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Finite Element and Experimental Analysis of Microstructural and Hardness Variations in Plasma Arc Welding of AISI 304 Stainless Steel

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Abstract: AISI 304 is widely regarded as the most common austenitic stainless steel and is utilized in various household and industrial applications, including food handling equipment, machinery components, and heat exchangers. Its popularity stems from its excellent mechanical properties, corrosion resistance, and ease of manufacturing. Given its diverse applications, it is crucial to study the microstructural evolution and mechanical properties of the welded zone, especially considering the potential for weld decay during fusion welding. In this context, two critical thermal-dependent factors for ensuring high-quality welds are grain growth and hardness variation in the heat-affected zone (HAZ) during the welding process. This paper presents an innovative finite element (FE) model developed to analyze the grain growth and hardness reduction that occur in the HAZ during plasma arc welding (PAW) of AISI 304 steel for solid expansion tube (SET) technology. Using the commercial FE software SFTC DEFORM-3D™, a user subroutine was created that integrates a physics-based model with the Hall–Petch (H-P) equation to predict changes in grain size and hardness. This study introduces a comprehensive numerical model, encompassing the user subroutine, heat source fitting, and geometry, which accurately predicts the thermal phenomena associated with grain coarsening and hardness reduction in the HAZ during the welding of austenitic stainless steel. The results from the numerical model, including the customized user routines, show good agreement with experimental data, leading to a maximum error prediction of 10 HV in hardness, 30 µm in grain size, and 10% in HAZ extension.

Keywords: plasma arc welding; grain size; AISI 304; solid expansion tube; finite element modeling; hardness; heat source model; heat-affected zone



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1. Introduction

The welding process is one of the most important techniques for material joining across various manufacturing sectors. Despite its relatively straightforward execution, the weld region near the joint undergoes complex thermo-mechanical cycles, typically causing non-uniform expansion during the heating phase and contraction during cooling. These cycles often lead to distortion and the formation of joint gaps [1–3]. Such issues can significantly affect both the functional performance and the service safety of the components. Therefore, understanding and controlling the thermo-mechanical processing of steels is critical to achieving the desired properties in welded components.

Although various welding processes are available today, they generally share the challenge of managing heat input, which can become uncontrolled and excessive in conventional metal inert gas (MIG) and tungsten inert gas (TIG) welding methods [4]. This excessive heat input can result in an enlarged HAZ with coarser grains, thereby degrading the mechanical properties of the welded joint. For example, Kong et al. [5] observed that coarsened grains in the HAZ significantly impair the fracture toughness of the welded joint. Davis and King [6] identified that during multi-pass welding, the intercritically

reheated coarse-grained HAZ is the most degraded region, while Bayraktar et al. [7] found that large grains near the welded joints can reduce the fatigue resistance of welds by approximately 20%.

To mitigate these challenges, high-energy density welding techniques, such as laser beam welding (LBW) and electron beam welding (EBW), are often employed. These methods offer several advantages, including a reduced HAZ and minimal weld distortion, which are especially beneficial for thin sheets [8,9]. However, their high equipment costs can limit their widespread adoption across various industries. In contrast, PAW has emerged as a highly effective technique, providing superior arc control and a smaller HAZ compared to conventional arc welding methods. Additionally, PAW provides notable advantages over conventional gas tungsten arc welding (GTAW) in terms of penetration depth and thermal distortion [10,11]. PAW is particularly valuable in solid expandable tube technology, where it ensures that tubes are easy to expand while retaining high strength after expansion to avoid process failures. Thus, understanding and controlling the microstructural evolution of the HAZ along the welding line of pre-expanded tubes is vital to prevent the formation of zones with increased susceptibility to cracking, which could compromise the tubes' formability and the overall manufacturing process [12]. As with all welding processes, for PAW, the research primarily focuses on gathering experimental and numerical evidence to better understand the key phenomena occurring during the process. The goal is to gain deeper insights into the influence of various process parameters on the final product, which is essential for meeting industrial needs to enhance productivity, reliability, and product quality.

