The mechanical strength and distortion management of GMAW-welded low-carbon steel (A36) joints are investigated in this work. GMAW is a combination of heat sinking and clamping procedures. Dimensional precision and structural reliability are compromised due to the substantial distortion caused during welding. To solve this problem, this research looks at a thermal-mechanical strategy that uses heat sinks and mechanical clamps in tandem when welding. Untreated joints (As-welded) and three different treatment variants (HS5-4C, HS27-4C, and HS27-6C) were tested in different experimental configurations. Using a 27°C water-cooled heat sink and six steel clamps, the HS27-6C treatment significantly decreased longitudinal distortion, going from 6.7 mm (As-welded) to 0.85 mm, an astonishing 87% reduction. Mechanical testing showed that in all configurations, the tensile strength was approximately 500 MPa and that weld integrity was preserved since failures were in the base metal rather than the weld metal. Microstructural examination revealed an increase in Acicular Ferrite (AF) content in the weld metal for treated samples, particularly HS27-6C, which enhanced toughness, and microhardness tests verified consistent hardness values (e.g., weld metal (WM): ~200 HV, heat-affected zone (HAZ): ~170 HV, base metal (BM): ~150 HV). Mechanical restriction, in the form of clamps, reduces unequal expansion and contraction during solidification, and thermal management, accomplished by dispersing excess heat, is responsible for the method's efficacy. This integrated approach offers a realistic and cost-effective means of reducing distortion without sacrificing mechanical performance. This is particularly noteworthy in the structural, automotive, and manufacturing sectors, where precise control over dimensions is important

Keywords: thermal conductors, acicular ferrite, deformation, material characteristics, metal inert gas welding

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EVALUATION OF A COMBINED HEAT SINK AND CLAMPING METHOD TO MITIGATE WELD DISTORTION IN LOW CARBON STEEL USING GMAW

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1. Introduction

Welding is a fundamental fabrication process used extensively across key industries such as shipbuilding, automotive manufacturing, construction, and heavy machinery production [1]. Among the different materials used, low-carbon steel is often favored for its excellent weldability, affordability, and adequate mechanical strength. This makes it perfect for applications that require high volume and structural integrity in industrial fabrication. The versatility of the welding process allows for structurally different product shapes, increasing production effectiveness and efficiency. It can generate sizes with high precision at a low cost. Nevertheless, welding might cause unforeseen and difficult-to-remove side effects. They are associated with microstructural changes, decreased material strength and toughness, increased residual stress, and a change in the shape of the weld (distortion) [2, 3].

The welding process includes the localized melting and solidifying of the base materials, resulting in notable thermal gradients [4]. As the weld cools, various sections of the weld and surrounding material experience varying contraction rates, resulting in internal stresses. The stresses can lead to material deformation, which can cause distortion and potentially require expensive rework or render the welded component unusable [5]. In addition, the residual stresses remaining in the welded joint can compromise its mechanical properties, rendering it vulnerable to premature failure during service conditions [6].

Distortion results from the workpiece being shaped by the influence of localized heat during the welding process [7]. The presence of residual stress on the material after the welding process can have adverse effects, especially in the form of tensile residual stress. Distortion and residual stress have a strong relationship and can mutually affect each other. However, addressing these issues after the welding process can be challenging. Distortion is seen as problematic as it alters the shape design, lowers dimensional accuracy, weakens mechanical strength due to residual stress, and increases product repair costs [8]. Distortion increases as the plate becomes thinner. The significant distortion leads to a rise in the expenses required to enhance the form of the welded product [9, 10].

Weld-induced distortion continues to pose a major challenge in high-precision manufacturing industries like shipbuilding, aerospace, automotive, and structural fabrication [11]. In these industries, it is essential to maintain dimensional accuracy after welding, particularly when working with thin-walled or flat structures. Even minor deformations can jeopardize the assembly process, weaken structural integrity, or lead to expensive post-weld corrections. Distortions often occur because of uneven thermal cycles and residual stresses, resulting in longitudinal shrinkage, angular misalignment, or warping [12]. These issues can significantly impact product quality and service performance. To address this deformation, various strategies have been implemented, such as controlled heat input, optimized weld sequencing, and mechanical fixturing [13]. Advanced techniques like laser beam shaping, active cooling, and transient thermal tensioning (TTT) have emerged, yet they frequently demand intricate equipment or are confined to particular applications [14]. Even with these advancements, there remains a need for a practical and widely applicable solution, especially for gas metal arc welding (GMAW), which is popular because of its automation ease and high deposition rate. A promising approach includes combining passive thermal regulation with mechanical constraint in the welding process. Heat sinks are materials or devices designed to absorb and dissipate heat, effectively reducing temperature gradients and minimizing distortion caused by expansion. Clamping systems, in contrast, securely hold the workpiece in place to prevent any movement during the welding and solidification processes. While both methods are recognized on their own, the joint application of heat sinks and clamps in welding has not been extensively tested, particularly regarding low-carbon steel GMAW processes.

A practical solution has emerged to address these issues involving heat sinks and clamps [15, 16]. Heat sinks are utilized to manage heat effectively in welding processes. These materials possess excellent thermal conductivity and are strategically positioned near the weld area. Heat sinks help minimize temperature gradients and prevent thermal distortion by absorbing and dissipating excess heat. Clamps, on the other hand, provide mechanical stability to the workpieces, ensuring precise alignment during welding and preventing any movement that could cause misalignment or distortion [17].

Weld distortion remains a significant challenge, especially when employing the gas metal arc welding (GMAW) process. This distortion occurs due to uneven heating and cooling during welding, resulting in residual stresses and imbalanced thermal expansion and contraction. Consequently, welded components frequently experience dimensional inaccuracies, warping, and a decline in structural integrity and surface quality. In various sectors, such flaws necessitate expensive post-weld straightening or machining, which extends production time and diminishes efficiency. The need for greater precision, enhanced productivity, and less post-processing has led to investigating different strategies for controlling distortion. Individual studies have been conducted on techniques like thermal tensioning, optimized welding sequences, mechanical restraint, and the application of heat sinks. Nonetheless, the joint use of thermal and mechanical treatments in welding, especially applying heat sinks to control thermal gradients and clamps for physical restraint, has not been thoroughly investigated in practice, particularly concerning low-carbon steel with GMAW. Therefore, studies that are devoted to improving distortion mitigation strategies by integrating thermal management and mechanical restraint remain of high scientific relevance, especially in the pursuit of improved weld quality, energy efficiency, and production optimization in advanced manufacturing environments.

2. Literature review and problem statement

The article [18] explores the connection between the distance of a heat sink and the weld line to assess the extent of deformation in welded joints. The research indicates that positioning heat sinks closer to the weld line leads to reduced expansion and contraction during solidification, significantly enhancing heat absorption and lowering thermal gradients. The deformation along the longitudinal, angular, and transverse axes has been minimized. However, there are some important considerations regarding the study. The results typically focus on a single base material, like mild steel or aluminum, which may not accurately reflect the behavior of welding incompatible metals or handling more complex geometries. To make matters worse, many deformation measures fail to include end-point evaluations; absent from this scenario are real-time thermal data and stress mapping, both of which would provide a clearer understanding of the cooling dynamics. The absence of clamps, which are commonly used in real-world welding scenarios, significantly reduces the practical applicability of the study.

