



Experimental and numerical investigation of residual stresses in dissimilar butt-weld joint made of cast iron and mild steel

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ABSTRACT. Dissimilar welded joints, formed by joining materials with different mechanical and chemical properties, present significant challenges in terms of design and manufacturing. This is mainly due to the different properties of the materials, which exhibit different behaviours when they are subjected to high thermal gradients. The joint consisted of dissimilar materials, spheroidal cast iron (GJS500-7) and structural steel (S355) welded using the Flux-Cored Arc Welding (FCAW) process. The research focuses on analysing the effects of thermal gradients, due to welding, on residual stresses and deformation on the welded joint. To this aim, Finite Element Method (FEM) was used to simulate the thermo-mechanical behaviour of the joint during the welding process to predict both the distortions and the residual stresses distribution. The numerical results are in accordance with the experimental ones, providing good confidence in the use of the model to predict residual stresses and distortions for this type of application.

KEYWORDS. Residual stresses, Hybrid joint, Dissimilar materials, Cast Iron, Steel, FCAW.

INTRODUCTION

Welding currently represents the primary method for joining structural components within the vast family of metallic structures. This joining process is widely employed across various sectors, ranging from railways to aerospace and automotive industries. Consequently, recent scientific research has focused on analysing new types of welded joints and optimizing existing ones, aiming to increase efficiency and improve the mechanical performance of the



joints. While the welding of homogeneous components (the same material for both parts being joined) is a consolidated process with predictable behaviour, the joining of dissimilar materials is generating significant interest within the scientific community [1–3].

This interest in hybrid structures is growing rapidly, as it enables the strategic use of different materials within the same component. This constitutes a major advantage in applications aimed at reducing structural weight or where specific material properties are required at targeted locations. A prime example is the coupling of the high mechanical strength of steel with the damping and anti-vibration properties typical of cast iron. The fabrication of such joints poses significant challenges, as joining dissimilar materials aims to create structural continuity between two components made of materials with different physicochemical properties.

Exhibiting different thermal expansion coefficients, the two materials react differently to the welding process. The high localized thermal gradients generate strong non-linear temperature fields within the materials. Combined with the asymmetric thermal conductivity between the two materials, these can induce severe residual stresses and distortions during the heating and cooling cycles of the welding process, potentially compromising structural integrity [4]. To date, however, the experimental evaluation of these phenomena is often costly and limited to localized investigations. Therefore, numerical techniques, such as the finite element method (FEM), have increasingly become crucial for predicting the evolution of the stress-strain state during and after the welding process [5,6]. The accuracy of such models strictly depends on the correct implementation of process parameters (joint geometry, heat input, welding speed, number of passes) [7,8] and the thermal and mechanical properties of the utilized materials, which exhibit non-linear temperature dependence [9].

Despite the renewed scientific interest in dissimilar joints, evidenced by recent studies on complex configurations or high-energy density processes [10], a literature review reveals a significant gap regarding the thermomechanical modelling of hybrid cast iron-steel structural joints. As a matter of fact, existing studies mainly fall into two categories that do not encompass the phenomenology investigated herein. On the one hand, for example, Pouranvari et al. [11] have clarified the experimental metallurgical aspects, demonstrating the effectiveness of nickel-based filler metals in preventing brittle phases in the fusion zone (FZ). However, these kinds of studies are often limited to post-mortem analyses (microstructure and hardness), lacking a predictive perspective on the evolution of residual stresses during the thermal cycle induced by the welding process. On the other hand, recent contributions to numerical modelling, such as the work by Farahani et al. [12], represent progress in cast iron simulation, yet they strictly focus on repair welding. In this configuration, the constraint is imposed by the cavity of the base material itself (cast iron only), a condition radically different from that of a butt joint, where the materials being joined are dissimilar and the plates are free to deform asymmetrically under the influence of different thermal expansion coefficients.

Other studies on structural joints frequently refer to material combinations with more compatible characteristics, thereby limiting the transferability of their results to the hybrid cast iron-steel process. For instance, extensive research by Zhang et al. [13] has successfully characterized residual stresses in dissimilar steel joints (e.g., austenitic-ferritic). Although these works elucidate the mechanisms of asymmetric stress distribution, they deal with materials exhibiting relatively similar ductile behaviours, unlike the abrupt mismatch in physicochemical characteristics found between spheroidal cast iron and structural steel.

Even when cast iron-steel coupling is addressed, as in Haihan [14], the analysis is often constrained to specific geometries like pipe-to-pipe connections. In such cases, the circumferential constraint dominates, masking the fundamental thermo-mechanical evolution typical of linear butt welds.

Quiang et al. [15], do effectively evaluate residual stresses in hybrid cast iron-steel joints, but they focus on high-thickness configurations. These require multiple welding passes, and the large thermal inertias of the involved components could mask the effects that welding processes might have on more commonly used thicknesses.

A further reason explaining the scarcity of reference studies in the literature concerning residual stresses in cast iron-steel joints is related to the intrinsic complexity of welding cast iron. The operational criticalities associated with this material, primarily attributable to its high carbon content, are widely acknowledged within the scientific community [16,17]. Indeed, various types of defects can arise during the welding process: cold cracking due to shrinkage stresses near the fusion zone, porosity caused by the reaction between carbon and oxygen at high temperatures, and lack of fusion induced by the high presence of graphite, which hinders the proper melting of the base material. Furthermore, when cast iron is subjected to rapid cooling (typical of the post-welding phase), extremely hard and brittle heat-affected zones can form due to the inability of carbon to precipitate again as graphite, leading to the subsequent transformation of austenite into martensite.

In this framework, the present work intends to bridge the scientific gap by proposing an advanced numerical model for the simulation of the welding of a cast iron-steel butt joint.

The primary strength of this model lies in the geometric simplicity of the analysed configuration, featuring thicknesses typically utilized in industrial applications and a limited number of welding passes. This approach made it possible to derive

residual stresses and deformations by isolating the fundamental thermo-mechanical phenomenology from scale and geometric effects (typical of large thicknesses) that could obscure the outcomes in other scenarios.

The development of a welding process and the parallel fabrication of a cast iron-steel joint allowed for the implementation of real welding parameter values into the model, while simultaneously providing an experimental benchmark for the validation of the numerical model.

The analysis conducted on the numerical model permitted, primarily, the evaluation of heat redistribution during welding and how it partitions differently between the two materials (via thermal analysis); then, the model allowed to carry out analyses of the residual stresses and deformations generated by the process (via mechanical analysis).

Furthermore, having subjected the physical joint to non-destructive testing and hardness evaluations, the resulting joint also serves as a reference for other potential applications involving cast iron-steel welded joints.

The work thus conducted aims to: provide a validated predictive tool capable of quantifying global thermomechanical effects in hybrid cast iron-steel joints as welding parameters vary and offer a reference for the attainable stress and deformation values, thereby serving as a foundation for the future structural design of complex hybrid cast iron-steel components.

MATERIAL AND METHODS

The experimental campaign focused on a dissimilar butt joint characterized by a single 60° V-groove preparation. The specimen consists of an S355 structural steel plate joined to a GJS500-7 spheroidal graphite cast iron plate; the specific geometrical dimensions are detailed in Fig. 1. The chemical compositions and mechanical properties of the base materials are reported in Tabs. 1 and 2, respectively. The welding process employed was Flux-Cored Arc Welding (FCAW), utilizing a 1.2 mm diameter (Nickel-Iron based) filler wire with an Ar-CO₂ shielding gas mixture. The joint was completed in two subsequent passes; the specific process parameters adopted are summarised in Tab. 3.

