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Enhancing Welding Efficiency and Reliability in Unstructured Environments: A Computational Analysis of Spot-Welded Steel Sheet Connections

Abstract: - High-strength steels play a crucial role in various industries such as shipbuilding, construction, and aerospace due to their unique properties. Welding of these steels in unstructured workspaces presents challenges in terms of variability in workpiece position, shape, and environmental conditions. The research utilizes a portable robotic welding system with a novel seam-tracking method to address the challenges of welding in unstructured workspaces. Additionally, the study involves the analysis of different steel grades, including tool steels, stainless steel 440A, to understand their mechanical properties and applications. Experimental results demonstrate the effectiveness of the portable robotic welding system in accurately tracking welding seams in various positions. The study also provides insights into the mechanical properties and applications of different high-strength steel grades, emphasizing the importance of understanding spot weld behavior for improved structural performance. The findings underscore the significance of welding parameters, base-metal properties, and welding characteristics in determining the quality and durability of spot-welded joints.

Keywords: High-Strength Steels, Welding Parameters, Base-Metal Properties, Mechanical Properties, Computational Analysis.

1. Introduction

High strength steels are important in building and construction due to their advantages such as lightness, strength, durability, physical stability, sustainability, and cost-effectiveness [1]. These steels, particularly cold-formed steel (CFS) profiles, are increasingly being used in structural systems and non-structural architectural components, including earthquake resistant buildings [2]. The use of CFS based buildings has been growing in recent years, especially in earthquake resistant buildings where lightness plays a key role. Additionally, the industrialization of construction has led to the development and application of prefabrication techniques, such as the Prefabricated Rebar Cage (PRC) method for high-rise buildings. The PRC method offers benefits in terms of reduced carbon emissions during on-site construction, making it a sustainable option for high-rise buildings. Overall, the importance of high strength steels in building and construction lies in their ability to provide lightweight, strong, and sustainable solutions for various constructional elements. Spot welding is commonly used to join steel sheets in auto bodies. However, the welding process in heavy industries, such as shipbuilding and construction, is conducted in unstructured workspaces, which are irregular, changeable, and unmodeled [3]. This poses challenges for welding, as the workpiece position and shape, as well as the environmental background and illumination, can vary. Manual operation is currently used for welding in these conditions, resulting in high cost, low efficiency, and inconsistent quality. To address these issues, a portable robotic welding system and a novel seam-tracking method have been proposed. This system can track general and complex spatial weld seams, adjust working parameters to avoid collisions, and use point cloud registration to locate multi-segment weld seams globally. Experimental results show that the robot can accurately track welding seams even when deployed in different positions. Tool steels, including H11 and H13 grades, are commonly used for hot work applications due to their good hardness/toughness compromise at working temperature [4]. These steels are designed to withstand high cyclic stresses and increased tool surface temperature, making them suitable for forging, die casting, and extrusion dies. On the other hand, 440A stainless steel is a high-strength steel grade used in aerospace for critical parts such as landing gear components and control surface hinges [5]. It offers extremely high strength and stiffness, meeting the requirements for landing gear steels. The development of hot rolled high strength and ultra-high strength steel grades, such as ALFORM700M and ALFORM900M, has also been a focus, with a minimum yield strength of 700MPa and 900MPa, respectively [6]. These grades are used in automotive, truck, construction, and engineering industries. The wear resistance, hardness, and durability of tool steels are achieved through the presence of carbide-forming alloys such as chromium, molybdenum, tungsten, and vanadium [7]. The need for a better understanding of spot weld behavior is underscored by the complex three-dimensional stress field in spot welds, which can significantly impact their structural performance and failure modes [8]. This understanding is crucial for crash analysis, where spot welds are often subjected to loads beyond their yield strength [9]. Detailed modeling techniques, such as those using Gurson's material model, can help predict strain rate effects and eliminate

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imperfections, leading to more accurate spot weld models [10]. Furthermore, the accuracy of spot weld models in dynamic analysis can be improved by optimizing the physical parameters based on experimental data [11].

