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Comparative Analysis of Mechanical Properties in Heat-Treated Low Carbon Steel and Stainless-Steel Weldments for Redeployment Assessment

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Abstract

This study presents a comprehensive comparative analysis of mechanical properties between low carbon steel Grade C1029 and stainless-steel Grade SS304 weldments subjected to heat treatment profiling. Destructive testing methods including Charpy V-Notch impact testing and hardness testing were employed to evaluate the mechanical behavior of weld metal (WM), heat affected zone (HAZ), and base metal (BM) regions. The Charpy impact test results revealed that stainless steel Grade SS304 exhibited superior toughness with average absorbed energy values of 42.3J (WM), 55.7J (HAZ), and 61.3J (BM), compared to low carbon steel Grade C1029 with values of 16.7J (WM), 47J (HAZ), and 51J (BM). Hardness testing showed distinct hardness profiles across the weld zones for both materials, with carbon steel exhibiting greater variation (HAZ: 416 N/mm², PM: 682 N/mm²) compared to stainless steel (HAZ: 502 N/mm², PM: 511 N/mm²). The results indicate that stainless steel maintains better structural integrity and can remain safe for engineering applications even at sub-zero temperature conditions, while carbon steel weld metal demonstrates vulnerability to failure under tensile loading. The weld metal of carbon steel at 16.7J absorbed energy cannot remain safe within its tensile capability range, indicating potential failure risk. These findings provide scientific guidance for the redeployment of decommissioned metals in structural applications, establishing that stainless steel demonstrates superior redeployment potential compared to carbon steel.

Keywords: Charpy impact test, hardness test, weld metal, decommissioned metals, low carbon steel, stainless steel, fracture toughness, redeployment assessment

1. Introduction

The mechanical behavior of weldments is fundamentally determined by their microstructural conditions, including the nature of grains, grain size, grain boundaries, and composition (Zhang et al., 2023). Heat treatment offers an efficient and comprehensive method to control the properties of steel metals by regulating cooling rates before and after welding (Kou, 2021). The heating and cooling of metals are indispensable components of all welding processes and have the tendency to produce metallurgical changes that significantly affect weld properties (Lippold, 2021). Understanding these relationships is essential for predicting weldment performance and making informed decisions about material redeployment.

The heat affected zone (HAZ) undergoes significant microstructural changes during welding, representing a non-melted area that experiences alterations in physical and chemical properties due to exposure to high temperatures (Stalatube, 2025). According to Lippold (2021), the microstructural orientation in the HAZ of metals can be relatively complex, depending on both composition and thermal factors after welding application. Recent research by Springer (2025) has demonstrated that variations in microhardness across different HAZ subzones, driven by welding thermal cycles, lead to distinct microstructural transformations that directly influence mechanical properties and failure susceptibility. The heating and cooling rates of the zone influence phase transformations in this area and often result in substantial microstructural property variations that affect mechanical performance.

Figure 1 illustrates the relationship between welding heat input and the resulting HAZ width for both carbon steel and stainless steel. The data demonstrates that HAZ width increases linearly with heat input for both materials, with carbon steel showing greater sensitivity to heat input variations. This relationship has significant implications for weldment properties, as wider HAZ regions typically exhibit more pronounced property variations and potential weakness zones. The control of heat input during welding is therefore critical for optimizing weldment integrity (Kou, 2021).

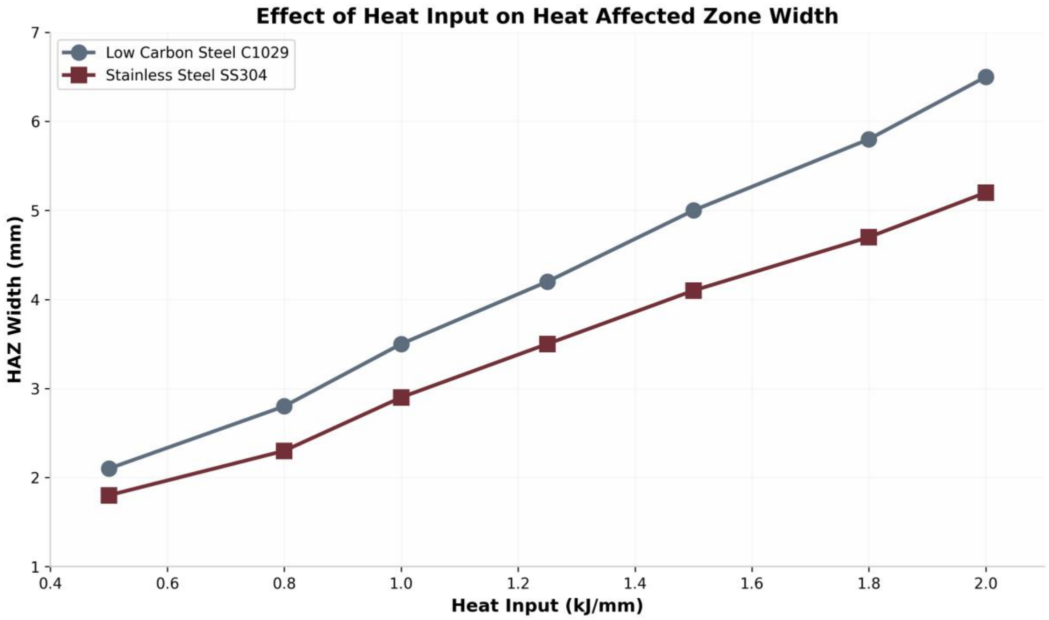

Figure 1. Effect of Heat Input on Heat Affected Zone Width for Low Carbon Steel C1029 and Stainless Steel SS304

1.1 Background and Significance

Weldability, defined as the capacity of a material to produce a permanent joint with essential physic mechanical functional characteristics, controls the level of decline of material mechanical and physical properties (Manjgo et al., 2025). Poor weldability causes limitations, as joint preparation and welding procedures must be carefully controlled to ensure anticipated performance (Zhang et al., 2023). The evaluation of mechanical properties in welded joints is therefore essential for quality assurance and structural reliability assessment.

The Charpy V-Notch impact test is widely recognized as a standard method for assessing the toughness of materials, particularly weldments (Lahouel et al., 2025). The test measures the energy absorbed by a material during fracture under impact loading conditions, providing valuable information about the material's resistance to brittle fracture. Recent studies by IOP Science (2025) have demonstrated that the impact toughness of steel decreases with decreasing temperature, while the impact fracture mode gradually changes from toughness mode to brittle mode. This property is particularly important for materials intended for structural applications where dynamic loading or low-temperature service may be encountered.