Materials:	C	Si	Mn	P	S	Cu	N
S355	0.14÷0.24	Max (0.55)	Max (1.6)	Max (0.035)	Max (0.035)	Max (0.55)	Max (0.012)
GJS500-7	2.7÷3.7	0.8÷2.9	0.3÷0.7	Max (0.10)	Max (0.020)	-	-

Table 1: Chemical composition (wt%).

Materials	σ_y [MPa]	σ_R [MPa]	A (%)
S355	>355	470÷630	22
GJS500-7	>320	500÷675	7

Table 2: Mechanical properties of the base materials at room temperature.

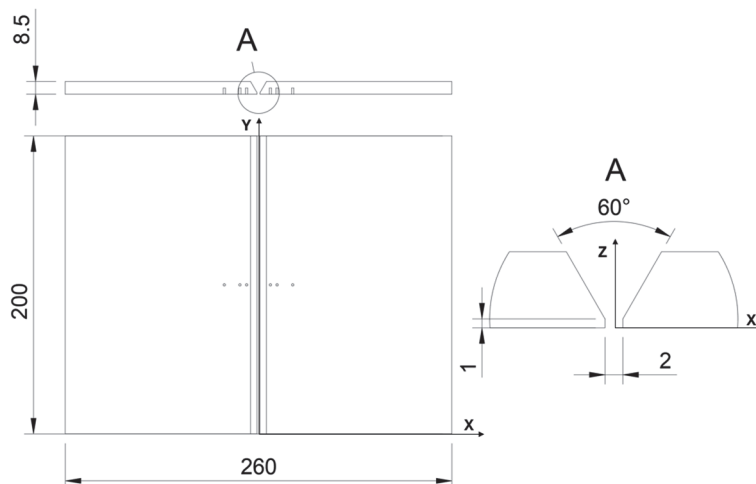


Figure 1: Joint dimensions in [mm].

Parameters	Values for 1st pass	Values for 2nd pass
Voltage V [V]	22	24.5
Current I [A]	160	175
Welding efficiency η [-]	0.8	0.8
Welding speed v [mm/s]	4.7	3.5
Depth [mm]	3.8	4.7

Table 3: Welding parameters.

Temperature acquisition

To evaluate the thermal cycles and calibrate the numerical heat source, six K-type thermocouples were installed on the joint. The sensors were embedded at the mid-thickness of the plates (4.25 mm depth) through drilled blind holes, as detailed in Fig. 2.

The thermocouples were arranged in a symmetrical configuration with respect to the Weld Centre Line (WCL): three on the S355 steel side and three on the GJS500-7 cast iron side. They were positioned at specific distances from the WCL (specifically at 23, 12.5, 8 mm) to evaluate the temperature distribution and cooling rates in both the Heat Affected Zone (HAZ) and the base material. Real-time temperature data acquisition was performed using a National Instruments PCI-6221 card interfaced with LabVIEW 8.5 software.

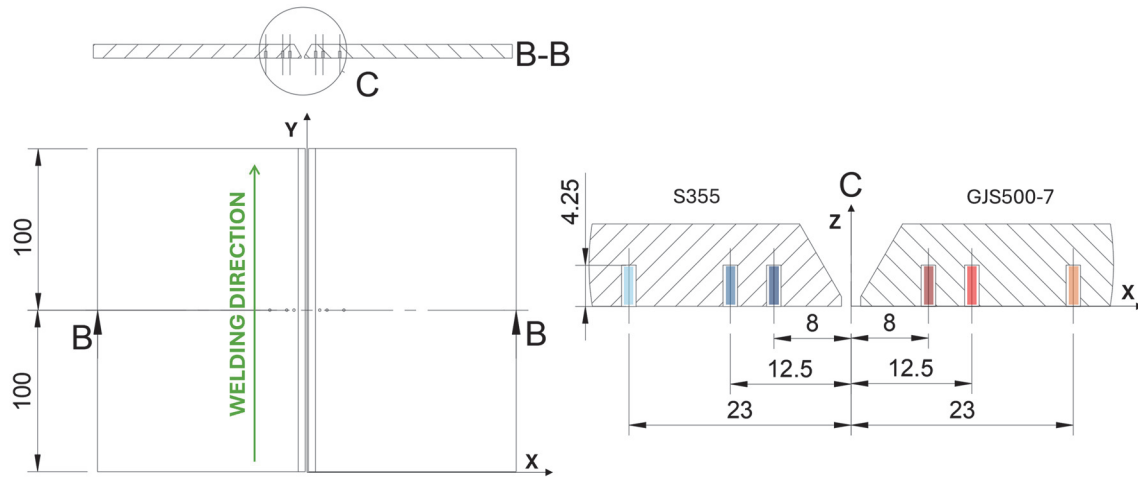


Figure 2: Position of thermocouples in [mm].

Joint defect detection and hardness

Upon completion of the welding process, the joint underwent a post-process inspection to verify its structural integrity. Ensuring the absence of internal macro-defects (such as porosity, lack of fusion, or cracks) is a fundamental prerequisite for the validation phase, as the Finite Element (FE) model simulates an ideal continuum free from process-induced discontinuities.

Non-Destructive Testing (NDT) was performed via Digital Radiography (RT). The inspection employed a Gilardoni XE-L industrial radioscopy and tomography system equipped with a 0.4 mm microfocus source, capable of detecting fine internal flaws. The specific acquisition parameters adopted for the radiographic test are detailed in Tab. 4.

Following the non-destructive inspection, a transverse macro-section was extracted transversal to WCL for metallographic analysis and hardness testing. Standard sample preparation was performed: the specimen was hot mounted in thermosetting phenolic resin to ensure edge retention and planar polishing. The surface was ground and polished to a mirror finish, then chemically etched using a 5% Nital solution to reveal the macrostructural features and the distinct zones of the joint.



The macrographic analysis served a dual purpose: it confirmed the absence of micro-defects undetected by radiography and, crucially, provided the experimental geometrical dimensions of the FZ and HAZ. These measurements were fundamental to calibrate the shape of the heat source in the numerical model.

Parameters	Values
Voltage [kV]	181.0
Current [mA]	2.5
Focus-Detector distance [mm]	1260.0
Focus-Object distance [mm]	908.0
Pixel size [μm]	179
Gain [1pF]	2
Exposure [fps]	18

Table 4: Parameters of radiographic test.

Finally, a Vickers hardness profile (HV10) was measured across the joint cross-section. The indentations were spaced at 1 mm intervals along a line transverse to the welding direction, centred on the WCL, allowing for a detailed mapping of the mechanical property variations from the steel to the cast iron side.

FE MODEL

A sequentially coupled thermal-mechanical analysis was adopted to predict the residual stress field. This approach assumes that the mechanical deformation has a negligible effect on the thermal history, significantly reducing computational cost without compromising accuracy. This methodology is consistent with previous numerical investigations conducted by the authors on similar joint configurations [18]. All simulations were performed using the commercial F code Abaqus/CAE 6.14-1.

To ensure consistency between the thermal and mechanical solutions, an identical mesh topology was employed for both analyses, differing only in the element type: 8-node linear heat transfer brick elements (DC3D8) were used for the thermal solver, while 8-node linear brick elements (C3D8) were selected for the structural analysis. The mesh discretization was refined in the FZ and HAZ to capture the steep thermal gradients.