Given this context, a comprehensive understanding of the thermo-mechanical aspects of the PAW process is essential to identify and mitigate issues, ensuring reliable outcomes. Furthermore, FE modeling has become a critical tool for predicting and analyzing not only the conventional manufacturing process as machining [13] but also the welding process. Significant progress has been made in both experimental and numerical research to investigate various aspects of the joining process, including distortion, residual stresses, heat source modeling, and clamping systems [14–16]. The literature highlights that microstructural changes within the HAZ play a significant role in the final properties of welded components.

Thus, developing a robust FE numerical model to predict and control the thermo-mechanical phenomena occurring during welding is crucial for ensuring optimal mechanical performance and product quality. This study aims to advance the scientific understanding of the welding process by introducing a novel numerical model that incorporates grain size evolution to predict microstructural changes and hardness variations in the HAZ during plasma arc welding of AISI 304 austenitic stainless steel, a material widely used in various industrial applications due to its excellent corrosion resistance, fabricability, and favorable mechanical properties at elevated temperatures. A customized user subroutine was developed and integrated into the commercial FE software SFTC DEFORM-3D™ to effectively predict grain growth and hardness changes throughout the welding process. Additionally, this work outlines the numerical procedures for defining the heat source, including its geometry and movement. To validate the model, numerical predictions were compared with experimental data, demonstrating the effectiveness of the proposed approach. This ensures the successful production of expanded tubes, helping to avoid the increased costs and time typically associated with damaged components at the end of the manufacturing process. The novelty of the proposed work lies in a new numerical approach that separately predicts grain growth, hardness variation, and HAZ extension using unconventional welding software, illustrating their evolution due to the thermal phenomena occurring during the PAW process.

2. Experimental Procedure

PAW experiments were conducted on AISI 304 austenitic stainless steel (Table 1) using a fully automated torch movement system (SITEC BSL 1000 LTC) with a plasma welding torch (THERMAL ARC 4A DUAL FLOW TORCH). The welding was performed on a sheet with a hardness of 220 [HV_{0.1}] and a thickness of 0.5 [mm], which was appropriately folded to create tubes with a diameter of 130 [mm], as shown in Figure 1.

Table 1. AISI 304 material chemical composition (weight %).

Elements	Cr	C	Mn	Si	Ni	P	S
Weight %	18.35	0.06	0.86	0.03	8.20	0.03	0.01

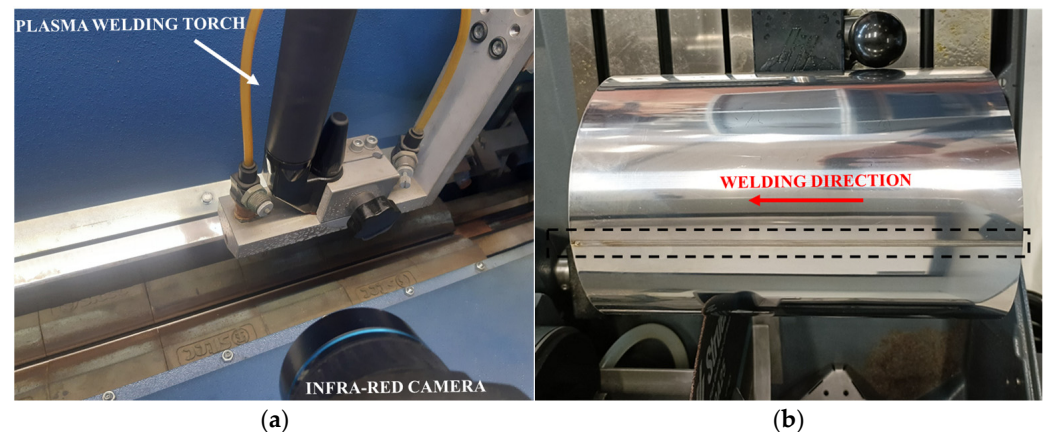


Figure 1. (a) Experimental set up and (b) sample geometry.