Prior research has extensively explored the failure behavior of spot welds in tensile testing for spot welded steel sheet connections. Tao (2008) and Marashi (2010) [12,13] both investigated the failure modes and mechanisms of spot welds, with Tao focusing on deformation and failure in tension and shear, and Marashi on the failure behavior of dissimilar thickness welds. Zhang (2014) [14] further analyzed the failure modes of dissimilar thickness dual-phase steel welds, identifying interfacial, partial interfacial, and pullout failure modes. Song (2008) [15] evaluated the dynamic failure load of spot welds under combined axial and shear loading conditions, finding that the failure contour expands with increasing strain rates. These studies collectively provide a comprehensive understanding of the factors influencing spot weld failure in tensile testing. A range of studies have explored the impact of steel grade on weld strength for spot-welded steel sheet connections. Kong (2007) [16] used a computational approach to predict the effects of welding parameters on joint strength, while De (1996) [17] focused on the influence of welding current, electrode force, and weld time on weld strength. Mukhopadhyay (2009) [18] found that the strength of spot-welds in interstitial free steels remained consistent across different loading modes but increased with nugget size. Khan (2008) [19] further investigated the effects of welding microstructure on the performance of resistance spot welded joints in advanced high strength steels, highlighting the importance of steel grade in determining joint strength and failure mode. Tensile testing is a crucial method for characterizing the mechanical properties of spot-welded steel sheet connections. Javaheri (2019) [20] and Acharya (2013) [21] both used tensile tests to assess the mechanical properties of spot welds, with Javaheri focusing on the effect of resistance spot welding on DP1000 steel and Acharya on the estimation of tensile and yield strength of weld nuggets. Davidson (1984) [22] found that the fatigue life of spot-welded sheet steels was influenced by base-metal tensile properties, while Bayraktar (2004) [23] applied impact tensile testing to evaluate the behavior of thin welds in dynamic loading conditions. These studies collectively demonstrate the importance of tensile testing in understanding the mechanical properties of spot-welded steel sheet connections.

The objective of the research is to develop a simulation model that accurately predicts the tensile strength and failure modes of spot-welded connections in steel sheet, and to understand the effects of parameters like sheet thickness, weld size, and electrode force on the static and fatigue strength of resistance spot welds. This is achieved through a combination of physical tensile testing and mathematical modeling, with a focus on the impact of design changes on fatigue strength. The study also investigates the influence of welding parameters on the quality of welding joints, including nugget size and mechanical properties. Additionally, the research characterizes the material properties of different weld zones and their impact on the tensile-shear strength of welded joints. Finally, the study explores the use of dynamic contact resistance as a means of monitoring the quality of spot welds.

1. Model Construction

The methodology in the research paper involved the utilization of computational analysis software, specifically Ansys Workbench, for finite element analysis simulations to evaluate the tensile behavior of different steel grades under varying loading conditions. This computational approach allowed for the modeling and analysis of the mechanical properties of spot-welded connections, providing insights into the effects of welding parameters on joint strength and reliability. Additionally, the study incorporated numerical simulations to analyze thermal properties and heat transfer phenomena, aiding in engineering decisions and validating theoretical models.

1.1. Simulation Design

The tensile strength properties of stainless-steel grade 440A and tool steel grade D2 were analyzed using the finite element analysis software. The simulation process involved initializing Ansys workbench Static Structural analysis system and setting up the model. Two materials were defined to represent the stainless steel and tool steel grades, with specific values for elastic modulus, Poisson's ratio, and plastic strain. The analysis aimed to evaluate the tensile behavior of the two steel grades under different loading conditions which can be useful for design and engineering applications.

