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IDENTIFYING THE INFLUENCE OF ORBITAL PIPE WELDING PARAMETERS ON MECHANICAL PROPERTIES USING SS316L PIPE

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Pipeline systems play a pivotal role across various industries, serving as the lifelines for transporting materials like oil, water, and gas. Among the welding techniques, orbital pipe welding, particularly Gas Tungsten Arc Welding (GTAW) without filler metal, is the fitting method for joining these critical piping systems. This study examined orbital pipe welding on SS316L pipes with a 114-mm outer diameter and 3-mm thickness. The main goal was to evaluate the weld's tensile strength and microhardness carefully. Constant current and three welding speeds – 1.3, 1.4, and 1.5 mm/s – achieved this goal. In addition, welding experiments covered 0°, 90°, 180°, and 270° pipe positions. First, the necessary tools and test objects were prepared, and then the test materials were welded. The final phase was testing tensile strength and microhardness. This investigation used a 5G-specific prototype orbital pipe welding equipment. The 5G method requires horizontal welding with the vertical pipe axis. The study used ASTM E-8M-compliant standardized test material for precise and repeatable tensile strength measurements. This standardization ensured outcomes reliability. One of the significant findings was that 1.4 mm/s welding at the 270° pipe position with 110A current produced the maximum tensile strength. This shows that these conditions are best for welding SS316L-type stainless steel pipes with an outside diameter of 114 mm and a thickness of 3 mm. Strangely, microhardness testing showed that horizontal distribution welding quality decreased at 1.4 mm/s. This implies that further experimentation may be needed to fine-tune the welding parameters to optimize the process and achieve superior microhardness values

Keywords: orbital pipe welding, gas tungsten arc welding, SS316L, tensile strength, microhardness

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1. Introduction

Orbital pipe welding is a specialized welding technology that rotates the welding head around a fixed horizontal pipe or tube during an automated welding operation. This process is called "orbital" because the welding arc circles the workpiece, usually a tube or pipe. This welding technique theoretically allows a 360-degree rotation around the workpiece, but it's usually 410 degrees in practice. Orbital welding is widely used because it produces high-quality welds, is reliable, and boosts productivity. Many companies and places use this strategy. For instance, pharmaceutical piping welding requires precision and cleanliness. It's essential in dairy product pipelines, where hygiene is vital. Nuclear-spent fuel canisters need the best weld integrity; hence, orbital welding is necessary. Orbital welding's precision and reproducibility make it a vital tool in many industries, ensuring high-quality welds for crucial applications [1].

Pipe material depends on the sector and the contents being transported. Petrochemicals, pharmaceuticals, and food processing employ SS316L stainless steel pipes. Due to its corrosion resistance, high-temperature resistance, and endurance in hostile conditions, SS316L stainless steel is preferred [2]. Thus, the welding process must be carefully monitored to avoid faults compromising product quality and safety. It's vital to stress careful welding. Poor welding can damage the pipe system, causing leaks, product contamination, or catastrophic failures [3]. Weld flaws such as porosity, undercutting, and lack of fusion can reduce tensile strength. This weakening might make the weld more prone to cracking and rupture, threatening the pipe system.

The orbital pipe welding technique using SS 316L pipe is exciting and essential because careful current and speed control can affect tensile strength and microhardness. This study emphasizes the importance of proper welding current settings and speeds for high-quality, durable, and reliable welds. Realizing that ideal welding circumstances are a practical matter with real-world ramifications is important. Weld strength and microhardness are essential performance metrics that correlate with base material strength and microhardness. Creating a weld with base metal-like tensile strength and microhardness is crucial. This study examines the fundamentals of welded joint quality. This study examines the link between welding current, speed, and weld mechanical attributes to determine how process variables affect product integrity. Understanding this link is crucial to improving the reliability and lifetime of welded piping systems, making it reasonably practical.

As shown in this research, gas tungsten arc welding (GTAW) is used in orbital pipe welding. It is essential in aerospace, automotive, and nuclear industries. Both tensile strength and microhardness are crucial for evaluating weld quality. The maximum stress a weld may bear before failing is its tensile strength. However, microhardness indicates a material's resistance to indentation or penetration, affecting weld wear and deformation [4]. In GTAW welding, current and speed control tensile strength and microhardness. Increasing or slowing welding current can improve these mechanical properties and weld quality. However, this augmentation increases heat input, which could cause substantial distortion if the welding zone grows or slows. These complicated dynamics emphasize the importance of adjusting welding conditions to improve material mechanical properties and weld structural integrity and dimensional stability [5]. The problem and promise of GTAW orbital pipe welding lies in this junction.