The welding process parameters included a current of 115 A, a weld speed of 69.33 mm/s, and a plasma gas flow rate (argon and Enermix H5) of 15 L/min. Pure argon was used as the shielding gas, with a flow rate of 4 L/min. To ensure the reliability of the experimental data, three replications were performed, as the accuracy of the proposed FE strategy depends on the precision of the experimental outcomes used for calibration. The thermal field during welding was captured using a FLIR A655sc infrared camera (IRC), enabling the evaluation of temperature profiles on the welded surfaces. The material's emissivity was calibrated by comparing measurements from a thermocouple and the infrared camera for a sample heated in fixed temperature increments, resulting in an emissivity value of 0.44. A temperature acquisition range of 100–650 °C was set to analyze the cooling phase, which is the primary cause of distortion in welded components.

Thermal analysis was employed to calibrate the model using an iterative trial-and-error procedure. This method was applied to assess both the temperature and the convection coefficient of the heat exchange windows incorporated into SFTC DEFORM-3D™ for modeling the welding heat source. After welding, three samples, each 30 mm in length (along the welding direction, as shown in Figure 1), were cut for each experimental test, resulting in a total of nine samples. The transverse sections of the samples were embedded in black bakelite resin for microstructural investigation and hardness measurement. Metallographic preparation involved mechanical polishing followed by etching with a V2A reagent (119 mL distilled water, 12 mL nitric acid, and 119 mL hydrochloric acid). The cross-sections were examined using an optical microscope (Leica DFC320) at magnifications of 500× and 1000× to analyze weld bead geometry, HAZ extension, and grain size evolution. Figure 2 presents a micrograph obtained from the optical microscope, clearly distinguishing the weld metal (melted area), the HAZ, and the base metal (unaffected material). The HAZ size was approximately $477 \pm 33 \mu\text{m}$, determined by assessing both grain size evolution and hardness variation.

Micro-hardness [$HV_{0.1}$] was measured using an instrumented micro-indentation tester (MHT, Anton Paar GmbH).

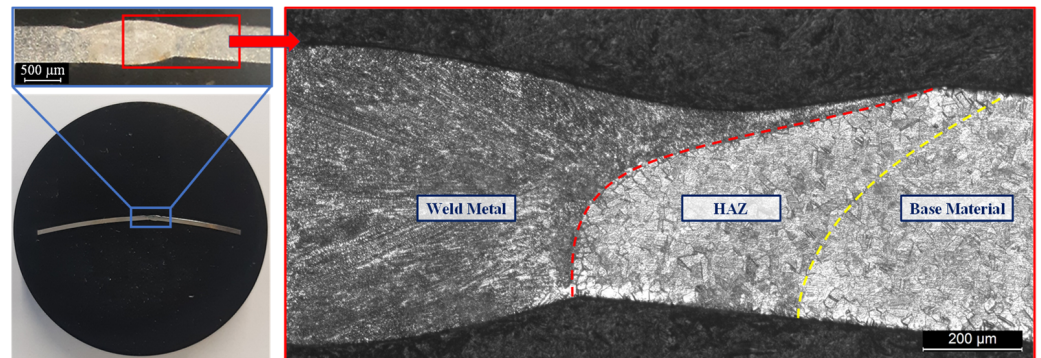


Figure 2. Transverse section metallographic analysis of the welded samples.

Figure 3 illustrates the grain size evolution across the different zones affected by the welding process. Grain size measurements were conducted using the commercial software ImageJ, which identifies individual grains based on their boundaries (Figure 3a). It shows an equiaxial grain structure in both the base material and HAZ, while a lamellar structure is observed in the weld metal. Specifically, Figure 3a represents the grain size in the unaffected zone (base material), with an average value of $60\ \mu\text{m}$. In contrast, Figure 3b highlights the coarser grains in the HAZ, with an average size of $145\ \mu\text{m}$, resulting from the elevated temperatures that promote grain growth. Finally, Figure 3c shows the lamellar grain structure in the weld zone.