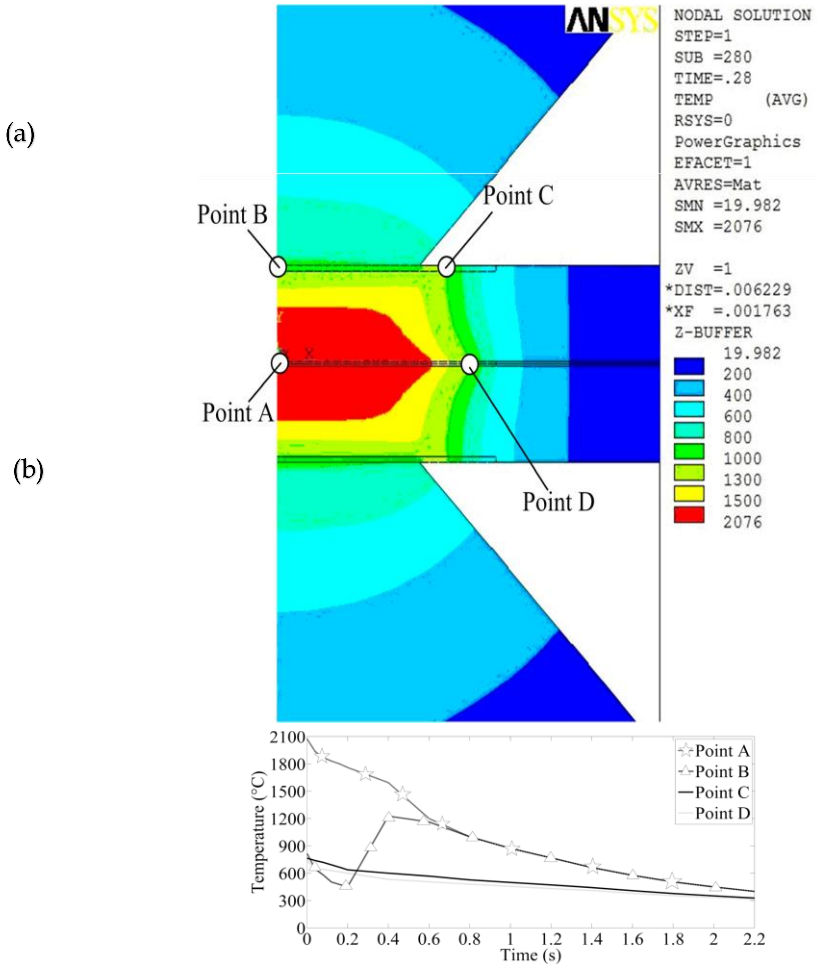

Fig (1). Modeling (FEA) of samples.

The results are from a finite element analysis simulation, representing thermal analysis. Figure (a) plots a temperature 600-2100 C contour over a model geometry using various visualization settings. The range and distribution highlight areas for further investigation, like points A-D. Figure (b) presents graphs the temperature profiles over time (0-2.2) at points A D, revealing different cooling rates that plateau at varied temperatures. Together, the figures represent for studying thermal properties using numerical simulations. Analyzing the trends aids engineering decisions and validates theoretical models on heat transfer phenomena.

1.2. Geometry simulation of field

The tensile strength test for stainless steel sheets (440A) and tool steel (D2) can be investigated using ANSYS Workbench. A new Static Structural analysis system should be created, and two materials should be defined: stainless steel grade 440A and tool steel grade D2. A solid model for the tensile test specimen based on standard dimensions should be created, and fixed constraints should be applied on one end of the specimen. Tensile loading should be applied on the other end, and the model should be meshed, and solution settings should be set up. The von Mises stress, total deformation, and equivalent plastic strain should be solved for. The results should be reviewed and compared between the 440A and D2 models, with 440A expected to have a higher ultimate tensile strength. Accurately defining the nonlinear material models in ANSYS using the provided mechanical properties is crucial, and fine-tuning of the mesh and solution settings may be necessary.

Table (1). Effect of Welding Parameters on Weld Diameter for Different Steel Grades.

Steel grade	Carbon (%)	Welding (W)/Weld bonding (W-B)	Thickness of the layer/ mm	Clamping force Fz, kN	Welding current Iz, kA	Welding time tz, ms	Diameter of the weld, mm
440A	0.95	W-B	2	3.2	8	200	2
D2	1.50	W-B	2	3.2	7	200	2

1.3. Materials Properties

The plastic strain of stainless steels, typically 12-16%, is influenced by various factors. Samuel (2005) [24] suggests that the "hardness state" of the material, expressed as an equivalent plastic strain, plays a significant role in this behavior. This is supported by Simmons (1997) [25], who found that the strain hardening rate and strength coefficient increase with nitrogen content in austenitic stainless steels. Ludwigson (1971) [26] further explains the plastic flow of these materials using a modified Ludwik model, which accounts for deviations at low strains. Cho (1982) [27] extends this understanding to creep behavior, developing nonlinear constitutive equations to predict the creep behavior of 304 stainless steel.

$$\sigma = \sigma 0 + K\varepsilon n \qquad (1)$$

Where:
$\sigma 0$ = yield stress
K = strength coefficient
n = strain hardening exponent

Table (2). Key Mechanical Properties of Engineering Materials.