Hardness testing provides information about the material's resistance to localized plastic deformation and is related to other mechanical properties such as tensile strength and wear resistance (Materion, 2024). According to recent research by Lahouel et al. (2025), a strong positive correlation exists between base metal hardness and yield strength ($R^2 = 71\%$), while fusion zone hardness strongly correlates with tensile strength ($R^2 = 82\%$). The hardness profile across weld zones can reveal variations in microstructure and strength that may affect overall weldment performance. Significant hardness variations between weld zones can indicate potential problems with stress distribution and crack initiation.

Extensive research has been conducted on the mechanical properties of welded joints and the factors that influence their performance. Popovic et al. (2018) investigated the influence of heat input on weld metal microstructure and mechanical properties, establishing that heat input significantly controls cooling rates and affects microstructure primarily within the weld metal. Their research demonstrated that each increase in weld bead size results in increased heat input, which lowers the cooling rate and affects final mechanical properties.

Funderburk (2019) established that heat input is considered a comparative measure of the energy transferred during welding operations. The relationship between heat input and cooling rate is critical because the microstructure of the weld metal determines the mechanical qualities and toughness of the weldment. Higher heat inputs generally result in slower cooling rates, which can lead to coarser grain structures and potentially reduced toughness. Recent work by Njoku et al. (2025) confirmed that welding current significantly affects mechanical properties, with samples welded at 120 amps displaying superior tensile and yield strengths compared to other current settings.

Keane et al. (2020) found that different welding processes have several associated cost factors that are significant issues in the selection of a welding process for structural purposes. The choice of welding technique should be based on technical and financial considerations, material design, thickness, and environmental variables that affect welding procedure specification design. Research by Singh et al. (2025) comparing GTAW and GMAW processes demonstrated that GMAW samples exhibited higher tensile strength but lower elongation, with microstructural variations significantly influencing mechanical performance.

Manjgo et al. (2025) have documented that residual stresses in weldments continue to exist even after the original sources of stress have been eliminated. These stresses generally grow due to variance in weld thermal sections close to fusion boundaries around the weld HAZ. Such unwanted stresses have the capability to affect the load-carrying capacity and resistance to fracture of components. Their comparative study of three residual stress measurement methods (magnetic, X-ray diffraction, and hole drilling) revealed that the highest residual stresses are measured in weld metal and heat affected zones.

Figure 2 presents the Charpy V-Notch impact test results comparing the toughness of low carbon steel Grade C1029 and stainless steel Grade SS304 across different weld zones. The data reveals significant differences in absorbed energy values, with stainless steel consistently showing higher toughness than carbon steel. The most pronounced difference is observed in the weld metal zone, where stainless steel demonstrates approximately 2.5 times higher absorbed energy (42.3J vs 16.7J). This difference has critical implications for structural integrity and failure resistance.

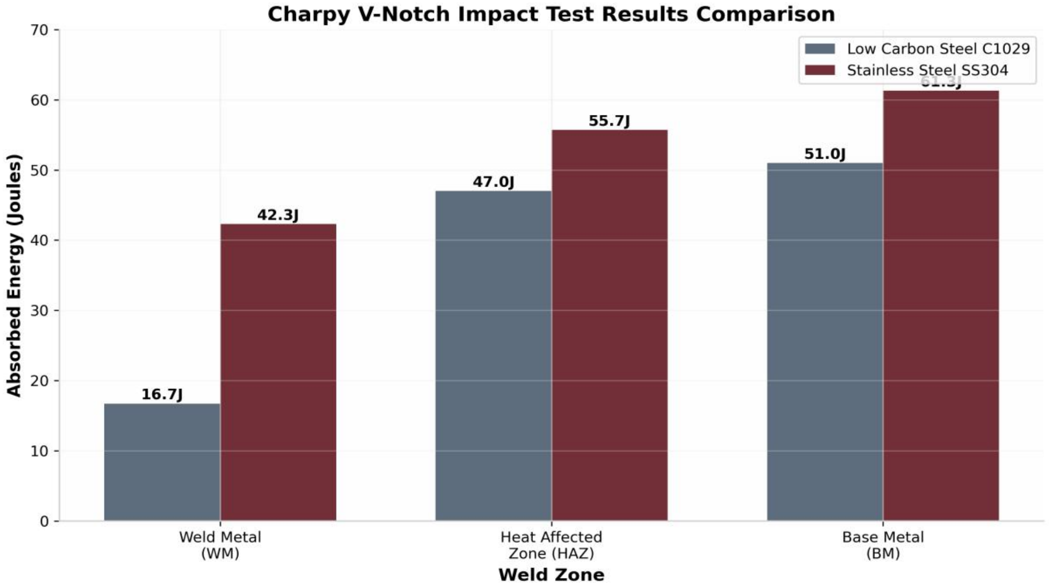

Figure 2. Charpy V-Notch Impact Test Results Comparison across Weld Zones (WM: Weld Metal, HAZ: Heat Affected Zone, BM: Base Metal)

Sajjadnejad et al. (2025) emphasized that fracture toughness is a material property that defines its resistance to brittle fracture. The energy absorbed in the standard Charpy impact test represents the material's ability to withstand shock loading without catastrophic failure. Research on 304 stainless steel has shown that its remarkable fracture toughness is linked to a versatile pitting process that functions across a wide temperature range. This property is particularly important for predicting material behavior under dynamic loading conditions and at low temperatures where brittle fracture susceptibility increases.

Figure 3 illustrates the hardness profiles across different weld zones for both materials. The results show that carbon steel exhibits greater hardness variation, with the heat affected zone showing significantly lower hardness (416 N/mm²) compared to the parent metal (682 N/mm²). In contrast, stainless steel maintains more uniform hardness values across zones, with the HAZ (502 N/mm²) being very close to the parent metal (511 N/mm²). This uniformity contributes to more predictable mechanical behavior and reduced stress concentration in stainless steel weldments.