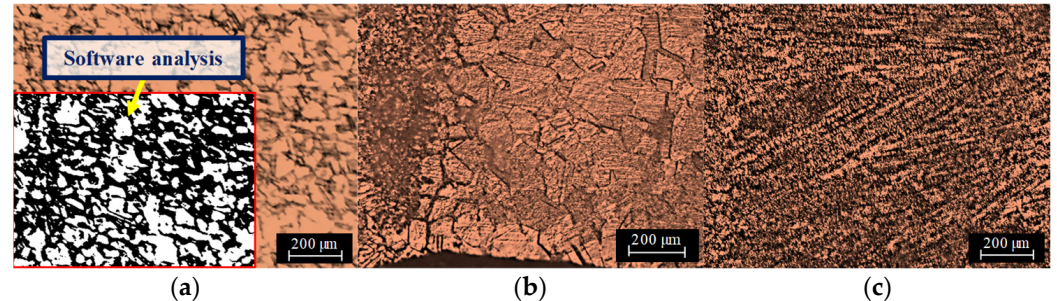


Figure 3. Transverse section grain size: (a) base metal; (b) HAZ; and (c) weld metal.

Micro-hardness measurements were conducted using an indentation matrix of 37×2 points, as shown in Figure 4. Hardness significantly decreased from the base metal (220 [HV]) to the HAZ (200 [HV]), a reduction of 20 [HV] (−10%). In contrast, the weld metal exhibited a hardness value of 240 [HV], which represents an increase of 40 [HV] (+20%) compared to the HAZ and an increase of 20 [HV] (+10%) compared to the base metal. These results clearly demonstrate the effects of thermal phenomena on HAZ softening, leading to a reduction in material strength due to both decreased hardness and grain growth. In fact, material strengthening is inversely related to the square root of grain size.

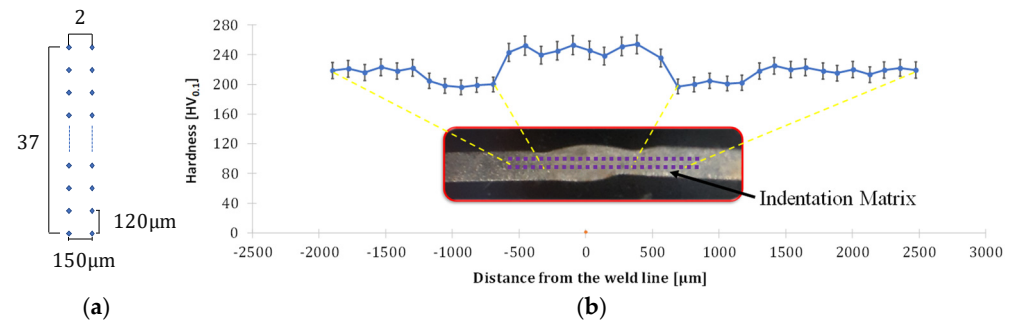


Figure 4. (a) Hardness indentation matrix and (b) transverse section indentation measurement.

This relationship aligns with the additive material flow stress model proposed by Hansen [17], which expresses how changes in grain size influence material properties, as shown in Equation (1).

$$\sigma_{gs} = kd^{-\frac{1}{2}} \quad (1)$$

In this equation, σ_{gs} represents the contribution from grain size-related strengthening, k is the strengthening coefficient, and d is the average grain size. Both microstructural analysis (including weld bead geometry, HAZ extension, and grain size evolution) and micro-hardness measurements provided valuable insights, enabling more accurate calibration of the heat source power and shape, thus achieving metallographic results that closely match experimental observations.