Materials	Yield Strength	Elasticity Modulus	Strain Hardening Modulus	Poisson’s Ratio	Density
Symbol	σs (MPa)	E (GPa)	Et (MPa)	ν	ρ (kg/m3)
Electrode	230	115	566	0.35	8900
440A	450	210	611	0.27	7650
D2	1300	205	600	0.29	7700

Tool steels, on the other hand, have a plastic strain of 8-10%. The elastic modulus of stainless steels ranges 210 GPa. In contrast, the elastic modulus of tool steels is around 205 GPa. The Poisson's ratio of stainless steels is typically in the range of 0.275, while tool steels generally have a Poisson's ratio around 0.29, the equation for Poisson's ratio (ν) for steel can be written as:

$$\nu = -\varepsilon trans/\varepsilon long \qquad (2)$$

Where:
ν = Poisson's ratio εtrans = lateral or transverse strain εlong = longitudinal strain. The behavior of stainless steel and tool steel grades under tensile loading was analyzed using a 3D solid model and finite element analysis (FEA) simulation. The simulation stainless steel grade 440A to improve ultimate tensile strength compared to the tool steel grade D2. Accurately defining the material models and fine-tuning the FEA simulation methodology were crucial for extracting useful insights into the tensile performance differences between these steel grades.

Table (3). Chemical composition of 440A and D2 steel.

Elements	C%	Si%	Mn%	Cr%	Ni%	P%	S%	Fe%
440A	0.95	0.35	2	18.02	8	0.01	0.003	balanced
D2	1.50	0.55	1.2	-	-	0.01	0.02	balanced

440A and D2 steels have distinct chemical compositions tailored to their intended applications. 440A is an austenitic stainless steel containing relatively high amounts of chromium (Cr) and nickel (Ni). The 18.02% Cr provides corrosion and oxidation resistance by forming a passive protective Cr-oxide surface layer. The 8% Ni enhances corrosion resistance while also improving toughness and ductility. Carbon content is moderately high at 0.95% to enable heat treatment for increased hardness and strength. Additional alloying elements like silicon (Si) and manganese (Mn) further augment the strength through solid solution strengthening. On the other hand, D2 steel is a high carbon high chromium tool steel. With 1.5% carbon content, it achieves very high hardness and wear resistance when heat treated, making it suitable for cold work cutting tools. However, ductility and toughness are reduced. The main alloying element is Cr at 12%, which gives mild corrosion resistance. Si and Mn are also present as strengtheners. Compared to 440A stainless, D2 lacks nickel and has over triple the carbon content, changing the microstructure and dominant properties. While 440A is tougher and more corrosion resistant, D2 is harder and has superior wear resistance. The differing elemental compositions tailor the steels towards either durability or cutting performance respectively.
The dimension of all samples was 30 × 9 × 2 mm (length * width * thickness).

2. Result and Discussion

The tensile strength of spot-welded steel sheet connections was found to increase significantly, with stainless steel 440A and tool steel D2 showing respective increases from 1800 MPa to 2400 MPa and from 700 MPa to 1100 MPa as shown in figure (3). However, different failure modes were observed, with stainless steel experiencing corrosion and fusion issues, and tool steel showing brittleness and weak joint strength. The effect of base-metal tensile properties on fatigue life was also explored, with fatigue life found to be independent of base-metal strength for lives greater than 10,000 cycles. The study also highlights the need for a better understanding of the behavior of stainless-steel connections.

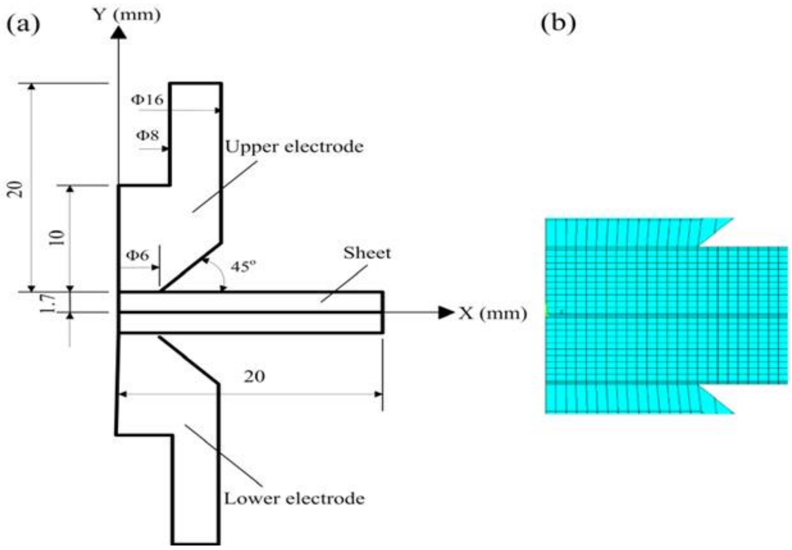

Fig (2). Finite element model employed to simulate design process: (a) overall view; and (b) enlarged view.