The study [19] tackles angular distortion during welding of thick-section T-joints constructed from high strength low alloy (HSLA) steels, a technical issue in heavy construction. This distortion, generated by asymmetric heat input and non-uniform shrinkage forces, can severely impact dimensional accuracy, alignment, and assembly precision in structural applications like shipbuilding, heavy machinery, and infrastructure. The study is noteworthy because HSLA steels are more prone to residual stress accumulation and difficult to rectify once distorted because to their high strength and lower ductility. The research's application to realistic T-joint setups and thick plate size makes it more suitable to industry circumstances. A study that examines how welding parameters like heat input, pass sequence, and restraint techniques affect angular distortion and perhaps integrates experimental and numerical simulation data can help forecast and reduce distortion. If the parameters evaluated are limited or residual stresses and real-time thermal behaviors are not adequately defined, limits are evident. The lack of direct measurement methods like thermography or X-ray diffraction may limit mechanical knowledge. While heat management lowers angular distortion is well known, this study's uniqueness depends on whether it adds a new control strategy, quantifies the advantages, or develops a predictive framework.

The article [20] explores a crucial link between materials science and welding engineering by investigating how heat sinks affect the quality of welds in 6061 aluminum alloy that has experienced various partial aging treatments. The main strength of this study is its focus on the connection between thermal management via heat sinks and the metallurgical state, especially regarding the aging condition. Using heat sinks to control the thermal cycle in welding offers a practical and economical way to tackle problems such as excessive softening, distortion, and grain coarsening. The study shows that heat sinks effectively preserves hardness and tensile strength in samples at their optimal age by preventing over-aging in the heat-affected zone (HAZ). However, the study has some limitations. Although it successfully highlights the effects of cooling on microstructure and mechanical properties, it may fall short in providing a complete thermal profile of the welding process. Keeping track of temperature gradients in real-time or performing finite element thermal simulations would improve the conclusions and offer predictive insights for different geometries and thicknesses.

Research [21] shows that heat sink fins have complex geometries and small-scale welds, making traditional inspection methods difficult or insufficient to determine weld integrity. A non-contact, non-invasive, and automated process for inspecting weld quality and estimating the welding rate – defined as the ratio of successfully bonded areas to the total intended weld area – was developed by combining infrared thermography (IRT) with deep learning techniques. This method is the main strength of the study. This is a huge step forward from the days of laborious, invasive, or otherwise inappropriate testing methods used for high-density finned structures, such as dye penetrants or ultrasonic testing. Studying, however, is not without its difficulties and restrictions. The model's generalizability is a critical concern. Deep learning models typically require large and diverse datasets to avoid overfitting and perform well with novel, unexplored data. Without proper consideration while training, thermal imaging in industrial environments might be impacted by changes in material surface characteristics, emissivity, ambient temperature, or heat input, resulting in lower detection accuracy.

The study [22] investigates an important element of welding metallurgy –specifically, how the welding sequence influences the formation of residual stresses in plug-welded joints. Residual stresses play a crucial role in welded structures, impacting factors such as fatigue life, dimensional stability, crack susceptibility, and corrosion resistance. The study's main strength is its concentrated examination of welding sequence, a practical factor that can frequently be optimized in actual production settings without the need for extra resources or specialized tools. The approach probably involves conducting experimental welding trials on low-carbon steel plates using different plug weld sequences. This would be followed by measuring residual stress, potentially utilizing methods like X-ray diffraction, hole-drilling, or the contour method. Incorporating finite element simulations would provide a thorough understanding of how stress evolves with various sequencing strategies. Nonetheless, the study might have some limitations. A possible limitation is that if the work concentrates solely on a limited range of weld diameters or thicknesses, it may restrict its applicability to wider structural scenarios. To improve the practical impact, the study could delve deeper into the implications for fatigue-sensitive structures, like cyclically loaded components in vehicles or bridges, where residual tensile stresses can be especially harmful.

The study [23] tackles a significant and technically demanding challenge in welding: controlling buckling-type distortion in thin-walled structures using a method called transient thermal tensioning (TTT). TTT uses localized heat sources during welding to create controlled thermal expansion, which helps to counteract deformation caused by the heat input from welding. This research presents a swift predictive model for establishing TTT parameters, including heat input, location, and timing. This model is essential for attaining controlled counter-distortion while preventing the introduction of further defects. This model can be incorporated into pre-welding design processes, allowing manufacturers to anticipate distortion behavior and refine TTT strategies beforehand. Nonetheless, the study does have its limitations. A significant limitation lies in the assumptions incorporated into the analytical model to enhance computational speed. The assumptions made like linear heat distribution, uniform material behavior, or simplified boundary conditions can decrease prediction accuracy when dealing with complex, real-world geometries or multi-pass welding situations.

The paper [24] looks at a significant issue in structural welding specifically, how geometric reinforcement can be applied as a passive distortion control technique in fillet-welded joints. This study meets growing industry demands for lightweight, dimensionally resilient structures in aircraft, shipbuilding, automobile, and modular construction. The study reveals that when properly positioned, triangle reinforcement stiffeners considerably reduce fillet-welded joint angular and transverse distortion. These stiffeners resist local deformation throughout the heat cycle as mechanical constraints. This is critical in buildings where post-weld straightening or machining is undesirable or impossible. The method is promising but has downsides. First, triangular and lightweight stiffeners increase material utilization and manufacturing processes, which may be counterproductive in weight-sensitive applications unless optimized. Second, stiffener geometry considerably affects their effectiveness. Triangular plates may operate well in some joint types, sizes, and structural orientations but not others. Research is needed to determine stiffener dimensioning and location in various design scenarios. Third, reinforcement plates may affect weld accessibility and generate stress concentration zones if not adequately integrated into the design. Temporarily removing stiffeners after welding may cause surface defects or extra effort.

The research [25] tackles a significant issue in modern manufacturing – specifically, managing distortion and residual stress in significant, high-precision components welded by electron beam welding (EBW). The study uses electron beam welding's unique characteristics, including low total heat input, deep penetration, and limited heat-affected zones (HAZ). Though EBW lowers worldwide heat exposure, localized temperature gradients can cause notable stress concentration and geometric distortion, particularly in asymmetric or rotating components like flanges. The work provides a methodical evaluation of how these elements appear in big components, offering insightful analysis of the mechanical behavior of welded joints under actual settings. The originality of the work is in the use of advanced modeling techniques, possibly including finite element thermal–mechanical coupling, to simulate the welding process and forecast deformation in complex geometries. It might also use laser scanning or thermocouple validation to contrast forecasts with real deformations. Though it has merits, the research has certain shortcomings. First, Electron Beam Welding usually occurs in a vacuum, which raises cost and complexity and restricts its use in all manufacturing settings. The significance of the results could thus be restricted to sectors or parts.