3. Numerical Model

The commercial FE software SFTC DEFORM-3D™ was employed to simulate the PAW process of AISI 304 austenitic stainless steel. The sheet was modeled as a plastic body discretized using 168,000 iso-parametric tetrahedral elements (Figure 5).

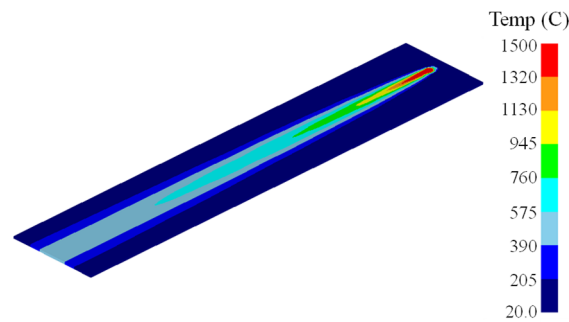


Figure 5. Finite element modeling.

To simulate the PAW process, a three-dimensional Gaussian conical heat source model was utilized, where r_e and r_i represent the upper and lower cone radii, respectively, and z_e and z_i denote the cone length parameters (Figure 6a). This heat source model was implemented in the software by defining a series of 3D heat exchange windows that replicated the shape of the Gaussian model (Figure 6c). The heat source was characterized by a movement velocity of 69.33 mm/s, in accordance with the experimental welding speed parameters.

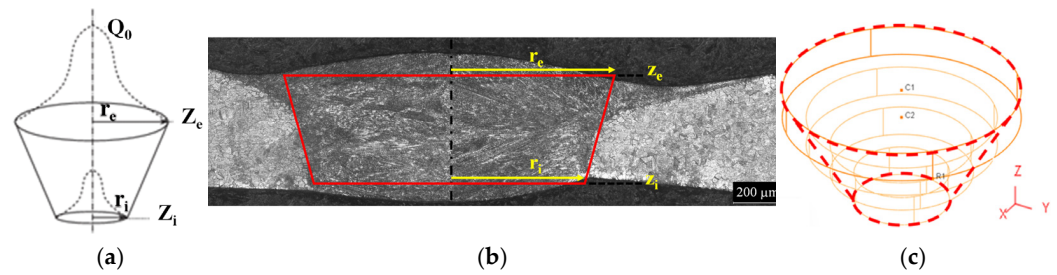


Figure 6. (a) Three-dimensional conical heat source model; (b) measurements of the Gaussian parameters; and (c) DEFORM heat exchange windows for heat source modeling.

All the aforementioned heat source parameters, along with the temperature and convection coefficient of the heat exchange windows, were determined experimentally, taking into account the weld bead geometry, HAZ size, temperatures, and grain size.

Specifically, the parameters r_e , r_i , z_e , and z_i were measured on the welded component (Figure 6b). Meanwhile, the temperature and convection coefficient of the heat exchange windows were calibrated using an iterative trial-and-error method, comparing numerical and experimental data for HAZ size, grain size, hardness, and temperatures (Figure 7).