The method of orbital pipe welding, frequently employed in stainless steel piping systems, is the subject of some research now being carried out. However, one of the limitations of the orbital pipe welding process is that it might be challenging to maintain a consistent level of weld quality at each pipe position. Combining the more conventional GTAW methods with orbital pipe welding is a common practice to solve this issue. As a result, there is still a need for attempts to improve the orbital pipe welding technique utilizing conventional GTAW so that it can continue to be relevant for further research.

2. Literature review and problem statement

Although widely used, orbital pipe welding still faces various material problems that must be solved to achieve strict quality standards. Failures include distortion, non-uniform penetration depth, and weld bead width, which affects welding efficiency and reliability. This makes tensile and microhardness tests essential for welding quality and integrity. They quantify weld mechanical qualities and suitability. Gas Tungsten Arc Welding (GTAW) orbital pipe welding requires appropriate settings for perfect results. Systematic welding experiments manipulating and observing parameters like welding current and speed are needed to optimize this. This empirical method allows welding settings to be fine-tuned to reduce material failures. GTAW orbital pipe welding methods must be optimized to improve reliability and performance to fulfill strict industry standards.

The research [4] topic on the influence of gravity on molten pool behavior and the analysis of microstructure in various welding positions in pulsed gas metal arc welding is captivating and significant, particularly in the field of welding and materials science. The study focuses on a crucial aspect of welding processes - the impact of gravity on the behavior of molten metal during welding. It is vital to consider the different welding positions, like overhead or vertical, frequently encountered in various industries. Gaining a deep understanding of the impact of gravity on the welding process can pave the way for significant enhancements in both the quality and efficiency of welding. The study should recognize any limitations, including the specific welding equipment used, environmental conditions, or other factors that could impact the results.

The review [6] should offer a thorough and all-encompassing examination of the existing research in the field, ensuring the incorporation of relevant studies from both recent and historical periods. This enables a more comprehensive assessment of the topic. The review should cover a complete range of pulse parameters, including pulse frequency, current, voltage, and pulse duration, to comprehensively understand their impact on weld quality. It is essential to establish a clear differentiation between these parameters. The review should highlight the significance of utilizing reliable quality assessment methods, including tensile testing, hardness testing, non-destructive testing, and microstructural analysis. It is crucial to consider the suitability of these metrics in various scenarios.

In contrast, a study by [3] suggests that using pulse current can lead to notable enhancements in welded joints' mechanical and metallurgical properties. This variation in research results emphasizes the significance of conducting comprehensive research to fully investigate the complexities of establishing current parameters and welding speed to attain the best possible outcomes in the realm of orbital pipe welding. This research is highly significant considering the crucial function of orbital pipe welding in various industries, such as the petrochemical, pharmaceutical, and food processing sectors. It is crucial to prioritize the integrity and quality of welds in these applications, as inadequate welds can result in problems like leaks, contamination, and even structural failures. Thus, it is crucial to comprehend the precise factors that impact the quality of the weld.

The research in [7] highlights the distinct demands of orbital TIG pipe welding, specifically the need for materials with specific characteristics such as high heat sink, thermal conductivity, and electrical conductivity. However, even with these insights, the issue of copper's weldability using TIG welding still requires more research to address adequately. Although some research has been conducted in this area, particularly [8], the extent of studies on the utilization of TIG welding for orbital applications is still quite restricted. The work in [8] focuses on optimizing orbital TIG welding process parameters using a systematic approach, explicitly employing the Taguchi method. When examining the welding of stainless-steel tubes for satellite propulsion feed systems, it becomes evident that the welding current is the primary factor affecting welding quality, closely followed by the welding speed. This study highlights the potential for enhancing weld quality and overall performance by optimizing parameters.

Welding distortion can compromise product precision and quality. Thus, many welding and procedure methods have been used to reduce distortion. According to [9], using filler wire during welding reduces distortion. High-frequency pulse current welding is another potential technology. This method reduces distortion by reducing heat input and temperature gradients. These experiments have been helpful, but further research is needed to optimize welding existing parameter values for best results. A comprehensive study on distortion mitigation [10] stresses the benefits of preheating the material before welding. Reducing temperature gradients and residual strains in the welded junction reduces distortion. This improves thermal stability, minimizing bending and deformation.

To address the strict requirements of Brazilian space applications, research like [11] develops efficient and reliable ways for welding pure titanium seamless tubes. This research created three orbital gas tungsten arc welding programs that produced defect-free welds with good morphology. The authors then performed mechanical and metallographic characterizations to assess weld quality. The findings in [7] highlight the benefits of programs with reduced heat input values. These algorithms produce smaller grain sizes for better hardness and mechanical characteristics. Controlling heat input may improve weld quality, a topic for further study.