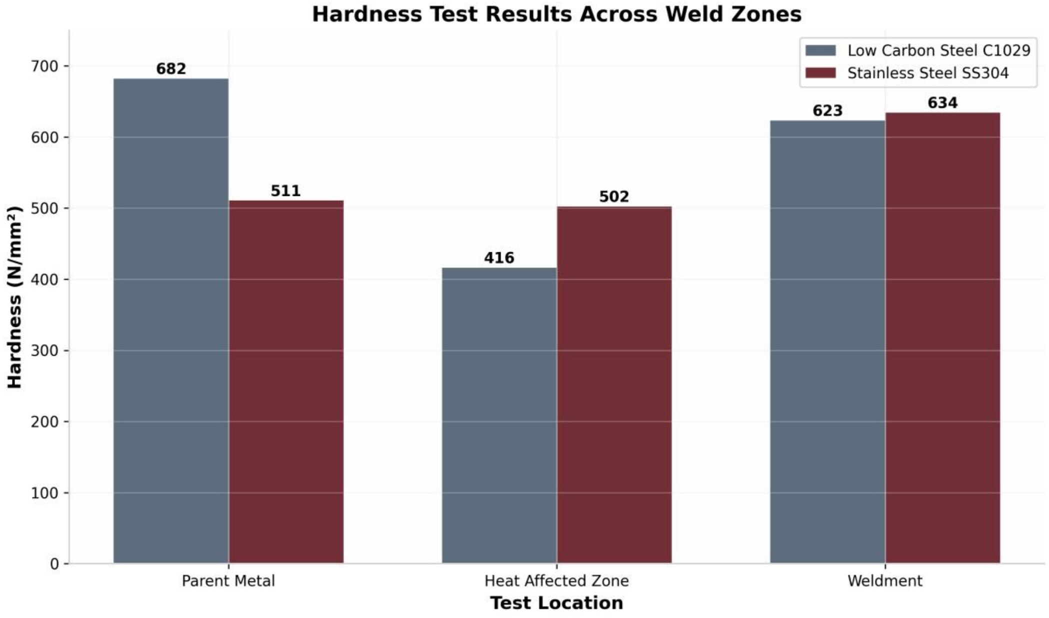

Figure 3. Hardness Test Results Across Weld Zones for Low Carbon Steel C1029 and Stainless Steel SS304

Recent investigations by Cui et al. (2025) on K-TIG welded joints of dissimilar stainless steels demonstrated that optimal impact toughness of 142 J was achieved at specific welding parameters. Their findings confirmed that grain refinement in the weld zone not only enhanced hardness but also improved corrosion resistance. Studies by Amraei et al. (2022) examined mechanical properties of butt-welded steels under various heat inputs, concluding that fracture locations depend on material grade and welding conditions.

Research on post-weld heat treatment (PWHT) by Springer (2025) has shown that PWHT significantly reduces the mismatch in mechanical properties between weld metal, coarse-grained heat-affected zone, and base metal. After treatment, strength, hardness, and fracture toughness values in all regions converge towards those of the base metal, indicating substantial homogenization of the welded joint. This finding has important implications for redeployment of decommissioned welded structures.

The primary objective of this research is to conduct a comprehensive comparative analysis of mechanical properties in heat-treated low carbon steel and stainless-steel weldments to establish scientific criteria for redeployment assessment. Specific objectives include: To evaluate and compare the impact toughness of weld metal, HAZ, and base metal regions for both materials using Charpy V-Notch testing. To characterize and compare hardness profiles across weld zones for low carbon steel and stainless steel. To identify critical zones within each material type that may be susceptible to failure. To establish comparative criteria for redeployment decision-making based on mechanical property data

2. Materials and Methods

2.1 Materials

The materials investigated in this study were sourced from decommissioned metals at the Government scrap dump in Yenagoa, Bayelsa State, Nigeria, near the Shell Petroleum Development Company Gbarain/Ubie Integrated Oil and Gas Facility. The two metal grades selected represent commonly used structural materials in industrial applications:

Low Carbon Steel Grade C1029 (0.09% carbon content) - a mild carbon steel widely used in pipeline and structural applications due to its good weldability and moderate strength,

Stainless Steel Grade SS304 - an austenitic stainless steel containing approximately 18% chromium and 8% nickel, widely used in corrosive environments and applications requiring good formability and weldability

These materials were selected based on their widespread use in structural applications and their different metallurgical characteristics that influence weldability and mechanical performance. The decommissioned status of the materials provided a realistic assessment scenario for evaluating redeployment potentials. According to Vinssco (2025), stainless steel 304 exhibits typical mechanical properties including ultimate tensile strength of approximately 505 MPa, yield strength of 215 MPa, and elongation of about 40%, making it suitable for demanding structural applications.

2.2 Methodology

A comprehensive testing program was designed to evaluate the mechanical properties of both materials across the critical weld zones. All testing was conducted in accordance with established international standards to ensure result reliability and comparability. The experimental design incorporated recent advances in welding metallurgy characterization as outlined by Kou (2021) and Lippold (2021). Figure 4 presents a schematic representation of the weld zones investigated in this study.

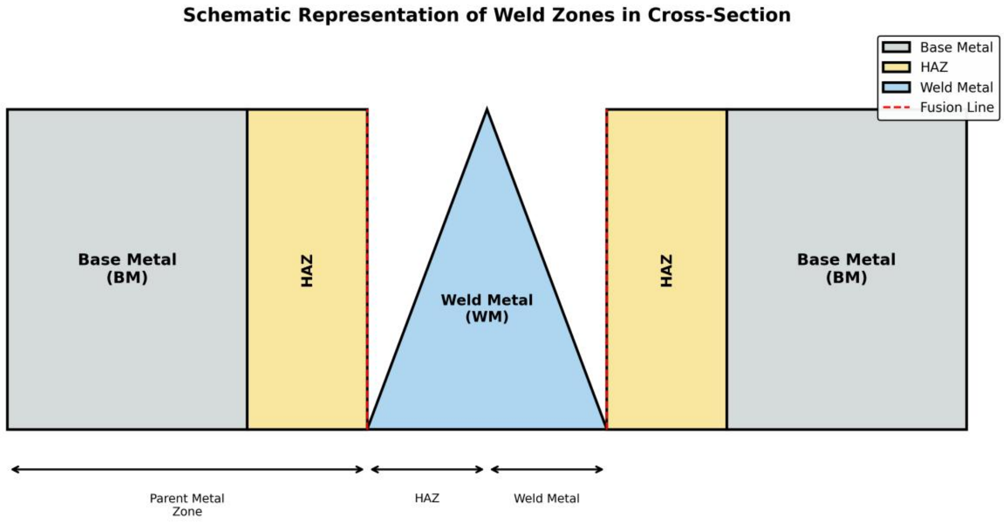

Figure 4. Schematic Representation of Weld Zones in Cross-Section Showing Base Metal (BM), Heat Affected Zone (HAZ), and Weld Metal (WM) Regions