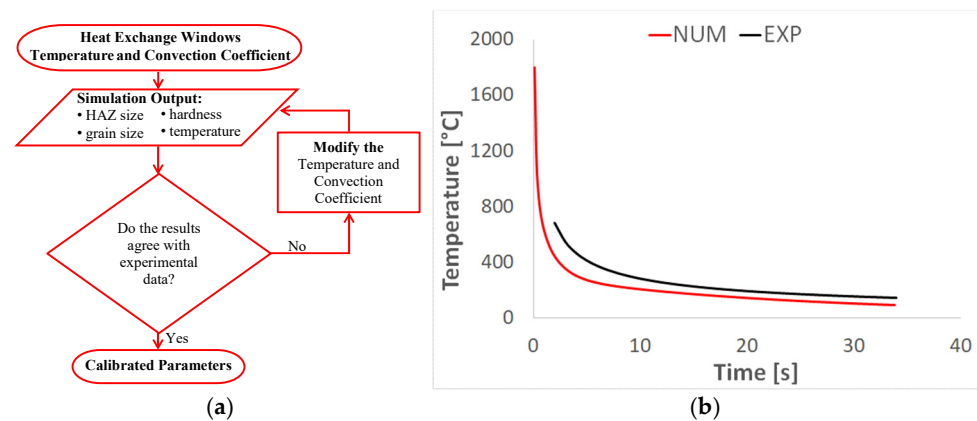


Figure 7. (a) Calibration procedure for the temperature and convection coefficient of the heat exchange window; (b) numerical and experimental comparison of the temperature.

The thermal phenomena influencing the microstructure (i.e., grain size) of the HAZ were predicted by implementing a customized user subroutine based on the classical kinetic theory for grain growth [18,19], as described in Equation (2)

$$D^m - D_0^m = t \cdot k \quad (2)$$

where D is the current grain size, D_0 is the initial grain size, m is the grain growth exponent, k is the kinetic constant, and t is the soaking time.

The grain growth kinetic constant k can be expressed in Arrhenius form as a function of temperature, as shown in Equation (3)

$$k = k_0 \exp\left(-\frac{Q}{RT}\right) \quad (3)$$

where k_0 is a constant, Q is the activation energy for grain growth, R is the universal gas constant, and T is the absolute temperature.

Using Equation (3) in Equation (2), it is possible to obtain the expression for grain growth kinetics, given by Equation (4).

$$D = \sqrt[m]{tk_0 \exp\left(-\frac{Q}{RT}\right)} + D_0^m \quad (4)$$

All parameter values used in Equation (4) are listed in Table 2.

Table 2. Numerical parameters for grain growth kinetics.

Q [J/mol]	R [J/mol × K]	m	D ₀ [mm]
285,000 [20]	8.314	4.5 [19]	0.06 [Exp]

For the product $t \times k_0$, a constant value of 5×10^7 was considered and validated during simulations. Finally, the modification of hardness based on grain size evolution was calculated using the Hall–Petch equation, which describes hardness as an inverse function of grain size as follows (Equation (5)):

$$HV = C_0 + \frac{C_1}{\sqrt{d}} \quad (5)$$

where C_0 and C_1 are material constants while d represents the average grain size. The values of C_0 and C_1 , were determined from previously measured hardness and grain size data for both the HAZ and base metal, resulting in values of 163.6 and 433.84, respectively.

Equations (4) and (5) were both implemented in the FE software SFTC DEFORM-3D™ using a customized *usr_upd* user subroutine.

The proposed numerical procedure successfully simulated the evolution of grain size in both the base material and the HAZ, which are characterized by equiaxial grains. However, this approach is limited by the grain size prediction equations used in this study, as they are unable to replicate the lamellar grain structure observed experimentally in the weld zone (Figure 3c). On the other hand, the hardness of the weld zone was accurately simulated by assigning the constant and uniform experimental value across all numerical nodes and elements within that zone.

4. FE Validation and Results

The FE model was validated by comparing experimental results—such as HAZ extension, grain size evolution, and hardness variations—with the corresponding numerical data. Figure 8 presents a comparison between the predicted shape of the HAZ and melting zones from the numerical model and the results from metallographic analysis, showing a strong agreement between the predicted and experimental data. Figure 9 illustrates the predicted grain growth regions and the corresponding hardness variations. These results highlight the reliability of the developed numerical model and user subroutines in accurately predicting the thermal phenomena during the PAW process, as well as the associated metallurgical changes in the HAZ.