the simulation of tensile testing for spot welded steel sheet connections provides valuable insights into the mechanical properties and behavior of spot-welded joints in steel sheets. By referencing studies such as Kong et al. (2007) [16], De et al. (1996) [17], and Mukhopadhyay et al. (2009) [18], the research highlights the importance of welding parameters, base-metal tensile properties, and nugget size in determining the strength and quality of spot-welded connections. Moreover, the study's focus on the effects of parameters like sheet thickness, weld size, and electrode force on the static and fatigue strength of resistance spot welds aligns with previous research by Khan et al. (2008) [19] and Javaheri et al. (2019) [20], which emphasized the influence of welding microstructure and material properties on joint performance. The characterization of different weld zones and their impact on tensile-shear strength, as discussed in Acharya and Ray (2013) [21], further enhances our understanding of spot-welded steel sheet connections. By incorporating dynamic contact resistance monitoring, as suggested by Bayraktar et al. (2004) [23], the research demonstrates a comprehensive approach to evaluating the quality of spot welds under dynamic loading conditions. The findings on the tensile strength enhancement of spot-welded connections in stainless steel 440A and tool steel D2, as presented in the study, contribute to the broader knowledge base on the mechanical behavior of high-strength steels in welding applications.

Table (4). Tensile Strength of 440A and D2 Steel Sheet Grades with and Without Spot Welding.

Steel Sheet Grade	Tensile Strength (MPa) without spot welded	Tensile Strength (MPa) with spot welded
440A	1800	2400
D2	700	1100

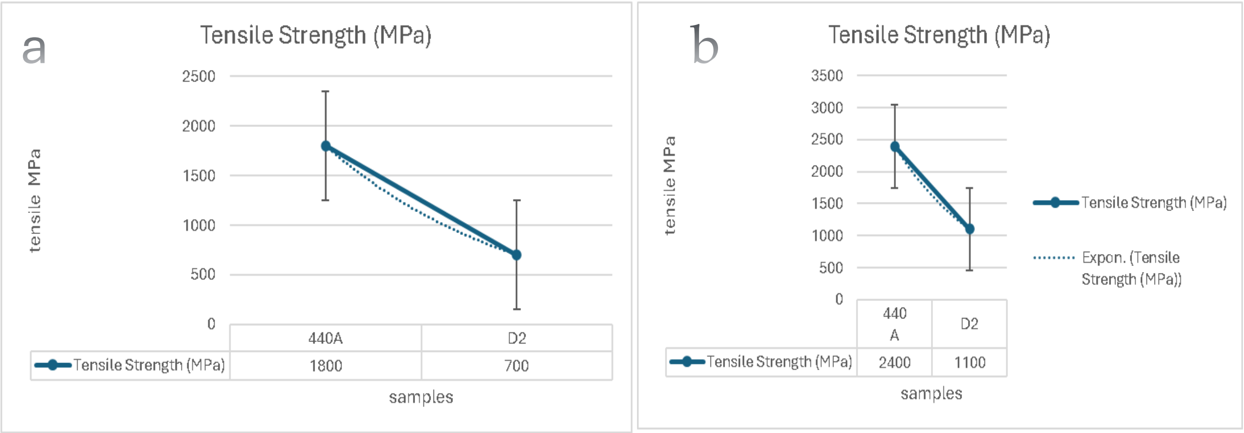

Fig (3). Tensile strength before and after welding spots.

The study explored the effect of base-metal tensile properties on fatigue life, revealing that fatigue life was independent of base-metal strength for lives greater than 20,000 cycles as shown in figure (4). This highlights the need for a better understanding of the behavior of stainless-steel connections. The studies also examined the influence of welding parameters on the quality of welding joints, including nugget size and mechanical properties. Additionally, the material properties of different weld zones and their impact on the tensile-shear strength of welded joints were characterized.