To accurately simulate the thermo-mechanical behaviour of the joint, the physical and mechanical properties of the materials involved were modelled as temperature-dependent functions. Since experimental characterization at high weld temperatures was not performed in this study and since these are alloys widely used in industry (not special alloys), the non-linear material properties (both thermal and mechanical) were derived from consolidated literature data. Specifically, the thermo-mechanical properties (conductivity, specific heat, density) (Fig. 3) for the S355 steel were adopted from the study by [19], while for the spheroidal cast iron, reference was made to the work of [12] on the influence of temperature on ductile iron. Regarding the elasto-plastic behaviour, temperature-dependent stress-strain curves were implemented based on experimental data reported by [20] for the steel component and by [12,21] for the nodular cast iron. As for the filler material, due to dilution with the base metals and the lack of specific data for the resulting alloy, the properties were assumed to be consistent with those of the spheroidal cast iron, a simplified approach successfully adopted in previous computational studies [12], in which the wire is simulated using the properties of the base material. This choice avoids steel because the massive carbon dilution from the cast iron makes the weld pool metallurgically closer to it. Furthermore, Ni-Fe fillers are engineered to match the thermal expansion of cast iron to minimize shrinkage stresses; modelling them this way avoids spurious stress peaks in the brittle cast iron HAZ, safely shifting the thermo-mechanical mismatch to the ductile and tough steel side. To simulate the progressive deposition of the filler material, the 'element birth and death' technique (Model Change option) was implemented. This modelling strategy, extensively tested by different research group to evaluate welding efficiency and distortions [22], involves discretizing the weld bead into multiple longitudinal sets, initially deactivated and progressively reactivated in synchronization with the moving heat source. The simulation steps replicated the experimental procedure:

1. deposition of the first pass;
2. inter-pass cooling time of 120 s;
3. deposition of the second pass;
4. final cooling to room temperature.

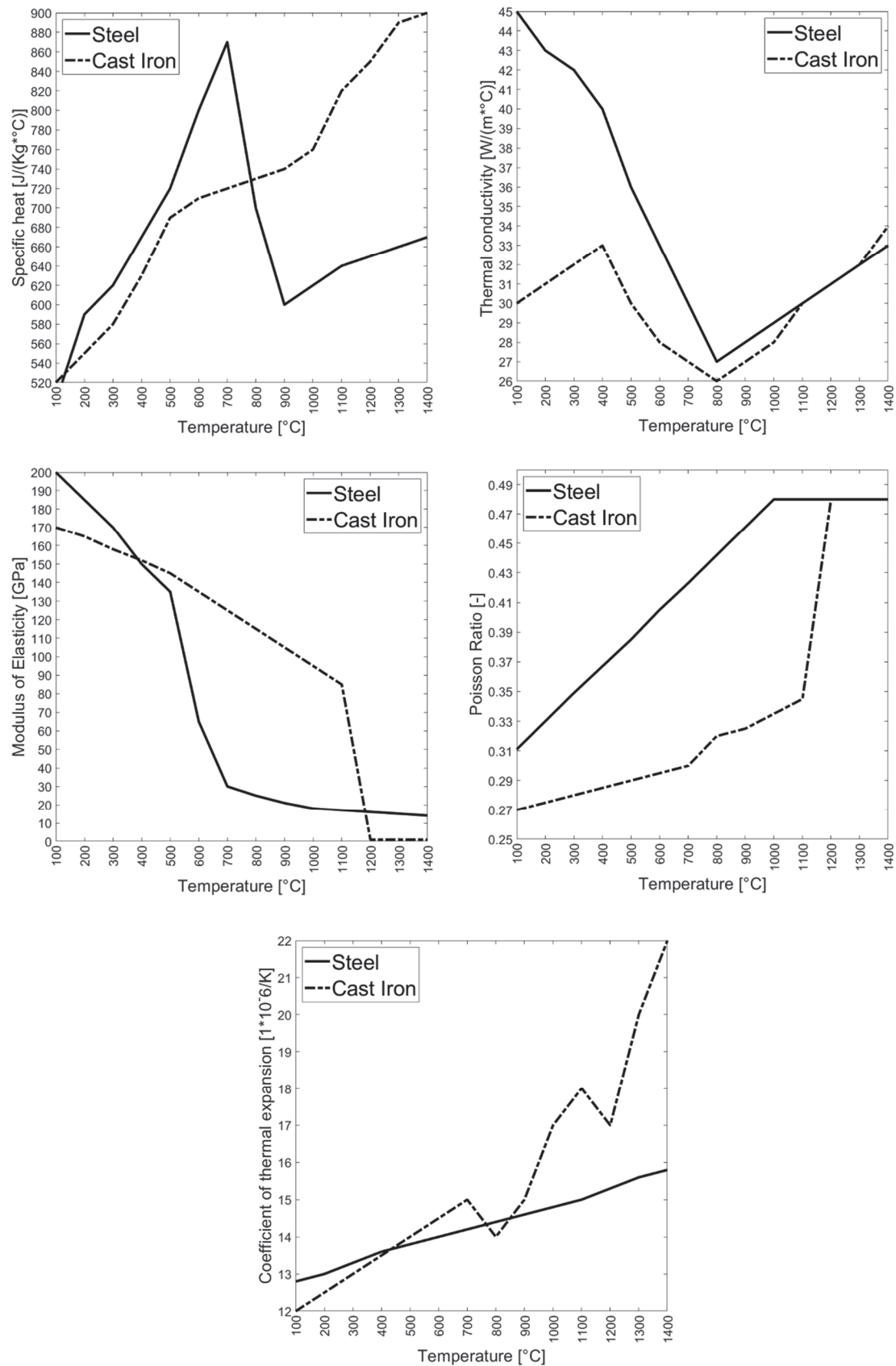


Figure 3: Thermo-mechanical properties for the S355 steel adopted from [19] and for the spheroidal cast iron from [12].



Thermal analysis

The thermal simulation of the welding process was carried out by solving the transient heat conduction problem, governed by Eqn. (1). This equation ensures energy conservation under nonlinear conditions, accounting for the temperature-dependent material properties (density, specific heat, and thermal conductivity), along with an internal heat generation term representing the energy input supplied by the welding arc. To simulate the moving heat source, a volumetric heat flux was applied to the active elements of the FZ, calibrated to reproduce the experimental net heat input. This modelling approach aligns with methodologies successfully validated by the authors in previous investigations on butt and T-joints [23]

The analysis also accounted for the effects of latent heat of fusion and solidification, which are essential for accurately predicting temperature peaks and the FZ size. Boundary conditions were defined by imposing heat losses due to natural convection and radiation on all free surfaces of the joint, adopting heat transfer coefficients consistent with literature and previous numerical calibrations [24]

$$\rho C \frac{\partial T}{\partial t} = \dot{q} + \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) \quad (1)$$

- T is the temperature distribution of the welded plate at time t ;
- ρ , C and k are the density, specific heat and thermal conductivity of the material, respectively;
- $\dot{q}$ is the rate of internal heat generation.

where: the initial condition assumes a uniform ambient temperature T_0 Eqn. (2), while boundary conditions include heat exchange through convection and radiation Eqn. (3).

$$T(x, y, z; t=0) = T_0 \quad (2)$$

$$\dot{q}_n(x, y, z; t) = - \left(k_x \frac{\partial T}{\partial x} n_x + k_y \frac{\partial T}{\partial y} n_y + k_z \frac{\partial T}{\partial z} n_z \right) \quad (3)$$

- $\dot{q}_n$ is the heat flux at a generic boundary, with a local unit vector having components (n_x, n_y, n_z) directed outwards;
- T_0 is the initial temperature.