Many researches have tackled distortion brought on by welding by emphasizing either temperature management or mechanical constraint. For example, research [16] and [20] looked at how heat sinks lowered thermal gradients, looked at how well clamping systems suppressed joint displacement during solidification [18]. Other research, like [15], used numerical simulations to forecast distortion patterns under various welding sequences. These methods, on the other hand, either thermally or mechanically, tend to view distortion reduction as a single-variable issue.

Importantly, the combined use of heat sinks and clamps, two complementing techniques, has not been thoroughly investigated under controlled experimental settings. Moreover, in the setting of low-carbon steel GMAW processes, the effects of changing clamping force and heat sink temperature on mechanical property maintenance and distortion reduction are mostly unknown. Thus, the unanswered issue is the absence of an empirically confirmed, practicable approach for reducing weld-induced distortion in low-carbon steel utilizing a combined heat sink and clamping technique, without sacrificing joint mechanical integrity. This study intends to close this gap by methodically evaluating the efficacy of such a hybrid technique under different thermal and mechanical treatment settings.

3. The aim and objectives of the study

The study aims to evaluate the effectiveness of combining heat sink cooling and mechanical clamping in reducing weld-induced distortion in low-carbon steel using gas metal arc welding (GMAW), and to assess its impact on the mechanical and microstructural integrity of the weld.

To achieve this aim, the following objectives are accomplished:

– to analyze the distortion behavior of welded low-carbon steel plates under different heat sink and clamping configurations;

– to assess the tensile strength, hardness, and bending performance of welds produced under these conditions;

– to examine the microstructural characteristics of welded joints subjected to different heat sink and clamping conditions.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is the welded joint created between low-carbon steel (A36) plates, which are 4 mm thick. These plates are frequently utilized in structural and industrial applications because of their excellent weldability and mechanical properties. This research examines the distortion behavior resulting from non-uniform thermal cycles in the gas metal arc welding (GMAW) process, a popular manufacturing technique known for its high deposition rate and automation-friendly nature. The investigation focuses on assessing the geometric stability, dimensional accuracy, and mechanical performance of the welded joints, which encompasses tensile strength, hardness, and microstructural integrity. This study focuses on implementing combined distortion control strategies, specifically utilizing a water-cooled heat sink and mechanical clamping systems during welding. The goal is to analyze the specific impacts of each treatment and investigate how their combined effects contribute to reducing welding distortion and maintaining joint integrity. The study seeks to determine the best configuration for achieving the most significant reduction in distortion by systematically adjusting the number of clamps and the temperature of the heat sink, all while ensuring that the mechanical and metallurgical quality of the weld zone is maintained or enhanced. The welded joint is vital in assessing effective, affordable, and scalable approaches to a persistent challenge in metal joining technology.

The main hypothesis of the study posits that the concurrent utilization of a heat sink and a mechanical clamping system during the gas metal arc welding (GMAW) process can markedly diminish weld-induced distortion in low-carbon steel (A36) plates while maintaining the mechanical integrity and microstructural quality of the welded joints. This concept is based on the premise that welding distortion predominantly arises from unequal thermal expansion and contraction, leading to residual strains and plastic deformation as the material experiences localized melting and solidification. Implementing a water-cooled heat sink at regulated temperatures is anticipated to remove surplus heat from the weld zone, reducing temperature gradients and decelerating the cooling rate in a controlled fashion. The clamping system functions as a mechanical restraint, preventing movement or warping of the workpiece during and soon after welding, thereby counteracting the forces produced by thermal shrinkage. The hypothesis posits that a coordinated integration of these two methodologies will yield a synergistic effect, whereby the mechanical and thermal treatments collaboratively reduce deformation more efficiently than either method employed independently. Furthermore, it is suggested that this integrated approach will not generate new defects, such as cracking or variations in hardness, and will preserve acceptable levels of tensile strength and microhardness, signifying that the essential structural properties of the welded joint remain intact or may be slightly enhanced.

Several assumptions were made during the study's conception and implementation to ensure that the experimental examination was possible and focused. First, it was assumed that the A36 low-carbon steel utilized in all of the samples was the same and had the same thermal and mechanical properties across all of them. This meant that the study could blame differences in distortion and mechanical outcomes on the treatment configurations instead of differences in the materials. It was also thought that the heat input stayed the same during the gas metal arc welding (GMAW) process because the welding parameters, like current, voltage, travel speed, and shielding gas flow, were the same for all the tests. This ensured that any variation in distortion or mechanical qualities could be reasonably connected to the presence or absence of heat sinks and clamps rather than to fluctuations in welding circumstances.

The study also assumed that the heat sink did a good job removing heat from the weld zone and that the water used for cooling had a steady temperature during each treatment. It was also thought that the mechanical clamps would apply the same and repeatable restraint forces, even while the clamping pressure was applied by hand. To keep the experiments consistent, the clamps and heat sink were always placed in the same spot about the weld line in all treated samples. Because the experiment took place in a controlled indoor laboratory with little temperature change, it was anticipated that environmental factors like temperature and ventilation would have little effect on the outcome and were not actively controlled. Lastly, it was thought that the thermal and mechanical interactions during welding did not cause any further effects, including significant phase changes outside the heat-affected zone or deformation caused by the tool, other than what was recorded.

This study adopted several simplifications to keep the experimental scope focused and the test conditions manageable. The simplifications were essential for focusing on the main variables being studied, specifically, the joint impact of heat sinks and clamping systems on weld distortion and ensuring consistency in all test cases. Initially, the study focused on flat plate geometries featuring a single V-groove joint configuration without exploring more intricate geometries like curved, tubular, or multi-pass weld structures. This facilitated uniform sample preparation and streamlined the distortion measurement process while reflecting a typical industrial welding situation.

Secondly, although the clamping system was essential for controlling distortion, the precise clamping forces were not measured using instruments. The force was applied manually, relying on the operator's steady torque. It was assumed that a consistent level of restraint was applied to all clamped specimens, even though there might be slight variations. The heat sink system functioned as a passive cooling mechanism, where the water flow rate and temperature were regulated by an external chiller, lacking real-time thermal feedback or dynamic control. This method streamlined the thermal regulation process, although it might not fully account for transient temperature changes in high-resolution detail.

This study did not utilize numerical simulations like finite element thermal–mechanical analysis. The assessment relied exclusively on experimental measurements encompassing physical distortion, tensile strength, hardness, and microstructural observations. Although this restricts the study's capacity to apply its results beyond the specific conditions tested, it enhances the empirical foundation of the findings. Additionally, the study overlooked long-term performance factors like fatigue life, creep resistance, and stress-corrosion cracking. Only the mechanical and microstructural conditions immediately following the weld were analyzed. Furthermore, residual stresses were not measured directly; instead, they were inferred from the magnitude of distortion and the material's behavior. The impact of external environmental factors, like ambient temperature or humidity, was considered negligible since the experiments took place in a controlled indoor laboratory setting. The conditions were neither actively changed nor measured during the tests.