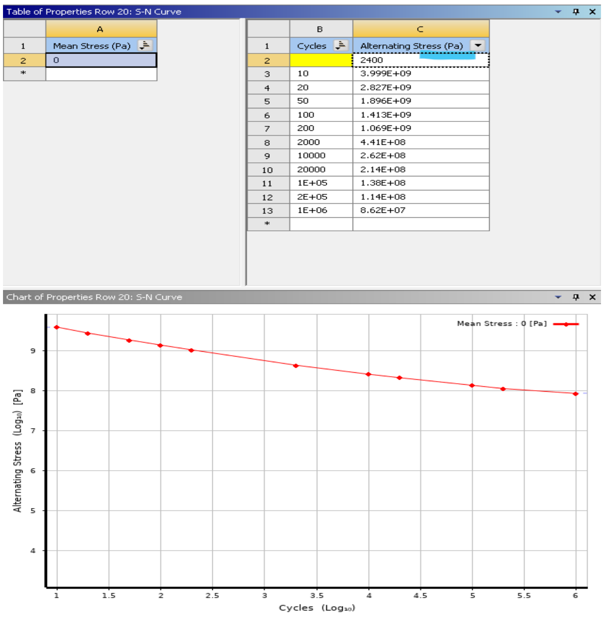

Table of Properties Row 20: S-N Curve

	A
1	Mean Stress (Pa)
2	0
*	

	B	C
1	Cycles	Alternating Stress (Pa)
2		2400
3	10	3.999E+09
4	20	2.827E+09
5	50	1.896E+09
6	100	1.413E+09
7	200	1.069E+09
8	2000	4.41E+08
9	10000	2.62E+08
10	20000	2.14E+08
11	1E+05	1.38E+08
12	2E+05	1.14E+08
13	1E+06	8.62E+07
*		

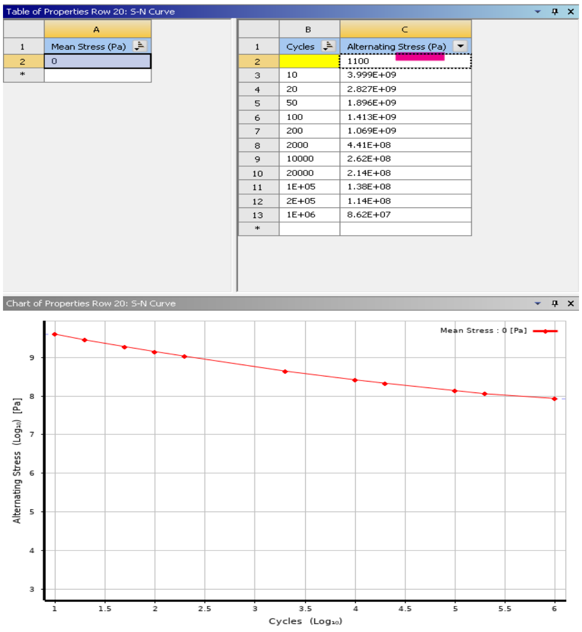

Table of Properties Row 20: S-N Curve

	A
1	Mean Stress (Pa)
2	0
*	

	B	C
1	Cycles	Alternating Stress (Pa)
2		1100
3	10	3.999E+09
4	20	2.827E+09
5	50	1.896E+09
6	100	1.413E+09
7	200	1.069E+09
8	2000	4.41E+08
9	10000	2.62E+08
10	20000	2.14E+08
11	1E+05	1.38E+08
12	2E+05	1.14E+08
13	1E+06	8.62E+07
*		