Convective losses Eqn. (4) and radiative losses Eqn. (5) are combined into a single temperature-dependent film coefficient H Eqn. (6), simplifying the treatment of external heat dissipation,

$$\dot{q}_{nc} = h_c (T(x, y, z; t) - T_0) \quad (4)$$

$$\dot{q}_{nr} = h_r (T(x, y, z; t) - T_r) \quad (5)$$

$$H = h_c + h_r \quad (6)$$

The heat supplied by the arc per unit length is calculated from process parameters such as voltage, current, welding speed, and arc efficiency Eqn. (7).

$$Q = \frac{\eta V I}{v} \quad (7)$$

This energy is partitioned into three contributions: $Q_{sensible}$ sensible heat required to raise the material from ambient to solidus temperature Eqn. (8), Q_{latent} latent heat associated with melting (where q_{latent} is the latent heat for unit of mass, for steel equal to 277,000 J kg⁻¹ and for cast iron 272,500 J kg⁻¹) Eqn. (9), $Q_{body \ flux}$ the remaining energy Eqn. (10). The elements



are activated at the melting point, and for this reason the only heat that needs to be added is $Q_{body\ flux}$ which is applied as a volumetric source to the activated elements Eqn. (11),

$$Q_{sensible} = vol_{seam} \int_{T_0}^{T_s} (\rho C dT) = m_{seam} \int_{T_0}^{T_s} (C dT) \quad (8)$$

$$Q_{latent} = m_{seam} q_{latent} \quad (9)$$

$$Q_{body\ flux} = Q_{real} - Q_{sensible} - Q_{latent} \quad \text{with} \quad Q_{real} = Q^* L_{seam} \quad (10)$$

$$Q_{component} = \frac{Q_{body\ flux}}{n_{component}} \quad (11)$$

where:

- L_{seam} , vol_{seam} and m_{seam} are the length, the volume and the mass of the seam, respectively;
- T_s is the solidus temperature;
- $n_{component}$ is the number of components of the seam.

To reproduce the progressive deposition of filler material, the weld bead is divided into discrete components. Each component receives heat input Eqn. (12) for a time interval corresponding to the torch travel speed Eqn. (13),

$$\dot{q} = \frac{Q_{component}}{vol_{component} t_{weld}} = \frac{Q_{body\ flux} v}{vol_{seam} L_{component}} \quad (12)$$

$$t_{weld} = \frac{L_{component}}{v} \quad (13)$$

where $L_{component}$ is the length of components of the seam.

Temperature-dependent thermal properties and phase-change effects are included, allowing accurate prediction of FZ and heat-affected zone geometry without requiring calibration of complex heat source models. This approach significantly reduces setup time while maintaining reliability in thermal field estimation.

Mechanical analysis

The mechanical analysis employs the nodal temperature history obtained from the thermal simulation as input to compute the stress-strain response of the welded joint. An elastoplastic material model was adopted, based on the von Mises yield criterion and isotropic hardening, accounting for temperature-dependent mechanical properties. This constitutive model, widely used for simulating steel [23,24], is expressed by the incremental form of the stress-strain law Eqn. (14), where the total stiffness matrix combines elastic and plastic contributions (15), incorporating thermal strains through the thermal stiffness term.

$$d\sigma = [D^{\phi}] d\varepsilon - [C^{th}] dT \quad (14)$$

$$[D^{\phi}] = [D^e] + [D^p] \quad (15)$$

where:

- $[D^{\phi}]$ is the total stiffness matrix;
- $[D^e]$ is the elastic stiffness matrix;

- $[D^p]$ is the plastic stiffness matrix;
- $[C^{tb}]$ is the thermal stiffness.

Boundary conditions were carefully defined to replicate the experimental setup and ensure numerical stability, translations along the X, Y and Z axes were locked at the start of the weld bead, while translations along the X and Z axes were locked at the opposite end. Kinematic constraints were applied to eliminate rigid body motion, while surface-to-surface contact algorithms modelled the interaction with the support table, allowing for a realistic simulation of stress relaxation or accumulation during the cooling phases.

Temperature-dependent mechanical properties, such as Young's modulus, yield stress, and thermal expansion coefficient, were incorporated to capture the material behaviour under high thermal gradients, a critical aspect highlighted in [24]. Plastic deformation was considered throughout the cooling phase, as it significantly influences residual stress formation and final distortions. This approach enables accurate prediction of longitudinal and transverse residual stresses, as well as out-of-plane distortions, without requiring complex fully coupled analyses. By integrating thermal loads from the previous step, the model provides reliable estimates of stress redistribution, which are essential for assessing structural integrity and fatigue performance [25].

RESULTS AND DISCUSSION

This section presents the results of experimental tests carried out to assess the quality of the weld and a comparison between the data obtained from numerical simulation of the process and the experimental results in order to validate the model developed and demonstrate its reliability. The thermomechanical model was therefore validated using a phenomenological approach. No direct experimental comparison was made with residual stresses (due to the high experimental uncertainty and the purely local nature of techniques such as XRD diffraction or drilling, [26–28]). Instead, the focus was on heat inputs and the deformations they generate, which are intrinsically linked to the resulting stress fields.

Radiographic inspection

The internal quality of the dissimilar joint was evaluated via digital radiography, as shown in Fig. 4. The inspection confirmed the soundness of the welding process: no macroscopic volumetric defects such as porosity, blowholes, or lack of fusion were detected in the FZ. Crucially, given the high susceptibility of GJS500-7 cast iron to brittle fracture, the radiograph reveals a crack-free interface, validating the effectiveness of the chosen process parameters and filler wire.

In terms of radiographic contrast, the image distinguishes three distinct regions: the filler material (that appears darker due to the increased thickness provided by the seam's overlay metal), the S355 steel plate and the GJS500-7 cast iron plate (that reflect their mismatch in terms of material density and composition with a different type of grey). The blind holes drilled for thermocouple placement are also clearly visible.

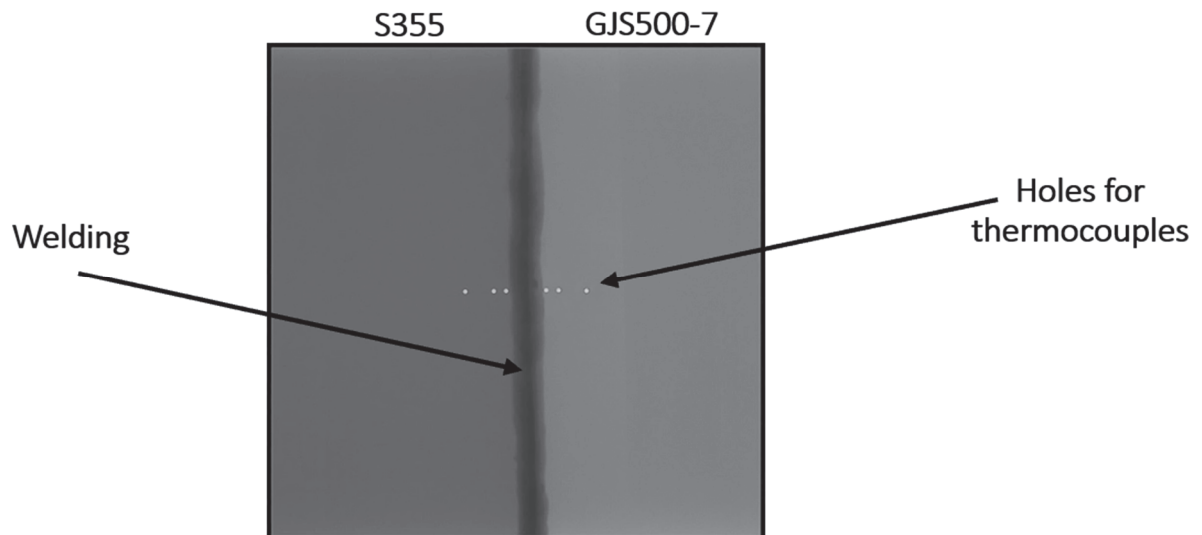


Figure 4: X-ray of the joint.