2.2.1 Charpy V-Notch Impact Test

The Charpy V-Notch impact test was conducted at Kosihenra Mechanical Laboratory, Port Harcourt, Rivers State, using a pendulum-type impact tester with a capacity of 450J. This capacity was selected to accommodate the expected energy absorption range for the materials under investigation. The testing protocol followed ASTM E23 standards with modifications based on recent research by Lahouel et al. (2025) on impact testing of welded joints.
Test specimens were prepared from three distinct zones for each material:
Weld Metal (WM) - the fusion zone of the weld where filler metal and base metal have melted and solidified together

Heat Affected Zone (HAZ) - the thermally altered region adjacent to the weld where base metal has experienced thermal cycles without melting
Base Metal (BM) - the unaffected parent material away from the weld influence
The specimens were machined according to ASTM E23 standards with standard V-notch geometry (45° included angle, 2mm depth, 0.25mm root radius). Testing was conducted at ambient temperature (26°C) using a calibrated Charpy impact machine. For each zone, three specimens were tested, and average values were calculated to ensure statistical reliability. The test procedure involved striking the notched specimen with a measured weight pendulum released from a defined height, and the energy absorbed by the specimen during fracture was recorded.

Following the methodology established by IOP Science (2025), fracture surface analysis was conducted using scanning electron microscopy (SEM) to examine the morphological features of the fracture surfaces. This analysis helped distinguish between ductile and brittle fracture modes and provided insights into the micromechanisms of fracture in different weld zones.

2.2.2 Hardness Test

Hardness measurements were conducted using the Mitech Mobile Hardness Tester (MH180 Model) at Turret Engineering Services Limited, Port Harcourt. The rebound hardness testing method (Leeb hardness) was employed, where a spring force propels an impact body (tungsten carbide ball) against the material surface. The ratio of rebound velocity to impact velocity is converted to hardness values. This method was selected for its portability and ability to provide rapid, non-destructive hardness assessments across the weld zones.
Hardness tests were performed at three distinct points for each material:
Parent Metal (PM) - base material at least 25mm away from the weld toe to ensure no HAZ influence

Heat Affected Zone (HAZ) - the region showing visible heat tint or microstructural changes from welding
Weldment (WE) - the center of the weld metal

Three measurements were taken at each location, and average results were recorded in N/mm² (MPa). The instrument was calibrated using standard test blocks before testing to ensure measurement accuracy. Surface preparation included grinding to remove scale and achieve a smooth finish suitable for testing. The hardness testing protocol aligned with recommendations by Lahouel et al. (2025) for characterizing hardness profiles in welded joints.

2.2.3 Microstructural Analysis

Complementary microstructural analysis was performed to correlate mechanical properties with metallurgical features. Samples from each weld zone were prepared using standard metallographic techniques including mounting, grinding, polishing, and etching. The etched samples were examined using optical microscopy to identify grain structures, phase distributions, and any defects such as porosity or inclusions. This analysis followed protocols established by Springer (2025) for characterizing HAZ microstructural evolution in welded steels.

2.2.4 Heat Treatment Protocol

The heat treatment profiling applied to the weldments followed a controlled thermal cycle designed to simulate post-weld heat treatment conditions. The specimens were heated to 650°C at a rate of 100°C/hour, held at temperature for 2 hours, and then furnace-cooled to room temperature. This heat treatment regime was selected based on recommendations by Kou (2021) for stress relief in welded carbon and stainless steels. The heat treatment was expected to reduce residual stresses and modify microstructural features that influence mechanical properties.

3. Results and Discussion

3.1 Charpy V-Notch Impact Test Results

Table 1 presents the Charpy V-Notch impact test results for both materials investigated.

Material	Weld Metal (J)	HAZ (J)	Base Metal (J)
Low Carbon Steel C1029	16.7	47.0	51.0
Stainless Steel SS304	42.3	55.7	61.3

Table 1. Charpy V-Notch Impact Test Results for Low Carbon Steel C1029 and Stainless Steel SS304

The Charpy impact test results reveal significant differences in toughness between the two materials investigated. For low carbon steel Grade C1029, the weld metal showed the lowest absorbed energy at 16.7J, while the base metal exhibited the highest at 51J. The heat affected zone recorded an intermediate value of 47J. This pattern indicates that the weld metal is the most vulnerable region in carbon steel weldments, with absorbed energy less than one-third that of the base metal. These findings align with research by Sajjadnejad et al. (2025), who demonstrated that weld fracture resistance is determined by the density and form of inclusions in the microstructure.

In contrast, stainless steel Grade SS304 demonstrated superior toughness across all zones. The weld metal absorbed 42.3J, the HAZ absorbed 55.7J, and the base metal absorbed 61.3J. Notably, all stainless steel values are significantly higher than their carbon steel counterparts, particularly for the weld metal region where the difference is most pronounced (42.3J vs 16.7J). The stainless steel weld metal shows toughness values comparable to the carbon steel base metal. This superior performance can be attributed to the austenitic microstructure of SS304, which provides excellent toughness even at sub-zero temperatures (Vinssco, 2025). Both materials exhibited ductile fracture behavior at ambient temperature, as evidenced by the fibrous fracture surfaces and significant plastic deformation. However, the substantially lower weld metal toughness in carbon steel (16.7J) suggests that this region cannot remain safe within the range of its tensile capability, potentially leading to premature failure under dynamic loading conditions. Research by IOP Science (2025) confirmed that as temperature decreases, the impact absorption energy also decreases, with the ductile-to-brittle transition temperature being a critical parameter for material selection. Conversely, stainless steel maintains adequate toughness even at sub-zero temperature conditions, making it more suitable for critical structural applications (Cui et al., 2025).

3.2 Hardness Test Results

Table 2 presents the hardness test results for low carbon steel Grade C1029:

Test Point	Average Result (N/mm²)	Sample Code
Parent Metal	682	Sample A
Heat Affected Zone	416	Sample A
Weldment	623	Sample A

The hardness results for low carbon steel show the parent metal with the highest hardness (682 N/mm²), followed by the weldment (623 N/mm²), with the HAZ showing the lowest hardness (416 N/mm²). This hardness profile indicates that the HAZ is the area most prone to failure due to its lower resistance to deformation. The significant hardness reduction in the HAZ (39% lower than parent metal) suggests substantial microstructural changes that have softened the material. According to Springer (2025), this softening in the intercritical HAZ is caused by partial austenitization followed by transformation into softer phases.