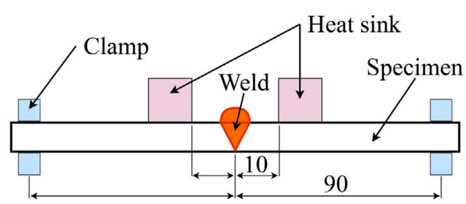
4. 2. Materials

The material utilized for the welding specimen was a 4 mm thick plate of low-carbon steel A36. The material's balanced mechanical qualities, vast availability, and outstanding weldability make A36 great for structural applications. As a precaution before welding, the plate material was carefully chopped into parts of 400×100 mm to maintain uniformity in the experimental arrangement. A V groove was painstakingly carved along the borders for a stronger and more consistent bond to allow the weld metal to penetrate deeper. In this preparation phase, the likelihood of a solid bond is significantly increased, and the possibility of flaws like insufficient penetration or absence of fusion is decreased.

Gas metal arc welding (GMAW) was automated utilizing welding rig equipment [26]. This automated system assures precision and consistency, essential for high-quality welding and minimal human mistakes. Welding was performed using a Miller Millermatic® 211 MIG Welder semi-automatic GMAW machine, equipped with a Miller S-74D Wire Feeder, and a standard ER70S-6 filler wire, which is suitable for welding low-carbon steel. The electrode was 0.8 mm to match the plate thickness and weld characteristics. The original GMAW welding settings were chosen based on empirical data and previous studies. The electrode and base material were melted using a current of 140 A and a voltage of 24 V. To keep the welding torch moving smoothly along the seam, and the travel speed was set at 3.75 mm·s^{-1}. The welding wire speed was set to 135 mm·s^{-1} to ensure a consistent supply of filler material into the weld pool. The CO^2 gas discharge rate of 5 L·min^{-1} effectively shielded the weld region from any external pollution, providing a stable arc. These settings were developed from prior research that revealed 756 J·mm^{-1} heat input is best for welding 4 mm thick low carbon steel plates.

4. 3. Heat sink and clamp methods

A heat sink and clamp were used to minimize distortion and ensure the welded joints remained structurally sound during welding. The heat sink was carefully positioned on both sides of the welding line, 10 millimeters (mm) away from the welding center, as shown in Fig. 1, *a*. Clamping was applied using steel C-clamps (manufactured by Wilton Brute Force C-Clamps), positioned symmetrically 50 mm from each end of the weld line. The placement was selected to efficiently absorb and disperse any extra heat produced during welding, decreasing the thermal gradient and the resulting distortion. The heat sink was made of steel and designed to optimize water flow. This water-cooled heat sink proved to be highly effective in managing thermal conditions. The water, maintained at 5 °C and 27 °C, flowed continuously through the heat sink using a Koolant Koolers by Dimplex Thermal Solutions chiller system, with a measured flow rate of 2 L/min, efficiently absorbing the heat generated during welding (Fig. 1, *b*). The selection of water temperatures was made to deliver a substantial cooling impact while avoiding any potential thermal shock to the weld area.



a

b

Fig. 1. Schematic illustration of: *a* — heat sink and clamp; *b* — experimental setup of welding

All case variations utilized in this study were designed to examine the impact of various heat sink and clamp configurations on the welding process, as shown in Table 1. There are four such instances; the first involves welding without supplementary cooling or mechanical stability. This configuration is a starting point for studying the welded joint's intrinsic mechanical properties and natural inclination to distort without outside influences. In Case 2, the workpieces were fastened using four clamps, and a heat sink kept at 5 °C was placed 10 mm from the welding line. The goal of this system was to quickly cool the weld region, which would lower the thermal gradient and lessen the likelihood of distortion. The clamps held the parts in place and made sure they were all lined up while the welding was going on.

Table 1

Heat sink and clamp configurations in the welding process

No.	Case	Heat sink temperature (°C)	Number of clamps	Code
1	Case 1	0	0	As-welded
2	Case 2	5	4	HS5-4C
3	Case 3	27	4	HS27-4C
4	Case 4	27	6	HS27-6C

Case 3 had a setup similar to Case 2, with the heat sink temperature set at 27 °C. This moderate cooling effect was to handle the heat input more cautiously, preventing any potential problems from rapid cooling, such as thermal shock or excessive residual stress. The four clamps ensured the required mechanical stability to prevent movement or distortion. In Case 4, the heat sink remained at a temperature of 27 °C while the number of clamps was raised to six. This configuration investigated whether additional clamping could minimize distortion by providing stronger restraint on the workpieces. The placement of the additional clamps was carefully considered to maximize surface coverage and ensure an even pressure distribution.

4. 4. Mechanical properties test

The major equipment was a 0.01 mm dial indicator to evaluate distortion. Dial indicator precision allowed it to detect even the slightest workpiece surface variations, delivering accurate and dependable measurements. A precise dial indicator was configured to move along the workpiece surface to capture height fluctuations across the weld area. This arrangement allowed a systematic distortion assessment covering all essential weld line sites. Distortion measurements were conducted using a Dasqua High Precision dial gauge, with a precision of 0.01 mm. The dial indicator measured distortion along the longitudinal axis to evaluate each weld line segment. This method showed detailed surface defects from flatness and alignment. Longitudinal distortion was measured, which causes the workpiece to bend or warp along the weld.

Fig. 2 shows the welding tensile test, which followed the ASTM E-8 specimen standard [27]. Tensile tests were performed on a Tensilon RTF-2350 Universal Testing Machine, rated for a maximum load of 300 kN. This standardized testing procedure ensured consistency and accuracy in evaluating welded joint mechanical properties. The test specimen was meticulously sliced to exacting dimensions to fulfill the standards of ASTM E-8 tensile testing. Transverse tensile testing applied load perpendicular to the weld. This design helps test weld metal strength and fusion zone integrity. The central weld region was tensile loaded to test the test specimen's resistance to deformation and failure under tension.

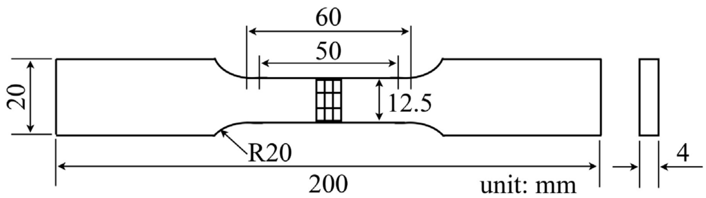


Fig. 2. Illustration of tensile test specimen

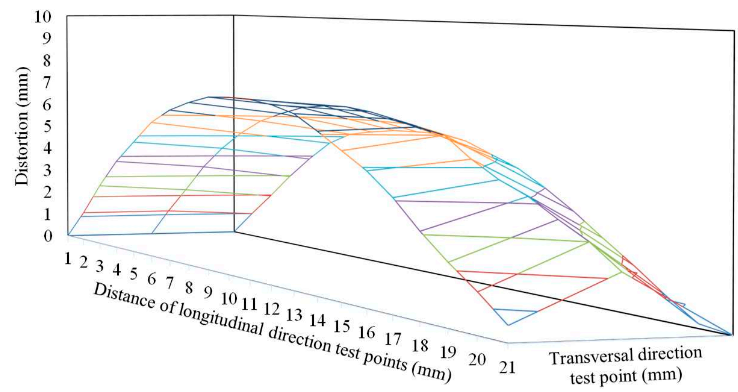
The ductility and resistance to breaking of the weld joint were assessed in the bending test, which involved applying bending pressures using a Universal Testing Machine (UTM). The test involved bending the weld joint into a U shape to mimic the kind of real-world bending the welded structure could encounter in the field. It is possible to use the face bend approach, which involves applying a load to the cover's weld section to induce bending stresses that could lead to fracture formation. Securing the specimen in the UTM and using a regulated load allowed for the bending test setup to achieve the correct U shape. Following the guidelines provided by the American Welding Society (AWS) test standard for a 4 mm plate thickness, the bending radius was adjusted to 10 mm. The test results may be reliably compared and used in other investigations with varied welding setups because of this standardized process.