Macrography and hardness of the joint

The macrographic examination (Fig. 5) corroborated the radiographic findings, confirming a defect-free joint with adequate fusion at the sidewalls. Quantitative analysis of the cross-section allowed for the precise geometrical characterization of the weld passes: the penetration depth was measured at 3.8 mm for the first pass and 4.7 mm for the second pass. These experimental dimensions were directly employed to define the heat source parameters in the numerical model, ensuring geometrical fidelity.

The hardness survey (HV10), plotted in Fig. 5, reveals the microstructural evolution across the interface. On the S355 steel side, hardness values remained stable in the range of [150-250] HV10, typical of a ferritic-pearlitic structure, indicating that the thermal cycle did not induce significant hardening or embrittlement in the steel HAZ.

Conversely, a sharp discontinuity was recorded on the GJS500-7 cast iron side. As illustrated in the profile, the hardness spikes to a peak value of [370-380] HV10 in the HAZ adjacent to the fusion line. This dramatic increase, consistent with findings in various studies [29,30], is attributed to the partial dissolution of graphite nodules and the rapid cooling rates experienced by the interface. These conditions promote the local formation of hard, brittle phases—specifically ledeburitic carbides and untempered martensite—which represent the critical region for potential crack initiation.

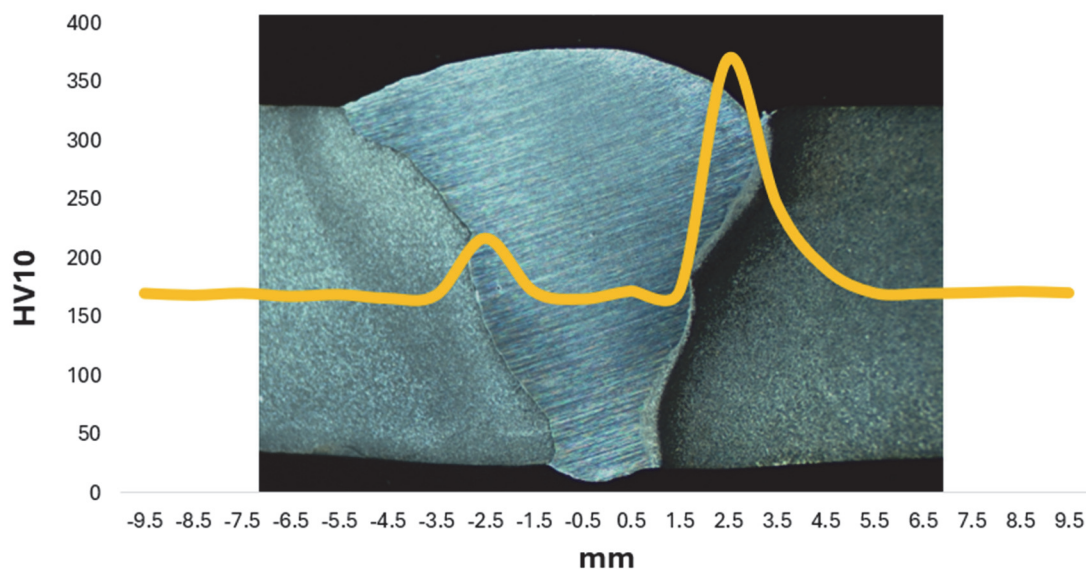


Figure 5: Macrography and hardness trends in the joint at $y = 100$ mm.

Thermal analysis

The reliability of the thermal finite element model was assessed through a quantitative comparison between the numerical thermal cycles and the experimental data recorded by the thermocouples, as depicted in Fig. 6. The plot highlights the characteristic double-peak temperature history induced by the two-pass welding procedure.

The correlation between the simulated and measured values is high. Specifically, the model exhibits excellent accuracy in predicting the peak temperatures (T_{peak}): the maximum discrepancy recorded across all monitoring points is less than 50 °C. It is worth noting that the slight deviations observed are primarily concentrated in the thermocouples positioned furthest from the weld bead. Conversely, the agreement becomes significantly tighter in the near-field region (proximal to the FZ). This is a crucial outcome, as the area immediately adjacent to the weld is the most critical for predicting microstructural transformations and residual stress formation. The fact that the highest accuracy is achieved in this zone confirms the model's reliability for the subsequent mechanical analysis. Furthermore, the simulation correctly captures the transient thermal gradients during both the rapid heating phase and the inter-pass cooling intervals. This confirms that the calibrated heat source model and the estimated heat transfer coefficients accurately represent the real energy input and dissipation phenomena. A further geometric validation was performed by evaluating the morphology of the HAZ. In the post-processing phase, the numerical HAZ was identified as the volume of material subjected to temperatures exceeding the eutectoid transformation point. This identification criterion follows the methodology already successfully applied and validated by the authors in previous investigations [23,31], allowing for a direct comparison with the experimental macrographs. As shown in Fig. 7, the boundaries of this simulated region match the real HAZ revealed by chemical etching



on the macro-section. The geometric correspondence confirms that the model correctly predicts not just the point-wise temperature, but the overall volumetric heat distribution within the dissimilar joint. A distinctive feature emerging from the numerical analysis is the marked asymmetry in the heat distribution transverse to the weld bead. Unlike the homogeneous joints studied in [32], where isotherms propagate specularly, the present hybrid joint exhibits a steeper thermal gradient on the cast iron (GJS500-7) side compared to the steel (S355). This discrepancy is consistent with recent findings in [10], which, despite employing different heat sources, observed a similar phenomenon attributed to the different thermal diffusivity of the two base materials. In the present case, the thermal conductivity of the spheroidal cast iron (which decreases differently from steel with temperature) acts as a 'thermal barrier', concentrating heat within the FZ and potentially extending the HAZ in a non-uniform manner.

Mechanical analysis

The mechanical accuracy of the FE model was validated by comparing the predicted out-of-plane distortions with the experimental measurements. The analysis focused on the displacement profile (U_z) extracted along a path transverse to the welding direction, located on the bottom surface of the joint at the mid-section.

To ensure a consistent comparison and eliminate potential offsets caused by rigid body motions during the measurement, a normalization procedure was applied: all measurements, both numerical and experimental, were taken relative to the position of the WCL.

As illustrated in Fig. 8, the numerical predictions show a strong correlation with the experimental profile. Quantitatively, the model demonstrates high fidelity, with a relative error of 9% on the steel side and remarkably only 3% on the cast iron side. The successful replication of this asymmetric distortion pattern confirms that the mechanical boundary conditions and the constitutive models were correctly defined, thereby validating the reliability of the simulation for the subsequent residual stress analysis.