According to paper [12], arc welding welds nuclear pressure containers and performs root passes on pipes, primarily by hand. Torch movement might affect the molten pool in various welding positions, making these techniques challenging to sustain. According to a research report [13], orbital pipe welding's pulse current approach can improve AISI 304L pipes' mechanical qualities. Studies [14] show that the sequence approach improves SS316L pipe mechanical qualities, particularly tensile strength, and hardness at various pipe places. A study [15] noted that operating factors significantly affect bead shape and tensile characteristics. When welding current and voltage increase, tensile characteristics improve, but when welding speed increases, they decrease. Welding current has the most significant impact on tensile characteristics among operating conditions. These data demonstrate the importance of selecting and modifying welding parameters to achieve quality and reliability.

Comprehensive research has been conducted on pipe welding, covering a range of factors, including gravity, pulsed current methods, welding sequence techniques, distortion reduction, and optimization of welding parameters. However, there is still a need for a thorough analysis of how orbital pipe welding parameters, specifically welding current and welding speed, impact SS316L material. It is crucial to conduct a study to investigate the impact of various orbital pipe welding parameters on the mechanical properties of SS316L pipes, particularly in terms of tensile strength and microhardness. This unexplored area of research highlights the need for a thorough analysis. This research is crucial for improving our comprehension of orbital pipe welding processes and their utilization with materials that possess distinct properties, such as SS316L stainless steel. This study aims to address the existing gap and make a valuable contribution towards enhancing the quality and reliability of SS316L pipe welds. These welds are extensively utilized in various industries, making this research significant and beneficial.

3. The aim and objectives of the study

This study aims to identify opportunities for achieving optimal tensile strength and hardness in the orbital pipe welding process by adjusting welding current and speed.

To achieve this aim, the following objectives are accomplished:

– conduct orbital pipe welding experiments with variations in current parameters and welding speed, followed by tensile tests, to determine optimal welding current parameters and rate;

– carrying out microhardness testing to determine the optimal welding current parameters and welding speed in orbital pipe welding with SS 316L material by varying the welding current parameters and rates.

4. Methods and materials

The object of the research is mechanical properties such as tensile strength and microhardness of SS316L pipes. The main emphasis is on comprehending the effects of welding parameters, specifically welding current and welding speed adjustments on the tensile strength and microhardness of the welds, as these mechanical properties are of utmost importance. This research offers valuable insights into optimizing orbital pipe welding processes to improve welds' overall quality and reliability in SS316L pipes across different industries. Through thoroughly examining these influences, the study enhances the comprehension of orbital pipe welding techniques and their practicality in working with materials that possess distinct properties, like SS316L stainless steel.

The primary hypothesis of this research is that orbital pipe welding parameters, such as welding current and speed, greatly affect SS316L pipe mechanical qualities. It is well known that these characteristics are crucial to welded pipes' structural and material integrity, not only technical standards. A fundamental parameter, welding current, can transform. The theory states that carefully managing welding current can increase SS316L pipe tensile strength. The center of the weld, where metals join, can be strengthened to endure higher loads and pressures. Thus, careful welding current calibration protects mechanical qualities, making SS316L pipes more durable in their intended uses. For better mechanical qualities, welding speed is also important. This idea argues that welding speed optimization is like microhardness tuning. How metals ignite and cool during welding depends on the welding speed. Speed and heat input can be balanced to produce microhardier SS316L pipes. This increases the material's durability and reduces wear and tear.

The study relied on some assumptions to bolster the research design, methodology, and analysis. Considering the assumption that the SS316L material used in the study is homogeneous and consistent in terms of its chemical composition and material properties is crucial. Considerations regarding the reliability and accuracy of the welding equipment utilized in the experiments encompassing the dependability of the gas supply and the effectiveness of the orbital welding tool. It is important to note that the welding experiments were conducted under steady-state conditions, ensuring that external factors such as temperature and humidity were controlled and consistent throughout the testing. Considering the behavior of SS316L under various welding conditions, it is essential to note the potential effects of changes in welding current and speed on tensile strength and microhardness.