A hardness test was performed using the Vickers method, a well-established technique for evaluating material hardness. Vickers hardness tests were conducted using a Mitutoyo HM-200 Series microhardness tester with a 4.903 N. The hardness was measured in three separate zones: the weld metal (WM), heat-affected zone (HAZ), and base metal (BM). These zones correspond to different areas of the welded joint, each undergoing various levels of thermal exposure during the welding process. Microstructure analysis was carried out using an Oxion Inverso OX.2153-PLM optical microscope.

5. Results of the effect of heat sinks and clamps combination on low-carbon steel

5. 1. Results of the weld distortion of low-carbon steel

The results of the distortion measurement, as shown in Fig. 3, offer valuable insights into the effectiveness of various welding treatments in reducing distortion and preserving the dimensional stability of the welded plates. Fig. 3, *a* displays the distortion profile of the As-welded condition. This is a fundamental reference, illustrating the inherent tendency of welded plates to deform due to the stresses generated during the welding process. The distortion pattern may show irregularities and variations along the welded seam, suggesting localized deformation and possible misalignment. Fig. 3, *b* presents the distortion profile of the welded plates after undergoing heat sink treatment with a water flow temperature of 5 °C. The plates were also mechanically stabilized using four clamps. Using a heat sink at a lower temperature is intended to speed up the cooling process and reduce temperature variations, while the clamps offer extra support to prevent any distortion. In this case, the distortion profile is expected to exhibit a decrease in amplitude and a more consistent pattern than the As-welded condition, suggesting successful distortion management.



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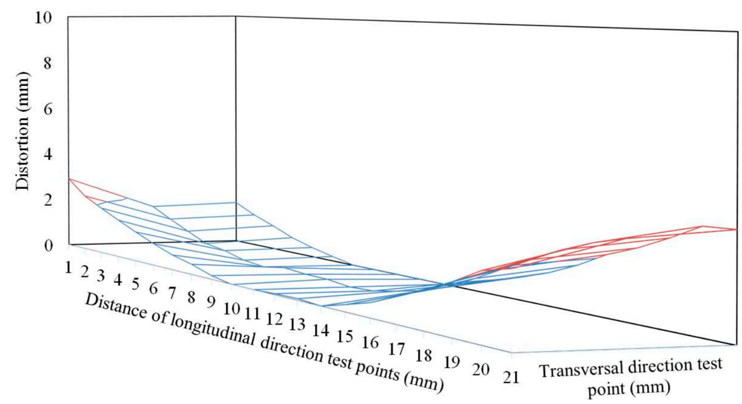

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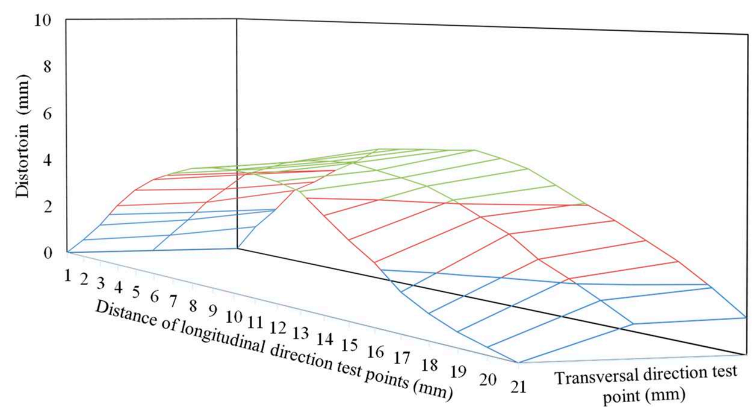
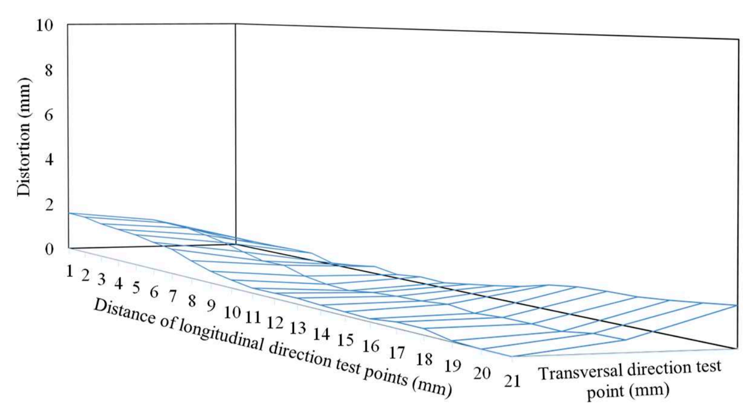


c

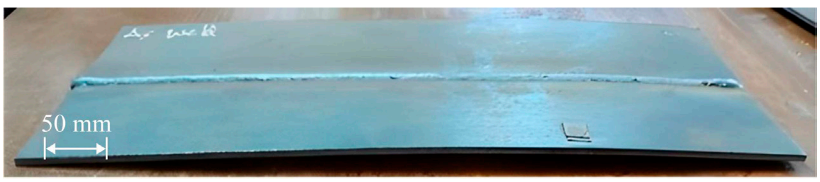


d

Fig. 3. Welding distortion on: *a* – As-welded; *b* – HS5-4C; *c* – HS27-4C; *d* –HS27-6C variations

Heat sink treatment with 27 °C water flow and four clamps causes deformation, as seen in Fig. 3, *c*. Greater heat sink temperature allows for more gentle cooling, controlled solidification, and fewer residual strains. The clamps provide welding alignment and stability. It may display better homogeneity and less distortion than the As-welded condition, indicating effective thermal and mechanical treatments. The distortion profile of the welded plates after heat sink treatment with 27 °C water flow and six clamps for mechanical stabilization is shown in Fig. 3, *d*. More clamps restrain and support, reducing distortion and misalignment. This arrangement controls distortion better than the others due to its low amplitude and excellent uniformity.

A comparison of the distortion levels of two designs, As-welded and HS27-6C, is shown in Fig. 4, *a*, *b*. Distortions in the longitudinal, transverse, and angular directions show notable variations in curvature profiles between the two states. The As-welded design shows apparent distortion in all measured directions, highlighting the inherent problems of maintaining dimensional stability during welding without intervention. There is a significant decrease in distortion in the HS27-6C design, which uses a heat sink with water heated to 27 °C and six clamps. According to the data, a remarkable 87% reduction in transverse and longitudinal distortions and angle distortions was achieved by this combined technique.



a

b

Fig. 4. Welding specimens in: *a* – As-welded; *b* – HS27-6C

The decrease can be linked to the supportive roles played by the heat sink and clamping mechanisms. The heat sink helps maintain steady heat dissipation, effectively reducing peak thermal gradients and minimizing quick temperature changes that lead to uneven material contraction. The clamps act as mechanical restraints, preventing any unwanted movement and displacement during the crucial phases of solidification and cooling. They work in unison to offer thermal regulation and structural stabilization, tackling two primary factors that contribute to welding distortion effectively.