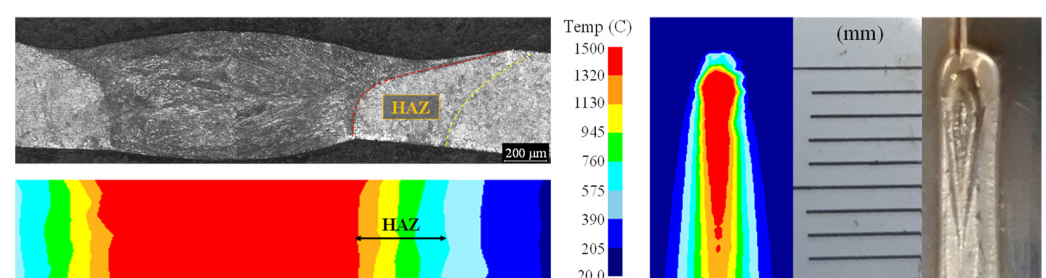


Figure 8. Validation of the predicted HAZ along with the shape and size of the welding zones.

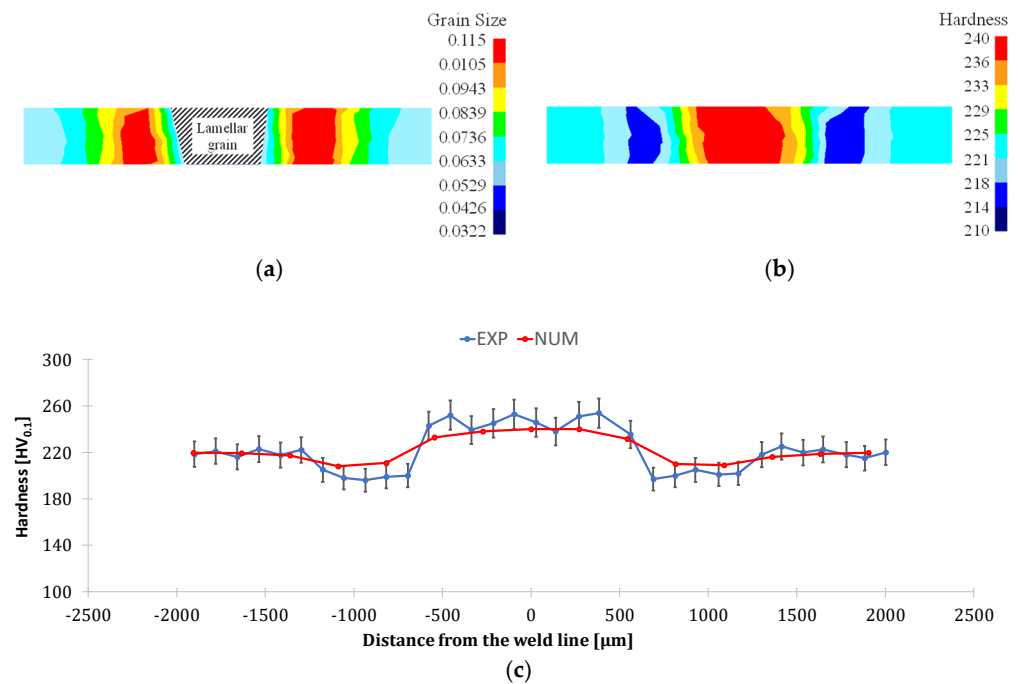


Figure 9. Numerical predicted (a) grain size in mm, (b) hardness [HV0.1] evolution, and (c) comparison between measured and predicted hardness variation.

The elevated temperatures during the welding process led to the formation of a new microstructure characterized by coarser grain sizes, which, in turn, affected the material's hardness. This trend aligns with experimental observations, resulting in a softer HAZ, as described by Equation (5). Although there is a slight discrepancy between the numerical and experimental results, several factors may account for this variation, including (i) the accuracy of the experimental data, (ii) the calibration process for defining the numerical constants in the FE model and user subroutine, (iii) the geometry of the numerical heat source, and (iv) mesh discretization.