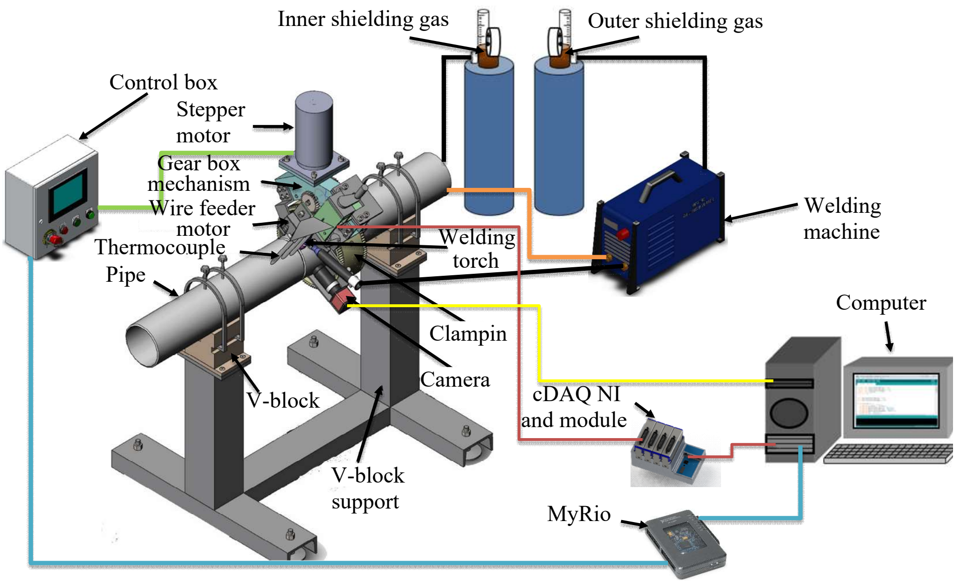
Research in this field depends on various simplifications and idealizations to streamline the study's focus and make the experiments more manageable. These simplifications aim to isolate specific variables and control conditions to enhance understanding. Typically, researchers manipulate one parameter at a time, such as welding current or speed, while maintaining the constant values of other variables. This streamlines the analysis and aids in comprehending the individual influence of each parameter.

Real-world welding processes require careful consideration of numerous variables that interact simultaneously. Many studies use small-scale samples for testing, which may not accurately reflect the behavior of full-sized pipes. Scaling effects can have a significant impact, and experiments conducted on smaller samples may fail to account for certain complexities that arise when dealing with a larger scale. Researchers commonly assume that welds are free of defects and have consistent thickness and penetration.

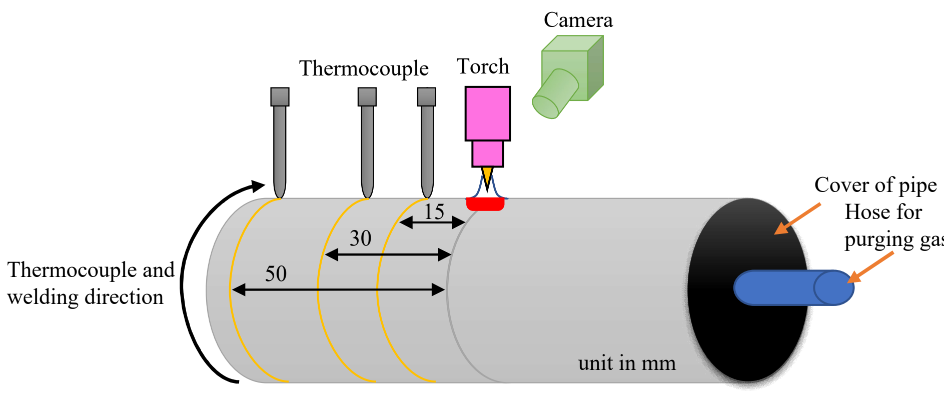
4. 1. Experimental setup tool and materials

As shown in Fig. 1, *a*, the experimental setup tool was instrumental in this study, enabling pipe welding in the 5G position and orbital pipe welding. Three types of K thermocouples and a CCD camera were used to monitor the temperature distribution during welding. Fig. 1, *b* illustrates the schematic arrangement of the thermocouple and camera positioning. The thermocouples were placed at 15, 30, and 50 mm from the center of the weld to ensure the most accurate and precise temperature readings possible. The positioning was crucial to maintain parallelity to the welding arc, thus reducing the possibility of errors. At the same time, the CCD camera was positioned at a 35° angle. The particular perspective provided a thorough and up-to-the-minute examination of the weld pool dynamics during the welding procedure. The careful observation and collection of data are essential for understanding the molten pool's behavior and the welding process's dynamics in the presence of gravity. The meticulous observations play a crucial role in characterizing the impact of gravitational forces on the behavior of the molten pool and comprehending the microstructural aspects at different welding positions.