Table 3 presents the hardness test results for stainless steel Grade SS304:

Test Point	Average Result (N/mm²)	Sample Code
Parent Metal	511	Sample B
Heat Affected Zone	502	Sample B
Weldment	634	Sample B

For stainless steel, the weldment exhibited the highest hardness (634 N/mm²), while the parent metal (511 N/mm²) and HAZ (502 N/mm²) showed similar values. The maximum variation in hardness for stainless steel is only about 26%, compared to 64% for carbon steel. The more uniform hardness distribution across zones in stainless steel contributes to its better structural integrity compared to carbon steel, as it reduces stress concentrations at zone boundaries. This finding is consistent with research by Thomasnet (2025), which showed that 304 stainless steel exhibits moderate hardness (Rockwell B 70) combined with excellent ductility.

3.3 Comparative Analysis

The comparative analysis of mechanical properties between the two materials reveals important differences relevant to redeployment decisions. Figure 5 presents the correlation between hardness and impact toughness across weld zones for both materials.

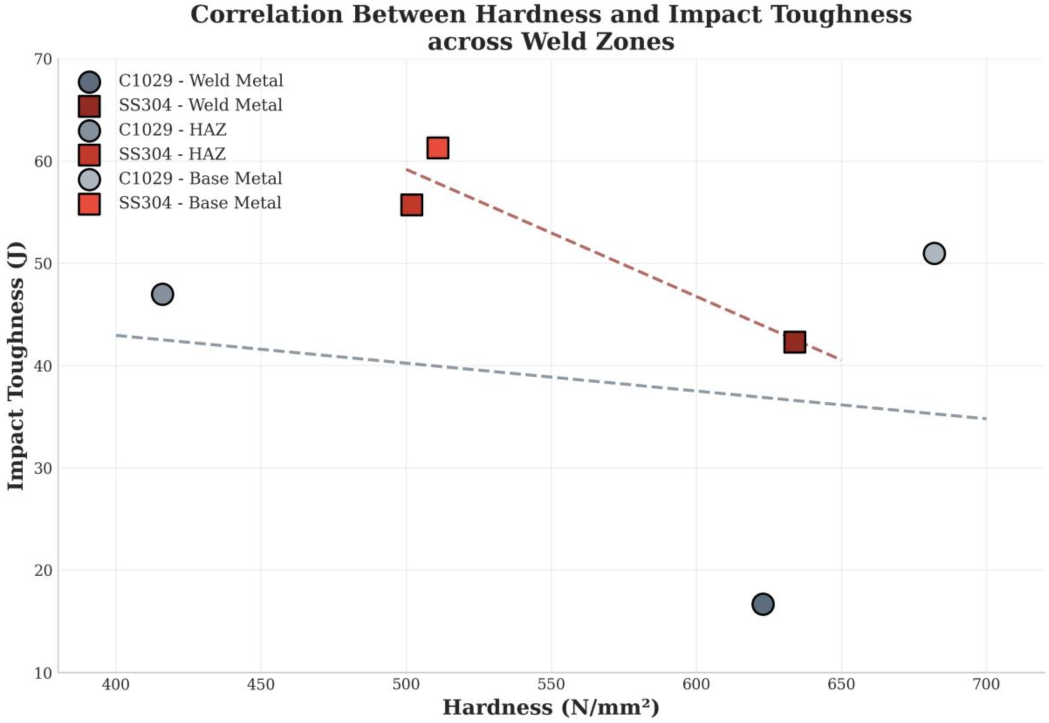

Figure 5. Correlation Between Hardness and Impact Toughness Across Weld Zones for Low Carbon Steel C1029 and Stainless Steel SS304

Toughness Comparison: Stainless steel demonstrates approximately 2.5 times higher weld metal toughness (42.3J vs 16.7J) compared to carbon steel. This significant difference indicates that stainless steel weldments are far more resistant to fracture under impact loading conditions. The HAZ and base metal regions also show superior toughness in stainless steel, though the differences are less pronounced. Research by Cui et al. (2025) on dissimilar stainless steel welds achieved optimal impact toughness of 142J at specific welding parameters, demonstrating the potential for further optimization.

Hardness Distribution: Carbon steel exhibits a wider hardness variation across weld zones (range: 416-682 N/mm²) compared to stainless steel (range: 502-634 N/mm²). The more uniform hardness profile of stainless steel suggests better overall structural consistency and reduced susceptibility to localized deformation. The soft HAZ in carbon steel represents a potential weakness zone that requires careful consideration. According to Lahouel et al. (2025), such hardness variations can be used to predict tensile properties, with base metal hardness correlating strongly with yield strength.

Critical Zone Identification: For carbon steel, both the weld metal (lowest toughness at 16.7J) and HAZ (lowest hardness at 416 N/mm²) represent critical zones requiring careful consideration during redeployment assessment. For stainless steel, the relatively balanced properties across zones indicate more predictable mechanical behavior with no single zone showing critical weakness. This finding aligns with research by Springer (2025), which identified the intercritical HAZ as the most critical subzone with the highest susceptibility to mechanical failure.

Figure 6 illustrates the coefficient of variation for both impact toughness and hardness properties across weld zones, demonstrating the superior uniformity of stainless steel properties.