The internal equilibrium of the welded joint results in a configuration where residual tensile stresses are distributed near the weld bead, balanced by compressive stresses in the areas furthest from the weld line. To strictly analyse this behaviour, the study examined two distinct paths: a transverse path (traced across the weld bead at the mid-section) and a longitudinal path (coinciding with the central axis of the welding trajectory).

Along the transverse path, the behaviour of the two materials shows marked differences.

Examining first the transverse residual stresses σ_x (Fig. 9a), it is observed that tensile values are predominant in the areas adjacent to the WCL. These stresses are generated by the restraint to contraction imposed by the base plates on the molten metal during cooling. As the distance from the FZ increases, the intensity of the stresses σ_x gradually decreases, tending towards zero.

Regarding the longitudinal residual stresses σ_y (Fig. 9b), the distribution displays a bimodal (or "M-shaped") profile. Instead of a single central peak, two distinct tensile peaks are evident in the HAZ. Contrary to what is often observed in homogeneous joints, the profile is asymmetric: the maximum stress peak is located on the spheroidal cast iron (GJS500-7) side, reaching a value of approximately 675 MPa, which is higher than that found on the S355 steel side, approximately 550 MPa. This asymmetry is attributable to the different metallurgical response of the materials: the microstructure of the cast iron HAZ, subject to local hardening, exhibits a higher local yield strength, allowing for the accumulation of higher residual stresses compared to the steel, which yields at lower levels.

A relevant aspect observed in the transverse profile is the marked discontinuity at the interface between the base material and the FZ. Although a stress variation is physically expected in dissimilar joints, the magnitude of this "jump" is further accentuated by the assumptions made during the modelling phase. Specifically, while experimentally the joint was performed using a Nickel-Iron based filler wire, the FE model adopted the thermo-mechanical properties of spheroidal cast iron for the FZ elements. This simplification, necessitated by the lack of specific high-temperature data for the diluted alloy in the literature, introduces a sharper property gradient at the interface with the steel compared to reality. However, the excellent correlation obtained in terms of deformations suggests that this local approximation did not compromise the global validity of the thermo-mechanical analysis.

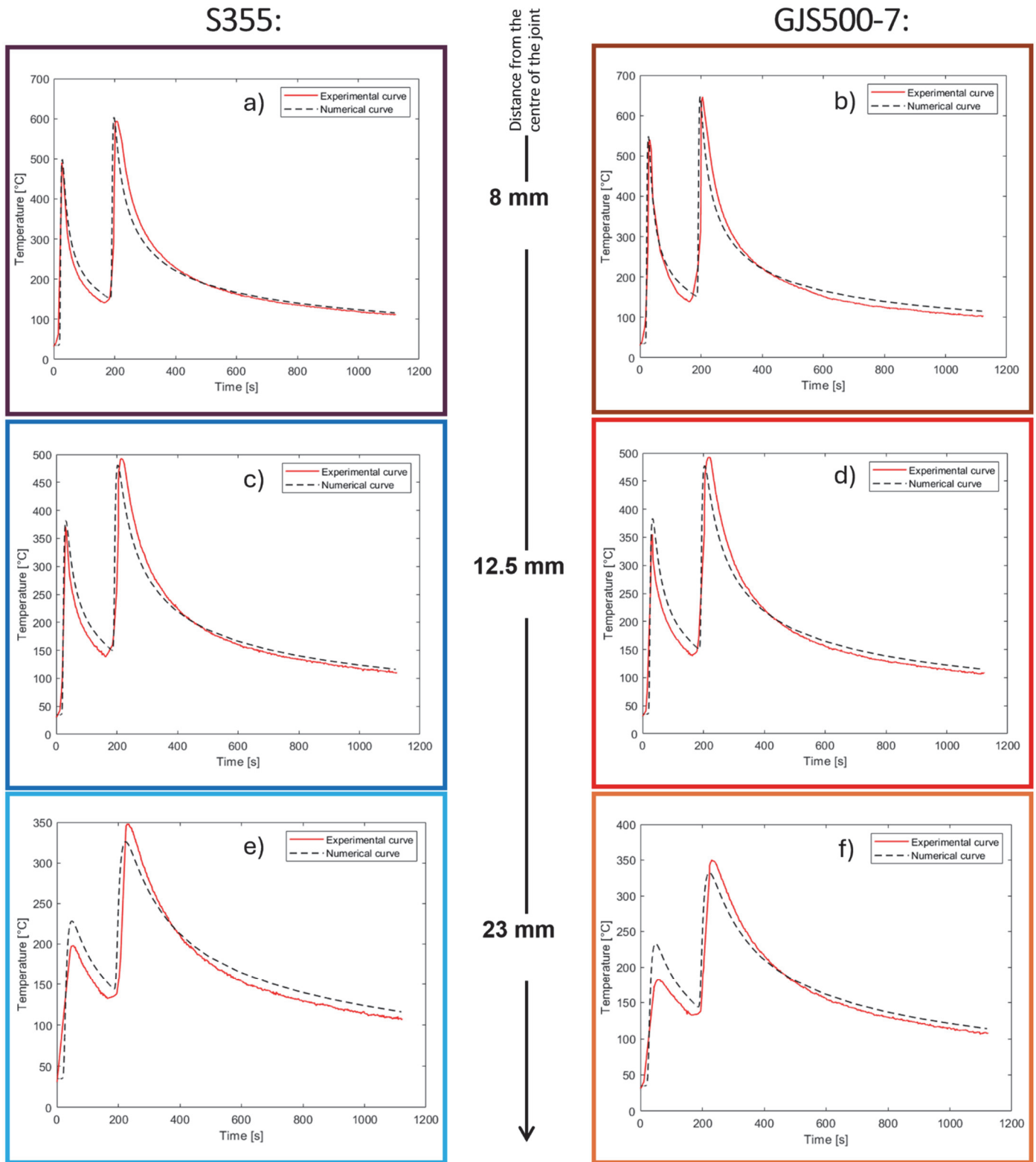


Figure 6: Comparison between experimental and numerical thermal history for steel a), b), c) at $x=-8\text{mm}$, $x=-12.5\text{mm}$ and $x=-23\text{ mm}$ and cast-iron d), e), f) at $x=8\text{mm}$, $x=12.5\text{mm}$ and $x=23\text{ mm}$.

