it is easier to handle due to its warmer temperature of -78.5 °C compared to liquid nitrogen (LN_2) at -195 °C and helium at -271 °C. This warmer temperature contributes to enhanced safety by reducing the risk of frostbite. Furthermore, solid CO_2 offers logistical benefits, as it does not require special containers.

The present investigation provides a set of recommendations for the GTAW process of SS316L, with the introduction of in-process cooling techniques for the purpose of fabricating lightweight and high-strength structures. These structures obtain application in various industries such as chemicals, pressure vessels, medical equipment, food industry, and fertilizer production, among others.

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