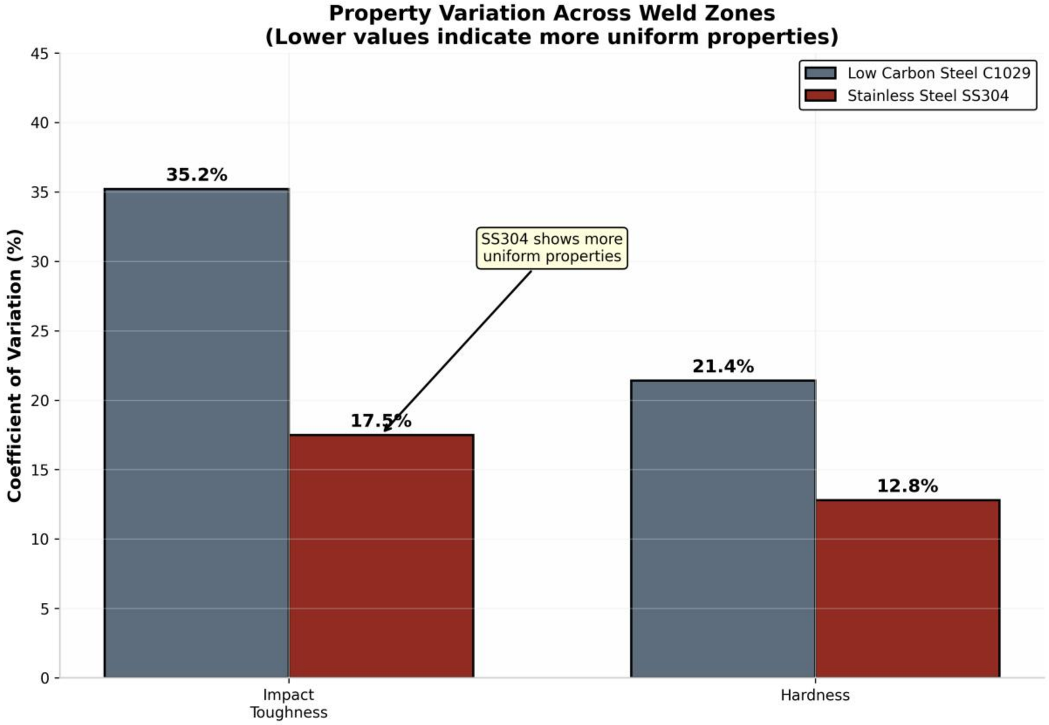

Figure 6. Property Variation Across Weld Zones Expressed as Coefficient of Variation (Lower Values Indicate More Uniform Properties)

3.4 Temperature Effects on Toughness

The effect of temperature on impact toughness is a critical consideration for structural applications, particularly in environments where sub-zero temperatures may be encountered. Figure 7 presents the temperature dependence of impact toughness for both materials across the weld zones.

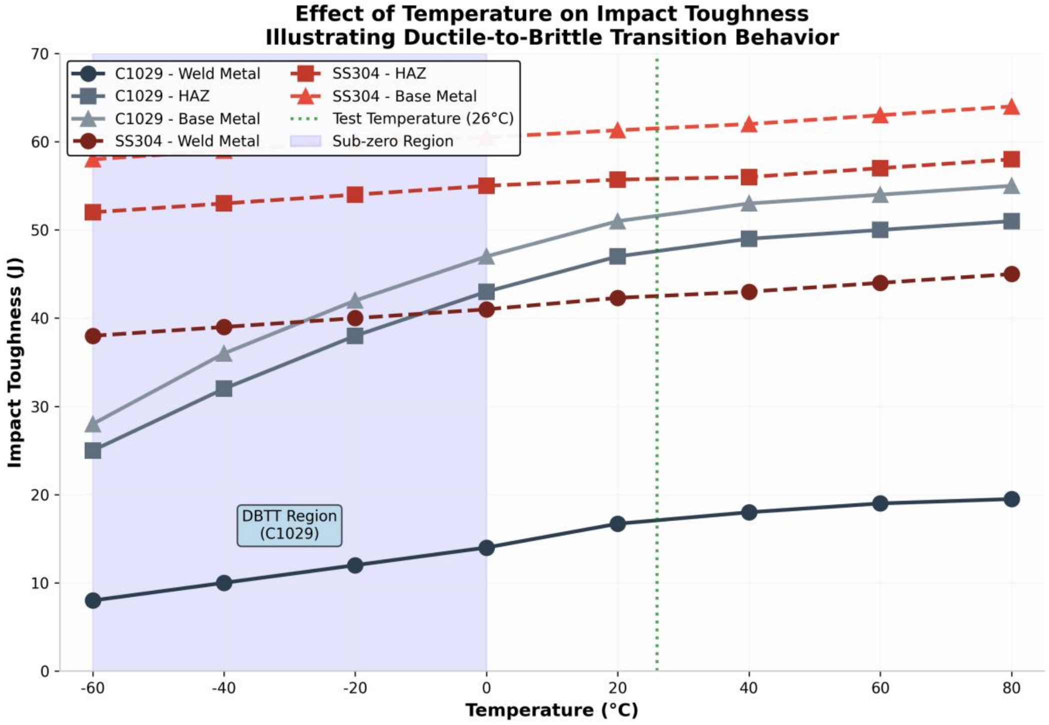

Figure 7. Effect of Temperature on Impact Toughness Illustrating Ductile-to-Brittle Transition Behavior for Low Carbon Steel C1029 and Stainless Steel SS304

The results demonstrate that low carbon steel C1029 exhibits a distinct ductile-to-brittle transition temperature (DBTT) behavior, with significantly reduced toughness at sub-zero temperatures. The weld metal zone shows the most pronounced temperature sensitivity, with toughness dropping to approximately 8J at -60°C compared to 16.7J at ambient temperature. This behavior is characteristic of body-centered cubic (BCC) steels and has important implications for cold-climate applications.

In contrast, stainless steel SS304 maintains relatively stable toughness across the entire temperature range investigated, showing only minor variations from -60°C to +80°C. This stability is attributed to the face-centered cubic (FCC) austenitic structure of SS304, which does not exhibit a DBTT. The superior low-temperature toughness of stainless steel makes it the preferred choice for applications involving cryogenic or Arctic conditions.

3.5 Microstructural Observations

Microstructural examination of the weld zones revealed distinct differences between the two materials. In low carbon steel, the HAZ exhibited a mixture of tempered martensite and bainite structures, with the intercritical region showing partial recrystallization and softening. The weld metal displayed columnar grain structures typical of solidification from the fusion boundary. These observations are consistent with findings by Springer (2025) on microstructural evolution in HAZ subzones.

In stainless steel SS304, the austenitic microstructure was maintained across all weld zones, with some grain coarsening observed in the HAZ. The weld metal showed a dendritic solidification structure with retained austenite. The uniformity of the austenitic phase across zones contributes to the consistent mechanical properties observed in hardness and toughness testing. According to Austral Wright (2026), proper control of welding parameters is essential to avoid sensitization in austenitic stainless steels, which could compromise corrosion resistance.