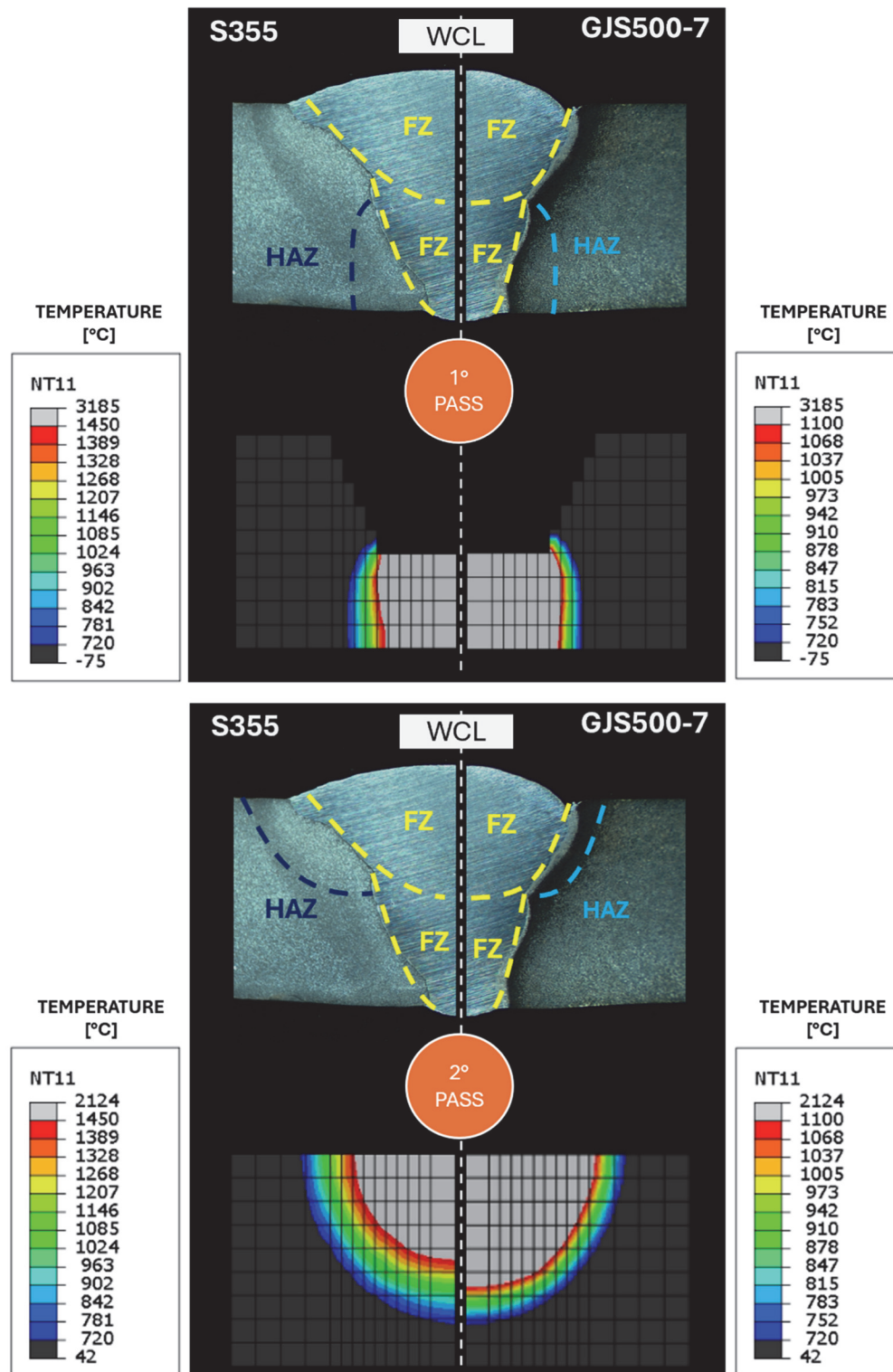


Figure 7: Comparison between experimental and numerical HAZ during 1st and 2nd passes at $y = 100\text{mm}$.

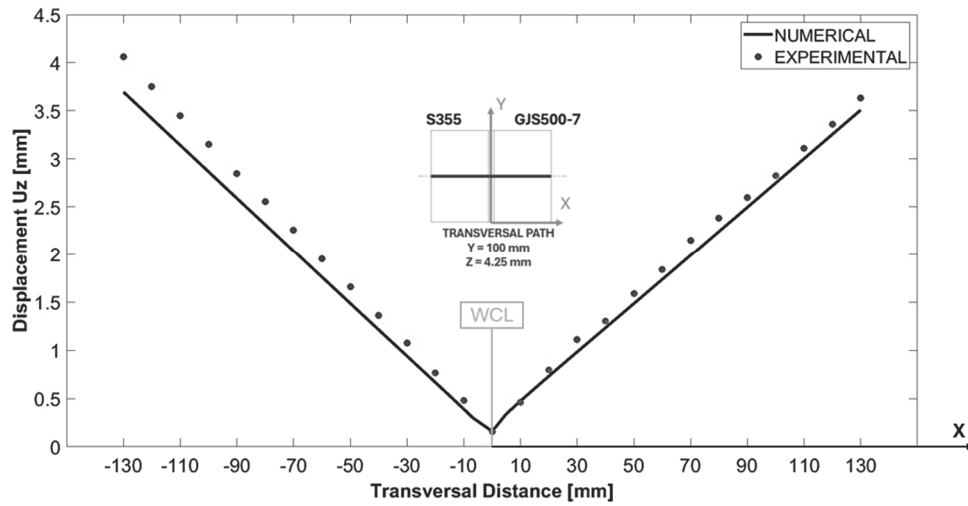


Figure 8: Comparison between experimental (points) and numerical (curve) U_z displacement.

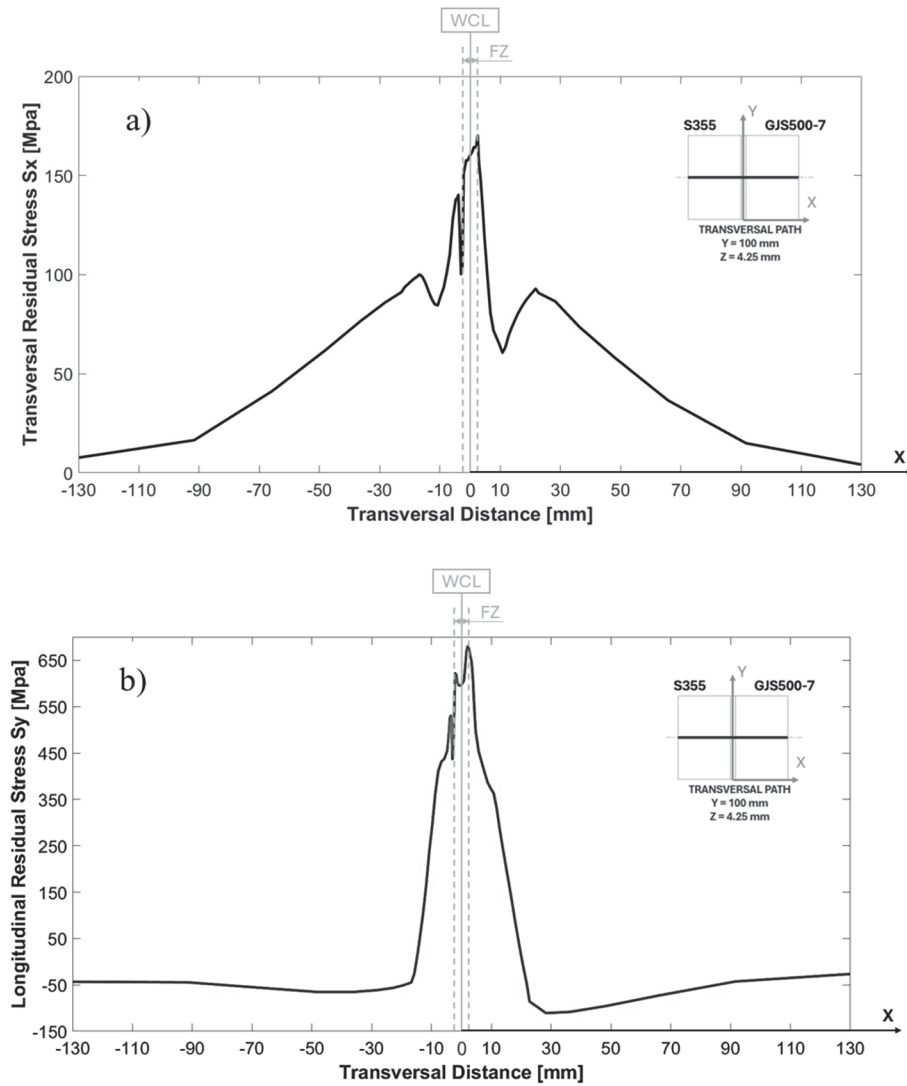


Figure 9: a) σ_x and b) σ_y stresses distributions along transversal path (along x-axis).