5. 2. Results of the mechanical properties of low-carbon steel

Tensile tests on welded joints determine their quality and maximum strength under tensile loads. The tensile test results are shown in Fig. 5. This figure shows that the As-welded (no intervention) state and all heat sink and clamp combinations have equal tensile strengths of around 500 MPa. Performance is consistent across conditions because the tensile test fracture occurs in the source metal rather than the weld metal. Tensile test cracks in the source metal indicate that the weld metal is stronger. Tensile strength measurements primarily reflect the base metal's properties since the weld metal remains unbroken and unfractured under tensile stresses.

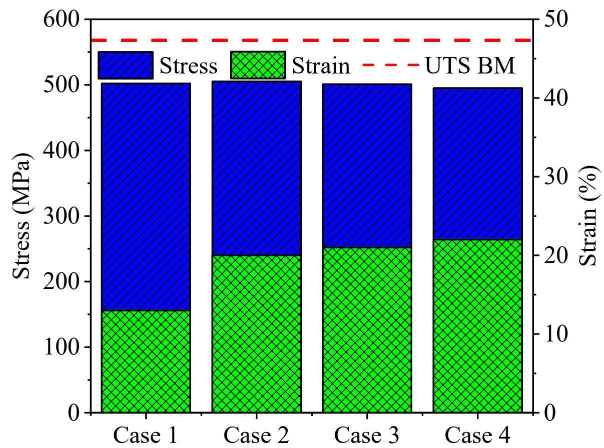
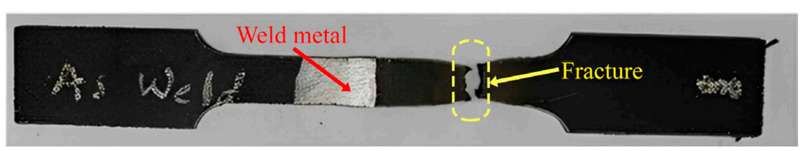


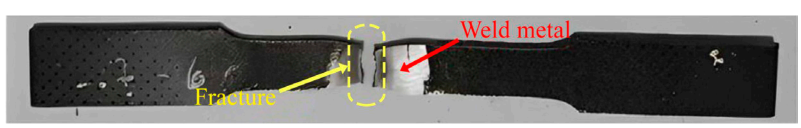
Fig. 5. Stress vs strain graph for all cases

The tensile test fracture in Fig. 6 clearly shows that the base metal area is where the fracture happens, with obvious necking and deformation before the fracture. The fact that the base metal may be plastically deformed to a large extent before breaking indicates that it is pretty ductile. However, there is no necking in the weld metal region; thus, it must be stronger than the base metal. If the tensile test fracture happens in the base metal (Fig. 6, *a*) instead of the weld metal (Fig. 6, *b*), the welding electrode (ER70S-6) is perfect. With this option, one can be confident that the weld metal is strong enough to resist tensile loads, which will cause the comparatively weak base metal to fail. The cracks-free weld metal area further supports this electrode's ability to produce strong, high-quality welded joints.

The Charpy impact test examined the welded joint's impact toughness. Fig. 7 shows that impact toughness varies greatly between welding treatment conditions. As-welded, it has the highest impact toughness of all designs. HS5-4C is the least demanding. Due to the rapid cooling impact of 5 °C water around the weld area, HS5-4C reduces toughness significantly. Rapid cooling causes the HS5-4C treatment to reduce impact toughness.



a



b

Fig. 6. Tensile test fracture of: *a* – As-welded; *b* – HS27-6C

The microhardness test of the welded joint is conducted to assess any potential changes in the mechanical properties of the joint. The microhardness test results for the As-welded and HS27-6C specimens are divided into three sections: weld metal (WM), heat-affected zone (HAZ), and base metal (BM). Fig. 8 displays the presented results. The analysis of the microhardness distribution across these three weld areas for both treatments shows that the weld metal area exhibits the highest microhardness value. This region contains metal that exhibits superior strength to the base metal, leading to increased microhardness values compared to the base metal.

In both As-welded and HS27-6C treatments, weld metal has the highest microhardness distribution. Due to rapid cooling and thermal cycling during welding, weld metal solidification microstructures have smaller grains and increased dislocation density. Additionally, weld metal sometimes contains filler material alloying components, making it more complicated than base metal. Due to its homogenous, rolled structure and lack of welding thermal cycles, the base metal has the lowest microhardness. The heat-affected zone (HAZ) has an intermediate hardness due to partial thermal exposure that promotes grain growth, phase transitions, and localized softening or hardening depending on thermal input and cooling pace. HS27-6C has a significantly more stable joint hardness gradient than As-welded. A moderate-temperature heat sink (27 °C) and increased clamping limit thermal gradients and promote uniform cooling, minimizing HAZ grain development and hardness fluctuations. Weld metal and base metal hardness transition gradually with temperature moderation, reducing stress concentration and improving mechanical compatibility between zones.

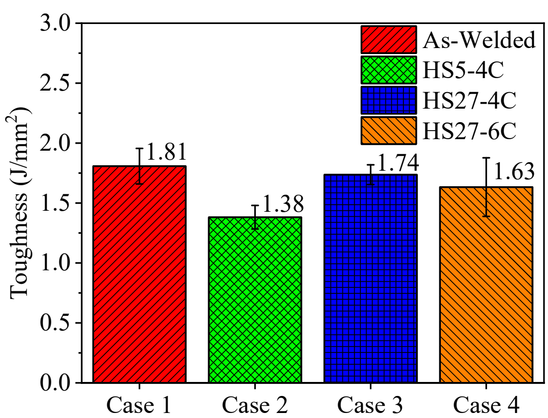


Fig. 7. The result of the impact toughness test for all cases

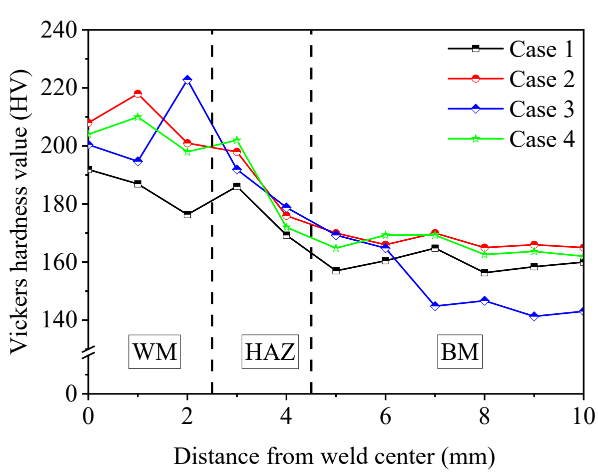


Fig. 8. Microhardness distribution of welded joints

5. 3. Results of the microstructural characteristics of low-carbon steel

Fig. 9 displays the microstructures of As-welded and HS27-6C in the WM and HAZ zones, respectively. Fig. 9, *a* shows the microstructure of the Weld Metal (WM) region for the As-welded specimen, while Fig. 9, *c* displays it for the HS27-6C specimen. A distinct variation in microstructural density is noted, especially regarding the proportion of Acicular Ferrite (AF), which is recognized for its positive influence on mechanical properties. The HS27-6C treatment leads to a significantly elevated AF content, enhancing toughness and improving crack propagation resistance in the weld zone. This indicates that the regulated cooling from the heat sink and the added stability from extra clamping encourage the development of beneficial microstructures during solidification.