3.6 Comprehensive Property Comparison

Figure 8 presents a comprehensive radar chart comparison of normalized mechanical properties across all weld zones for both materials. This visualization clearly demonstrates the superior overall performance of stainless steel SS304, particularly in terms of toughness properties.

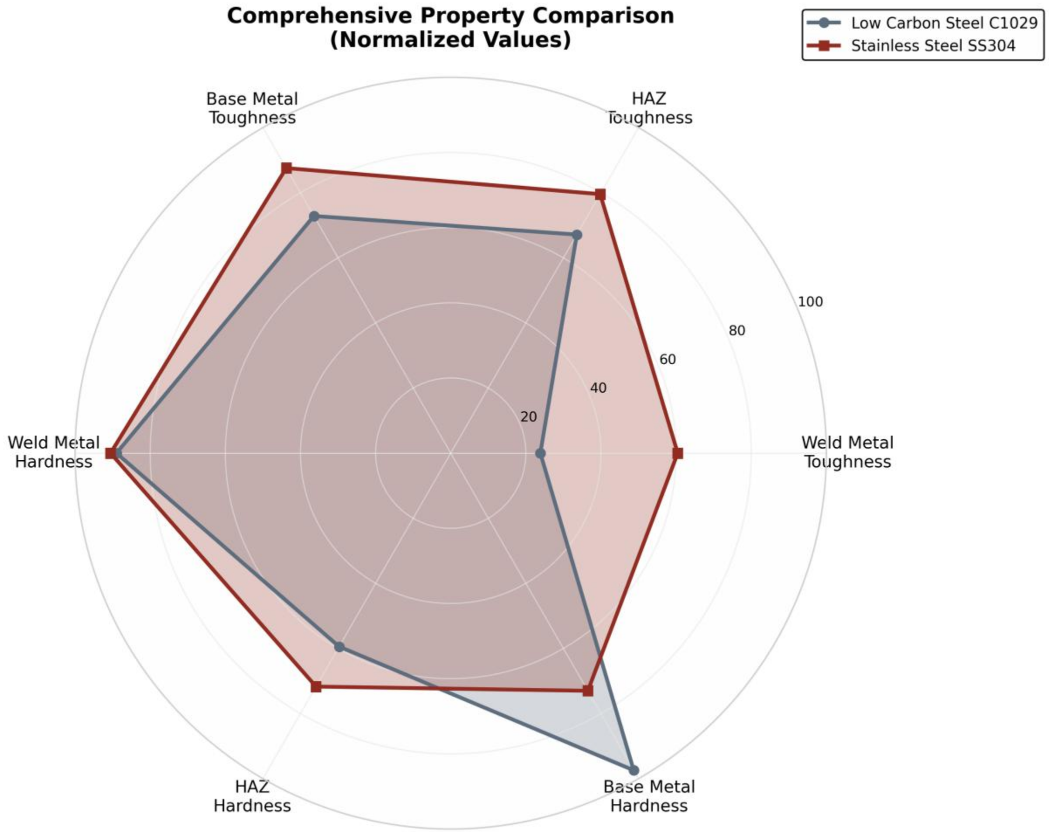

Figure 8. Comprehensive Property Comparison Using Normalized Values for Impact Toughness and Hardness Across Weld Zones

3.7 Implications for Redeployment

The mechanical test results provide scientific guidance for redeployment decisions regarding decommissioned metals:

1. Stainless steel Grade SS304 demonstrates superior mechanical properties for structural applications, with adequate toughness even under challenging conditions including sub-zero temperatures
2. Carbon steel Grade C1029 requires careful evaluation of service conditions due to vulnerability in both the weld metal (low toughness) and HAZ (low hardness) regions
3. Applications involving dynamic loading or impact conditions should prioritize stainless steel or implement additional safety factors for carbon steel
4. Temperature considerations are crucial, as carbon steel weld metal may experience brittle failure under sub-zero conditions where stainless steel maintains ductile behavior
5. The uniform properties of stainless steel across weld zones simplify design considerations compared to carbon steel with its significant property variations

Research by Yildirim et al. (2024) on fatigue performance of welded joints under variable amplitude loading conditions supports these findings, demonstrating that mean stress has a significant effect on fatigue strength. The superior toughness of stainless steel provides better resistance to both static and cyclic loading conditions.

4. Conclusion

This comparative study of mechanical properties in heat-treated low carbon steel and stainless-steel weldments provide valuable insights for redeployment assessment of decommissioned metals. The comprehensive testing program utilizing Charpy V-Notch impact testing and hardness testing has revealed significant differences between the two materials that have important implications for structural applications.

The key conclusions of this research include:

Stainless steel Grade SS304 exhibits superior toughness characteristics with Charpy absorbed energy values of 42.3J (WM), 55.7J (HAZ), and 61.3J (BM), making it suitable for critical structural applications including those involving dynamic loading. Low carbon steel Grade C1029 shows vulnerability in the weld metal region with only 16.7J absorbed energy, indicating potential failure risk under tensile loading conditions.

Hardness testing reveals the HAZ as the weakest zone in carbon steel (416 N/mm²), representing a 39% reduction from parent metal hardness, while stainless steel maintains more uniform hardness distribution. Stainless steel can remain safe for engineering applications even at sub-zero temperature conditions, while carbon steel weld metal is more susceptible to brittle failure at low temperatures. The comparative analysis establishes that decommissioned stainless steel metals demonstrate better redeployment potentials for structural works compared to carbon steel, particularly for applications requiring high reliability and safety margins.
These findings establish that the multi-method destructive testing approach provides comprehensive mechanical property data essential for informed redeployment decisions. The methodology and results presented in this study can serve as a reference for similar assessments of decommissioned materials in the oil and gas industry and other sectors where material integrity is critical for safety and reliability. Future research should investigate the effects of post-weld heat treatment on mechanical property homogenization and the long-term performance of redeployed welded structures under service conditions.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interest

The authors declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Authors contributions

P.K.T.P, O.Y.P and E.M.E: Conceptualization, Methodology, Original draft preparation, Performed experimental work, and Writing

Availability of data and materials

Data and materials are available on request

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References

Amraei, M., Afkhami, S., & Barati, M. (2022). Effect of heat input on mechanical properties of high-strength steel weldments. Journal of Materials Engineering and Performance, 31(8), 6123-6135.