Along the longitudinal path (Fig. 10a-b), coinciding with the welding direction, the stresses show a stable trend in the central part of the joint (steady-state zone), with very high tensile values, before dropping in the run-in and run-out zones. It is important to note that, in the central zone, the longitudinal stresses σ_y are significantly higher than the transverse stresses σ_x . In some locations, they exceed the nominal yield strength of the base materials, confirming the presence of strong plastic gradients induced by the longitudinal constraint exerted by the surrounding cold material.

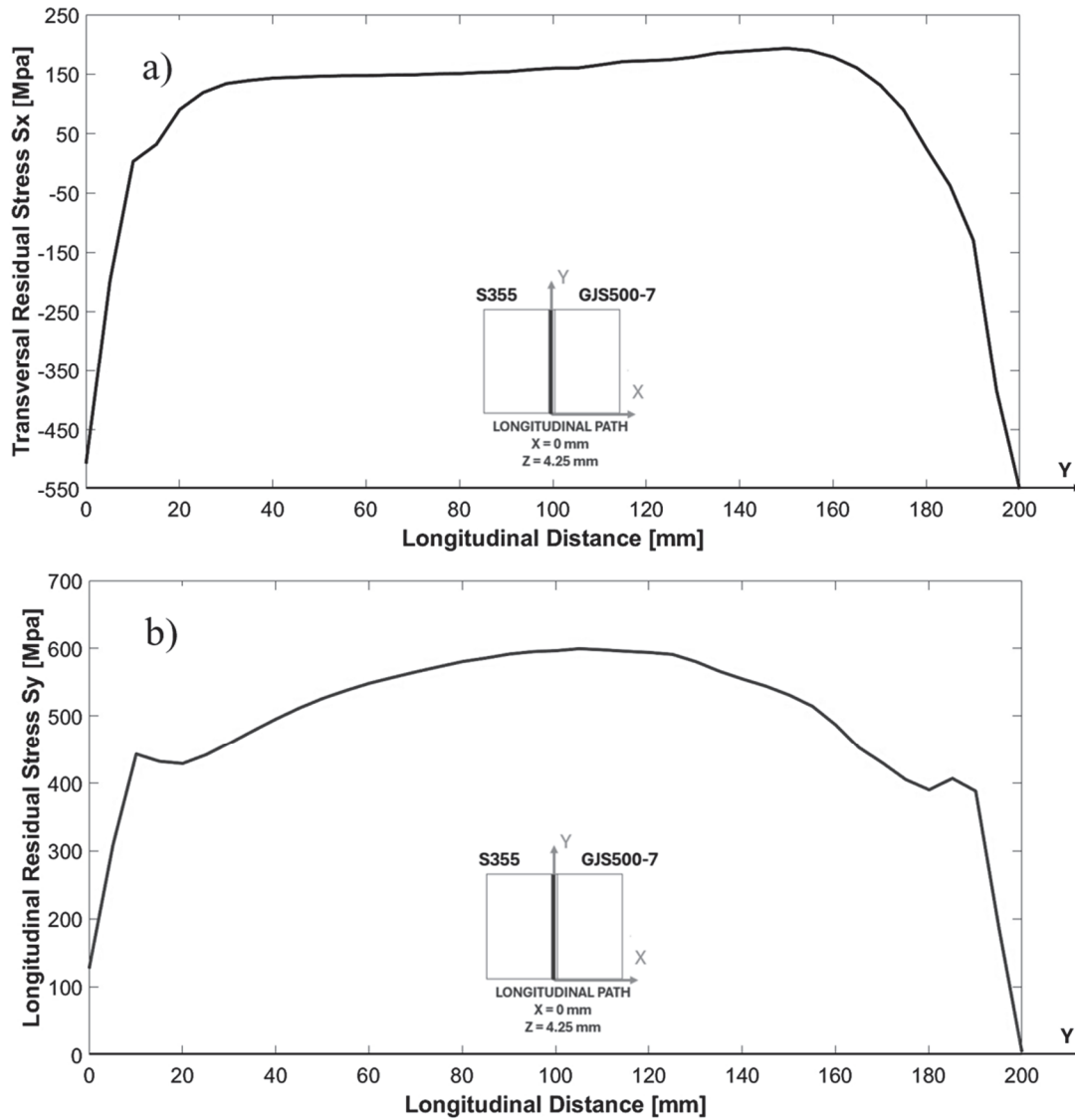


Figure 10: a) σ_x and b) σ_y stresses distributions along longitudinal path (along y-axis).

The results obtained find broad confirmation in the scientific literature. The influence of thermo-mechanical properties on the formation of asymmetric residual stresses is well documented by [33]. The bimodal distribution ("M-shape") with asymmetric peaks confirms that stress peaks tend to localize in the material with higher mechanical characteristics. Furthermore, the observation that longitudinal stresses reach values close to the yield strength aligns with classical FEM predictions [5]. Finally, the simplified approach for modelling the filler material is an accepted strategy to reduce computational complexity in the absence of specific data, as discussed in [12]. The good agreement with literature findings witnesses that the proposed approach is reliable and robust, although dissimilar joints obtained with materials like the ones used in the present study are still not deeply studied.



CONCLUSIONS

This research addressed the complexities inherent in joining dissimilar materials, specifically GJS500-7 spheroidal cast iron and S355 structural steel. The significant disparities in thermal and mechanical properties between these materials resulted in highly non-linear behaviour during the welding process, critically affecting temperature distribution, deformation, and residual stress formation.

The numerical model, developed using a sequential thermo-mechanical Finite Element approach, proved to be an effective tool for simulating the multi-pass welding process. The implementation of the progressive element activation technique ("element birth and death") allowed for a realistic reproduction of filler material deposition, optimizing computational costs without compromising accuracy.

Experimental validation confirmed the robustness of the model:

- thermal analysis: comparison with thermocouple data showed a strong correlation in terms of peak temperatures and cooling rates;
- mechanical analysis: verification of distortions revealed an error margin of less than 10%, demonstrating the model's reliability in predicting process-induced deformations;

The analysis of residual stresses provided new insights into the mechanical behaviour of the joint:

- bimodal distribution: the longitudinal stress profile exhibited an asymmetric "M-shape", with tensile peaks concentrated in the HAZs;
- material response: contrary to typical steel-steel joints, the maximum stress peak was observed on the cast iron side, driven by the higher local yield strength of the hardened microstructure;
- interface discontinuity: a stress discontinuity was observed at the interface, identified as a consequence of the modelling choice to assign cast iron properties to the filler material. This highlights the sensitivity of numerical results to material property assumptions in dissimilar welds.

In summary, this work demonstrates that a validated numerical approach is essential for the design of complex dissimilar joints. It allows for the prediction of critical stress concentrations and distortions, providing fundamental guidelines to ensure the structural integrity of hybrid Cast Iron-Steel components. The methodology and criteria used remain valid for the study of different joint configurations, as has already been done in previous studies, provided that the geometric model and the data obtained from the experimental process are adapted to the various application cases. Indeed, future applications may involve extending these concepts to geometrically more complex hybrid joint models.

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