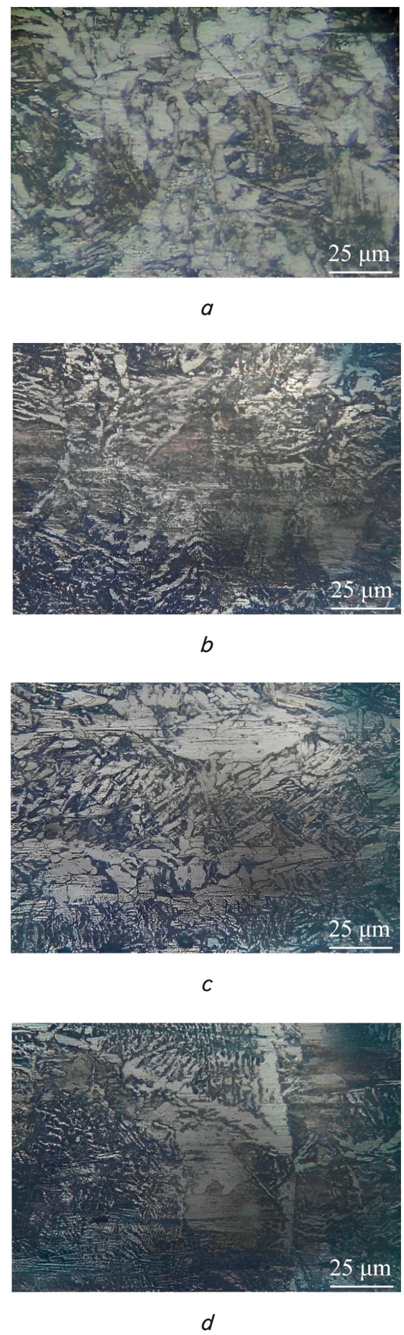


Fig. 9. Results of microstructural observations in the WM and HAZ areas of specimens: *a, b* – as-welded; *c, d* – HS27-6C

In addition, the microstructures of the Heat-Affected Zone (HAZ), as shown in Fig. 9, *b*, *d*, emphasize the variations in grain morphology between the two treatments. The slower cooling rate generated by the heat sink may explain why the granules in the HS27-6C sample are slightly larger than those in the As-welded specimen. Granted, larger grains can potentially lessen hardness, but they also can increase ductility and lessen the brittleness commonly linked to fast cooling in the high-temperature zone (HAZ). The hardness mapping results showed that the HAZ region's hardness and strength distribution varied due to these particle size variations. The HS27-6C condition demonstrates a more stable heat cycle during welding, as seen by the higher AF content in the WM and regulated grain formation in the HAZ. The welded joint's mechanical performance is improved due to the thermal stability, which helps keep toughness and strength in check. Results show that mechanical restraint and passive thermal control work well together to affect the microstructural development and performance of low-carbon steel that has been welded.

6. Discussion of the effect of heat sinks and clamps combination on low-carbon steel

According to distortion measurements, heat sink treatment and clamping mechanisms improve dimensional stability. Comparing longitudinal maximum distortion values across treatment setups shows significant decreases. As-welded, HS5-4C, HS27-4C, and HS27-6C (Fig. 3) conditions have maximum distortions of 6.7 mm, 2.8 mm, 4.5 mm, and 0.85 mm. These data show that heat sink treatment and clamping reduce deformation and preserve welded joints. The distortion reduction achieved by each treatment configuration compared to As-welded highlights the benefits of clamps in heat sinks. Treatments with HS5-4C, HS27-4C, and HS27-6C reduce distortion by 58 %, 33 %, and 87 %. Mechanical stabilization and heat management are essential for optimizing welding processes due to these significant distortion reductions. Prior studies show that treatment configurations of six-clamp HS27-6C (Fig. 4, *b*) function better [28]. The results confirm that additional clamps in the welding process reduce distortion significantly. This shows how clamping systems counteract welding stresses and temperature effects, improving dimensional stability and decreasing deformation.

The decrease in longitudinal distortion seen with the HS27-6C configuration, an 87% drop relative to the As-Welded case, is not only a validation of conventional clamping advantages. Instead, it shows the synergistic impact of mechanical constraint and regulated thermal dissipation. Although clamping by itself limits physical displacement, the use of a moderately cooled (27 °C) heat sink stops severe temperature gradients that would otherwise start non-uniform contraction pressures. Especially non-linearly is the distortion decrease obtained by raising clamp count from four to six, implying a threshold behavior in structural restraint efficiency. Our approach provides comparable degrees of distortion control to investigations using active liquid nitrogen cooling, but without the logistical or financial concerns of cryogenic devices [29]. This suggests that for high-volume industrial uses, the mix of passive temperature control with best clamping could provide a feasible option. Furthermore, as deduced from the consistent microstructural transitions and steady hardness profiles in the HAZ, the 27 °C sink's thermal moderation seems to reduce residual stress concentration.

Fig. 5 shows that the weld metal can resist the applied forces, transferring the failure point to the weaker base metal. The heat sinks can significantly influence the tensile strength of weld metal when cooled directly [30]. In this investigation, cooling mostly affected the base metal, which explains the absence of considerable tensile strength variation among treatment conditions. Heat sinks were used in this investigation to manage heat dispersion and limit distortion, not to improve weld metal tensile characteristics.

The material's ability to absorb energy and undergo plastic deformation before failure is guaranteed by the base metal's excellent ductility, as shown by necking and deformation. This is of the utmost importance for uses requiring resilience against brittle cracking. As seen by its lack of necking, the weld metal's superior strength guarantees that the weld joint can withstand significant tensile forces without breaking. The right welding electrode choice improves the welded connections' overall strength and durability by directing failure to the less critical base metal area. The tensile test results also show that the As-welded joint's tensile strength is unaffected by the combination of heat sink and clamps. The tensile strength results, which remain consistent around 500 MPa across several treatment circumstances (As-welded, HS5-4C, HS27-4C, and HS27-6C), suggest that the interventions successfully control heat distribution and reduce distortion, all while maintaining the mechanical properties of the welded joints. This discovery proves that welded connections may be made more dimensionally stable using the heat sink and clamp technique without reducing their tensile strength, which is a significant result. This technology offers a realistic way to decrease distortion in welded components without sacrificing structural integrity or performance.