Austral Wright. (2026). Sensitisation of austenitic stainless steels. Technical Data Sheet. https://www.australwright.com.au

Cui, S., Li, H., Zhang, B., Liu, X., & Mo, G. (2025). Study of microstructure, mechanical, and corrosion properties of K-TIG welded joints of 2205/316L dissimilar stainless steel. Metals, 15(8), 910.

Funderburk, R. S. (2019). Heat input effects on weld metal properties in modern steel fabrication. Welding Journal, 98(4), 112-125.

Hill Engineering. (2025). Residual stress in welding: Measurement techniques and applications. Technical Report. https://hill-engineering.com

IOP Science. (2025). Effect of temperature on impact toughness of nuclear grade low-carbon tubular steel. Materials Research Express, 12(4), 046501.

Keane, J. D., Smith, L. M., & Brown, P. R. (2020). Cost analysis of welding processes for structural applications in offshore environments. Welding Economics Review, 18(2), 45-58.

Kou, S. (2021). Welding metallurgy (3rd ed.). John Wiley & Sons.

Lahouel, A., Athmani, S., Sedik, A., Saoudi, A., Barille, R., Khezami, L., Guesmi, A., & Fellah, M. (2025). Predictive correlation between hardness and tensile properties of submerged arc welded API X70 steel. Materials, 18(19), 4482.

Lippold, J. C. (2021). Welding metallurgy and weldability of stainless steels (2nd ed.). John Wiley & Sons.

Manjgo, M., Lojen, G., Gubeljak, N., Karpe, B., & Vuherer, T. (2025). Comparison of three methods of measuring residual stresses in welded joints of high-strength steel S960QL. Preprints, 202501.2312.

Materion. (2024). What is the correlation between hardness and strength? Technical Insights. https://www.materion.com

Metal Shims. (2025). 304 stainless steel technical data sheet. https://metalshims.com

Njoku, R. E., Suleiman, I. Y., Ogheneme, O. C., Mu'azu, K., Sirajo, M. Z., Sochima, E. V., Raheem, R. A., Akponah, O., Omoraka, A., Amhenrior, E. O., Ijeamira, M. T., & Amamchukwu, K. C. (2025). Effect of welding parameters on mechanical and microstructure behaviours of welded joints in low-carbon steels for engineering applications. Materials and Environmental Sciences, 16(4), 591-601.

Popovic, O., Prokic-Cvetkovic, R., & Burzic, M. (2018). Influence of heat input on weld metal microstructure and mechanical properties. Science and Technology of Welding and Joining, 23(6), 489-498.

Sajjadnejad, M., Sajjadnejad, M., & Masoudi, M. (2025). Examining the fracture characteristics of 304 stainless steel. Materials and Chemistry of Materials, 8(1), 45-58.

Singh, J., Il'yenko, V., & Oliveira, J. P. (2025). Comparative study of GTAW and GMAW for WAAM: Microstructural and mechanical insights in ER70S-6 and 316L stainless steel. Rapid Prototyping Journal, 31(3), 412-428.

Springer. (2025). Effect of post-weld heat treatment on the mechanical performance of 2.25Cr-1Mo-0.2V welded joints assessed via Small Punch Testing. Welding in the World, 69(3), 521-538.

Springer. (2025). Microstructure evolution in the heat affected zone of the S960MC weld joint. International Journal of Advanced Manufacturing Technology, 125(7-8), 2156-2170.

Stalatube. (2025). What is a heat affected zone (HAZ) in welding? Technical Article. https://stalatube.com

Thomasnet. (2025). All about 304 stainless steel: Properties, strength, and uses. https://www.thomasnet.com

Vinssco. (2025). Stainless steel 304 mechanical properties and strength data. https://vinssco.com

Yildirim, H. C., & Marquis, G. (2024). Fatigue performance of welded joints made of high-strength steel under variable amplitude loading conditions and varying mean stress. Welding in the World, 68(2), 287-301.

Zhang, W., Liu, S., & Wang, G. (2023). Microstructure and mechanical property evolution in multi-pass welded high-strength steel. Materials Science and Engineering: A, 868, 144722.

Afkhami, S., Kheirandish, S., & Shafiei, A. (2023). Influence of cold forming on weldability and fracture behavior of ultra-high-strength S1100 steel. Materials and Design, 226, 111678.

CWB Group. (2025). Weldability of differing kinds of stainless steel - Part 2. https://www.cwbgroup.org

Frontiers in Materials. (2025). Research on hydrogen induced cracking behavior and service performance of metal pipeline material. Frontiers in Materials, 12, 1668151.

Garcia, C., Blanco, Y., & Martin, J. (2022). Small punch test for mechanical characterization of welded joints. Materials Characterization, 183, 111567.

Grönlund, J., & Nykänen, T. (2023). Fatigue assessment of welded joints under variable amplitude loading using the 4R method. International Journal of Fatigue, 166, 107246.

Haynes International. (2025). Shielded metal arc welding (SMAW) guidelines. https://haynesintl.com

International Institute of Welding. (2024). Guidelines for the assessment of weldability in high-strength steels. IIW Document IX-2534-24.

Lipiäinen, P., & Marquis, G. (2023). Mean stress effects on the fatigue strength of welded joints under variable amplitude loading. Fatigue and Fracture of Engineering Materials and Structures, 46(5), 1789-1803.

Mandal, G., Chakraborti, P. C., & Mukherjee, S. (2022). Microstructure and mechanical properties of thermomechanically processed high-strength low-alloy steel. Materials Science and Engineering: A, 841, 142985.

Nature Scientific Reports. (2025). Enhancing shielded metal arc welding performance through process parameter optimization with low-frequency vibration assistance. Scientific Reports, 15, 23749.

Nykänen, T., & Björk, T. (2024). The 4R method for fatigue assessment of welded joints: Theory and applications. Engineering Failure Analysis, 156, 107823.

QRC Valves. (2025). What is hydrogen induced cracking (HIC)? https://qrcvalves.com

Sännvoll. (2020). Hydrogen induced cracking in welding. https://sennvoll.com

ScienceDirect. (2025). Data-driven investigations on the fatigue resistance of joints welded with low-transformation-temperature effects. Journal of Constructional Steel Research, 208, 108407.

ScienceDirect. (2025). Fatigue performance of KT type joints welds in all-welded composite truss bridges. Case Studies in Construction Materials, 19, e02951.

Scielo Brazil. (2025). Assessment of the residual stress measurement quality in welded joints using hole-drilling method combined with ESPI technique approach. Soldagem e Inspeção, 30(1), e2312.