Despite these minor discrepancies, the numerical results are consistent with experimental findings, indicating that following the PAW process, the microstructure evolves, leading to an increase in average grain size, particularly in the HAZ, where the grains are coarser compared to the base material. As expected, and in accordance with the Hall–Petch relationship, this grain growth results in a decrease in hardness. This observation suggests that the thermal phenomena associated with the PAW process significantly alter both the microstructural and mechanical properties of the HAZ, which in turn leads to a degradation of the mechanical performance of the welded joint, as discussed in [5–7]. This effect is particularly detrimental in solid expansion tube technology, which is subject to tensile circumferential and radial stresses. These stresses can cause rupture along the HAZ, as the reduction in material strength due to grain growth makes the HAZ more susceptible to failure.

5. Discussion

The experimental results revealed coarser grains in the HAZ, with an average size of 145 μm, compared to the finer grains in the unaffected zone (base material), which had an average size of 60 μm. Furthermore, the hardness values exhibited a significant decrease from the base material (220 HV) to the HAZ (200 HV), representing a reduction of 10%. In contrast, the weld metal showed a hardness of 240 HV, which is an increase of 20% compared to the HAZ and 10% compared to the base material. These results clearly demonstrate the effects of thermal phenomena on HAZ softening, leading to a reduction in material strength due to both decreased hardness and grain growth. Based on these experimental findings, a numerical model was developed using SFTC DEFORM-3D™,

with a particular focus on the accuracy of the heat source model calibration. Key factors such as geometry, positioning, movement, temperature, and the convection coefficient of the heat exchange windows were carefully considered. The experimental macrograph of the weld bead, the size of the HAZ, and the thermal history of the process were crucial for ensuring the success of the procedure. At the conclusion of this approach, the extension and shape of the numerical HAZ aligned closely with the corresponding experimental test, thereby validating the accuracy of the numerical model. Moreover, the model enabled the analysis of hardness variation and grain size evolution. The numerical results, according to experimental outcomes, indicated a new microstructure characterized by coarser grains in the HAZ, which led to a corresponding decrease in hardness according to the H-P relationship. The data from the developed numerical model, including the customized user routines, were in good agreement with the experimental data. The maximum error in hardness prediction was within 10 HV, while the discrepancy in grain size was around 30 μm and the HAZ extension error was approximately 10%. In summary, the thermal phenomena occurring during the PAW process result in significant microstructural and mechanical property changes, which impact the mechanical performance and overall quality of the final welded components according to [21–25].

6. Conclusions

In this study, a numerical model was developed to simulate grain size evolution and hardness changes within the HAZ during plasma arc welding of commercial AISI 304 austenitic stainless steel plates for solid expansion tube technology. The analysis was performed using the commercial finite element software SFTC DEFORM-3D™, complemented by a customized user subroutine designed to predict grain size evolution based on classical kinetic theory and hardness changes using the Hall–Petch relationship. In particular, the model validated the capability to represent the 3D conical heat source model through a series of heat exchange windows available in the software. A strong correlation between the predicted and experimentally measured HAZ sizes further confirmed the model's accuracy in simulating the heat source shape and its impact on the thermal field. Additionally, the numerical results were validated against experimental data, demonstrating the success of the customized model and user subroutines in predicting grain growth and hardness reduction within the HAZ due to the high temperatures generated during plasma arc welding. As a result, the proposed finite element strategy proves to be an effective tool for simulating the plasma arc welding process of AISI 304 austenitic stainless steel plates, accounting for microstructural changes that influence material performance. This developed numerical tool holds significant potential for enhancing the monitoring and control of desired microstructures and associated mechanical properties in welded products, ultimately contributing to the production of tubes with excellent expansion performance and adequate post-expansion strength. Finally, it is important to emphasize that the proposed approach is limited by the grain size equations used in this study, which are unable to replicate the lamellar grain structure observed in the weld zone. This type of structure is characterized by two dimensions (length and width). Future work will focus on developing and implementing numerical microstructure models to predict the formation and evolution of lamellar grains and phase composition in the weld zone, thereby providing a comprehensive understanding of the thermally affected zone and its influence on the mechanical behavior of the welded component.

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