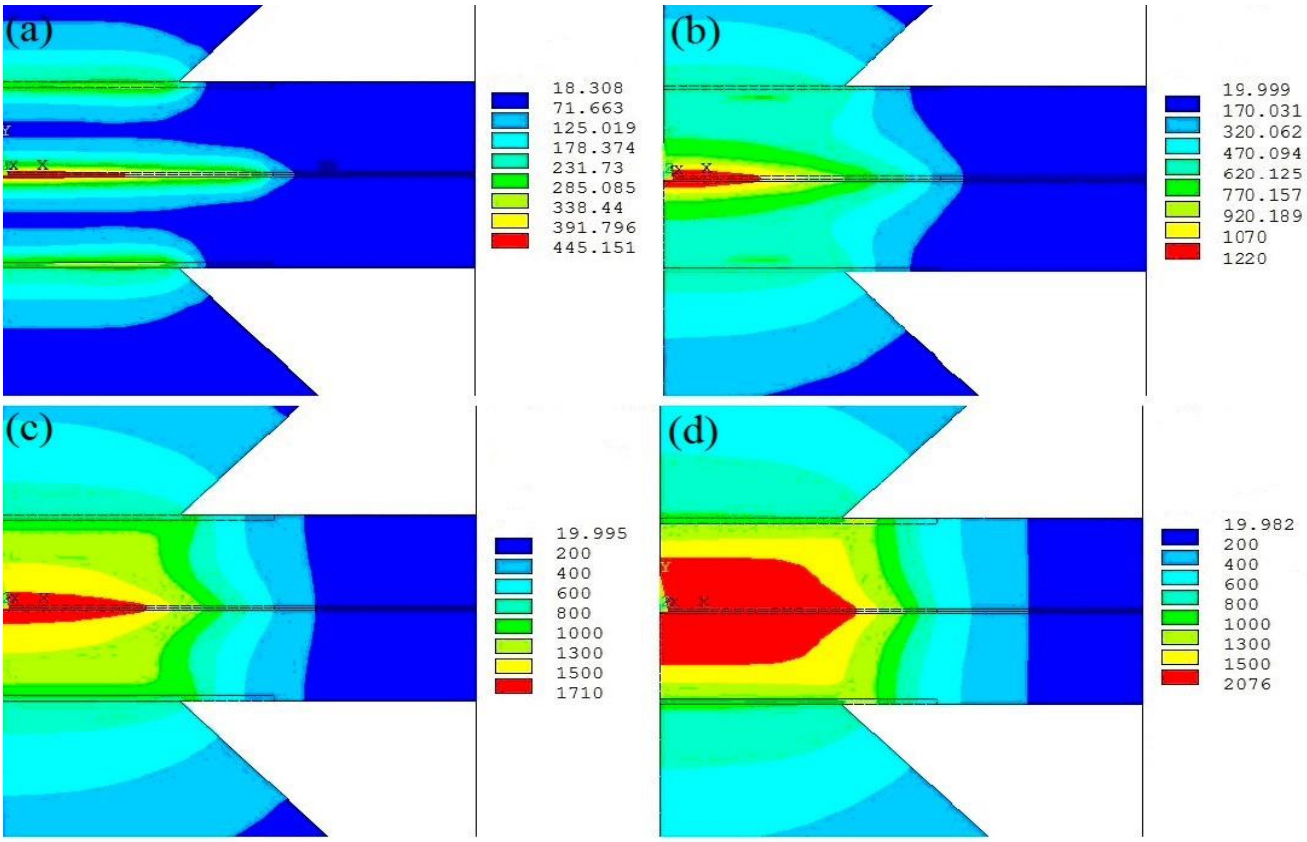

Fig (4). Temperature profile of the welding zone in the welding process (a) 0.007 s, (b) 0.05 s, (c) 0.13 s, and (d) 0.28 s.

3. Conclusion

In conclusion, the research paper on the simulation of tensile testing for spot welded steel sheet connections provides valuable insights into the mechanical properties, behavior, and performance of spot-welded joints in steel sheets. By examining the influence of welding parameters, base-metal tensile properties, nugget size, sheet thickness, weld size, and electrode force on the static and fatigue strength of resistance spot welds, this study contributes to a deeper understanding of the factors affecting the quality and durability of welded connections. Furthermore, the characterization of different weld zones and their impact on tensile-shear strength, along with the exploration of dynamic contact resistance monitoring, enhances our knowledge of spot-welded steel sheet connections under dynamic loading conditions. The findings on the tensile strength enhancement of spot-welded connections in stainless steel 440A and tool steel D2 add to the broader knowledge base on the mechanical behavior of high-strength steels in welding applications. Overall, this research underscores the importance of comprehensive testing, modeling, and analysis in optimizing the performance and reliability of spot-welded steel sheet connections in various industrial applications.

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Finding

Characterization of different weld zones and their impact on tensile-shear strength provided insights into the heterogeneous nature of spot-welded joints and the variations in mechanical properties across different regions of the weld. The exploration of dynamic contact resistance monitoring as a means of evaluating the quality of spot welds under dynamic loading conditions demonstrated a comprehensive approach to assessing the integrity and performance of welded connections. The findings on the tensile strength enhancement of spot-welded connections in stainless steel 440A and tool steel D2 contribute to the knowledge base on the mechanical behavior of high-strength steels in welding applications, emphasizing the importance of material selection and properties in achieving desired mechanical performance. Overall, the findings of this research paper underscore the importance of comprehensive testing, modeling, and analysis in optimizing the strength, quality, and reliability of spot-welded steel sheet connections for various industrial applications.

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