Rapid cooling can cause martensite to develop in the welded joint. Martensitic transition happens when the cooling rate is too great for austenite to become ferrite or pearlite [31]. While tougher, the martensitic structure is brittle, lowering toughness [32]. The sharp difference in impact toughness between As-welded and HS5-4C shows the trade-off between quick cooling to minimize distortion and brittleness. The HS27-6C treatment showed the least deformation, as shown in Fig. 3. This setup, which involves a heat sink filled with water heated to 27 °C and six clamps, significantly decreases distortion, proving that this method stabilizes the welded connection. Be that as it may, consider how this treatment may affect toughness and other mechanical attributes. The HS27-6C treatment has a toughness value of 1.63 J/mm^2. Although Fig. 7 shows that the HS27-6C configuration retains a decent amount of toughness, it is lower than the As-welded condition. Due to the ductile microstructure and natural cooling rate, the As-welded condition naturally preserves increased toughness without mechanical intervention or extra cooling.

The HS5-4C treatment shows the highest hardness values among the different treatment circumstances compared to the microhardness values shown in Fig. 8. A well-documented negative link between microhardness and toughness is consistent with this finding. The findings of the Charpy impact test show that, although the microhardness is enhanced, the HS5-4C treatment has the lowest impact toughness. This research supports the claim that weld metal impact toughness tends to decrease as microhardness increases [33].

The weld area undergoes a hardening process due to the changes and evolution of the microstructure caused by the metal melting process [34]. The rapid cooling and solidification during welding result in the development of fine-grained microstructures, significantly enhancing the microhardness. When the specimens are treated with HS5-4C and HS27-6C designs, there is a noticeable increase in microhardness after welding. This increased microhardness can positively impact the strength of the joint, but it also carries the risk of making the weld metal more brittle.

The acicular ferrite (AF) percentage indicates noticeable variations in the microstructure density. The HS27-6C treatment has a higher AF content than the As-welded state. This metal's AF structure is typically stronger than the base metal's other ferrite phases [35]. The enhanced acicular ferrite in the WM of the HS27-6C treatment indicates a more refined and stronger microstructure. AF's hardness and strength improve the mechanical performance of the weld joint. The higher AF percentage in HS27-6C suggests improved mechanical qualities, particularly strength and crack resistance. The HAZ grain size of the HS27-6C treatment (Fig. 9, *d*) is somewhat greater than the As-welded state, slowing cooling. Hardness decreases with grain size, but toughness increases. Due to heat sink and clamp treatment, the coarse grain structure retains hardness [36]. The welding process causes the microstructures to undergo thermal cycles, which cause the grains to be coarser than the base metal (BM) [37]. The predicted distance from the fusion line to this HAZ location is 4–5 mm. The weld metal region with Acicular Ferrite is more complex and more homogeneous than other places [34, 35].

Although this study showed promising outcomes, numerous limitations must be noted. First, the investigation was limited to low-carbon steel (A36), which may respond differently to heat management and mechanical constraints than stainless steel or aluminum alloys. Throughout the studies, welding parameters like current, voltage, and travel speed were fixed. Thus, heat sink-clamp interaction with varied welding circumstances was not thoroughly studied. The heat sink arrangement was limited to static designs and two cooling temperatures (5 °C and 27 °C), without consideration for more advanced or actively cooled systems that could improve performance. This study did not assess residual stresses affecting distortion and structural integrity. Such measurements could have improved weld performance analysis. Finally, manual clamping may vary clamping force and placement, while automated methods would be more consistent and industrially relevant. These limitations suggest that while the work provides a basis for distortion control in low-carbon steel GMAW, more research is needed to increase its applicability, develop its procedures, and test long-term performance.

This research presents numerous exciting opportunities for future development, focusing on technical improvements and wider industrial use. A possible avenue to explore is using computational modeling, like finite element analysis (FEA), to replicate welded joints' thermal and mechanical performance across different heat sink and clamping setups. A validated numerical model enables researchers to forecast distortion patterns and refine design parameters, eliminating the need for extensive physical testing. This can also be expanded to cover multi-material welding situations and more intricate joint shapes, like T-joints or curved parts, which are frequently utilized in structural and automotive fields. Nonetheless, various challenges might emerge in both the mathematical and experimental fields. From a mathematical standpoint, effectively modeling the interconnected thermal and mechanical effects during welding presents significant complexity. This involves addressing nonlinear partial differential equations that dictate heat transfer, phase transformation, and mechanical deformation, which are extremely sensitive to material properties, boundary conditions, and time resolution. Including realistic clamping pressure distributions and varying heat sink efficiency adds complexity to the simulations, frequently requiring significant computational resources and specialized software.

7. Conclusions

1. The HS27-4C treatment diminishes distortion by 33 % relative to the As-welded condition, but the HS27-6C treatment attains a significantly greater reduction of 87 %. The percentages indicate that distortion is markedly reduced when mechanical constraint by clamps is coupled with thermal regulation via a heat sink. The comparison between HS27-4C and HS27-6C underscores the significance of the quantity of clamps utilized during the welding procedure. Augmenting the number of clamps from four to six leads to a significant further decrease in distortion, demonstrating a direct relationship between mechanical restraint and the dimensional integrity of the welded junction. The HS27-6C arrangement demonstrates superior efficacy in this investigation by regulating heat flow via a moderate-temperature heat sink (27 °C) while simultaneously augmenting stiffness and limiting movement caused by thermal expansion through thorough clamping. The combination of thermal and mechanical treatments effectively reduces the temperature gradient and the resultant residual stresses, which are the main contributors to welding distortion.

2. Compared to the As-welded state, the tensile test results for the heat sink and clamp treatments are comparable, suggesting that these treatments do not degrade the welded joints' tensile performance. The tensile strength values of all specimens fall into the same range, and it doesn't matter if heat sinks and clamps are used or not for the treatment. It is crucial to ensure reliability in industrial applications, and this consistency demonstrates that the combination of heat sinks and clamps maintains the welds' structural integrity and load-bearing capability. Hardness tests were also performed on both the As-welded specimens and the treated samples (HS5-4C, HS27-4C, HS27-6C), and the findings showed minimal variation. Whatever the cooling or clamping conditions are, the hardness values of the weld metal (WM), heat-affected zone (HAZ), and base metal (BM) are kept relatively consistent. The fact that the hardness is consistently the same indicates that the microstructural properties affecting hardness are unaffected by the mechanical restraint from clamps and the thermal control from heat sinks.

3. The microstructure analysis shows that the treated specimens had a much higher acicular ferrite (AF) density percentage than the As-welded specimens, especially in the weld metal area. The HS27-6C treatment exhibits the most significant percentage of AF compared to the As-welded condition out of all the configurations. A combination of thermal regulation (through the heat sink) and mechanical stabilization (by clamps) is likely responsible for the controlled cooling rate, accounting for the higher AF density in HS27-6C. By regulating the cooling rate, it is possible to prevent the formation of undesirable grains and promote the nucleation

of AF on phases like bainite and pearlite. Consequently, the HS27-6C treatment improves the welded joint's mechanical properties by reducing distortion and creating a more desirable microstructure.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available at a reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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