SS316L stainless steel pipe with a diameter of 114.3 mm was used as a test object in this research. The test specimen pipe is in the form of 2 sections with a length of 110 mm each. The pipe workpieces are joined using a square butt joint. The workpiece preparation scheme is shown in Fig. 1, *c*.



a



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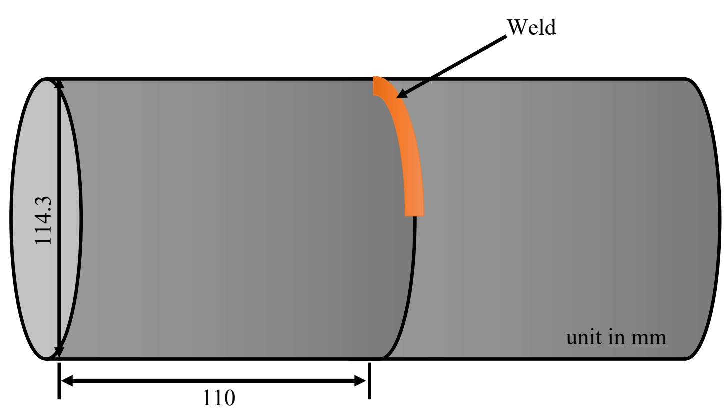


c

Fig. 1. Schematic setup *a* — test tool; *b* — thermocouple; *c* — pipe workpiece preparation [14]

4. 2. Welding test materials

The prototype of the orbital pipe welding machine used for welding in the 5G pipe position is shown in Fig. 2. This machine is designed to revolve around the pipe during welding. In contrast, the pipe is held securely in place using pipe supports. The supports also help position the specimen accurately, and they can be attached at both ends to prevent any unwanted movement during the welding process. The welding machine's design allows for precise and consistent welding of the SS316L stainless steel pipe, which is crucial for ensuring the desired mechanical properties of the welded joint.

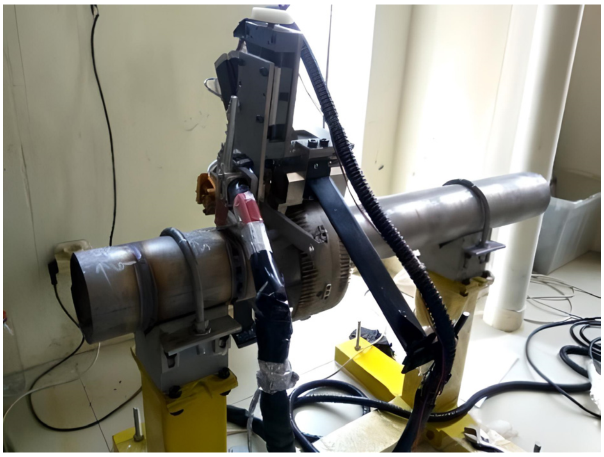


Fig. 2. Prototype orbital pipe welding tool

A systematic approach was used to collect data for this investigation. The 110 mm-long SS316L stainless steel pipe was prepared first. The first step was cutting and carefully sanding the pipe with 80–600 grit sandpaper. The designed pipe was then cleaned with acetone to remove impurities that could interfere with welding. Securing the pipe for orbital pipe welding was the next step. Clamps secured the pipe to pipe supports. The orbital pipe welding tool was carefully placed into the pipe and secured with four binding bolts to ensure stability and precision during welding. Temperature monitoring was vital to this experiment. Three thermocouples were placed 15, 30, and 50 mm from the welding region's midpoint to help.

The electrode height was also changed to maintain a 3 mm spacing during welding. Argon gas shielded the weld region and prevented reactions. Argon gas was supplied at 11 liters per minute outside the pipe and 5 liters per minute inside to maintain the welding atmosphere. After careful setup, the welding machine's voltage sources and control boxes were activated. The welding current and speed were adjusted to meet the predefined limitations to ensure the procedure followed the requirements. Our welding process started at 330° clockwise. After finishing, welding was purposefully stopped before restarting. After welding, the power sources and control boxes were turned off, and the test object cooled slowly. The orbital pipe welding equipment's limiting fastener was loosened to position the welding tool for future welding spots. This method permitted precise welding spot selection.

4. 3. Mechanical properties testing

Mechanical characteristics are assessed after properly preparing test items. The tensile test is crucial to this evaluation. The ASTM E-8M test technique, shown in Fig. 3, is performed at 0°, 90°, 180°, and 270° orientations. A modern 50 kN tensile RTF 2350 machine is used for the testing, maintaining a 5 mm/min tensile speed. The equipment holds and tenses the test specimens until they break. The material's maximum stress before breaking is meticulously recorded during this operation. The yield strength, ultimate tensile strength, and elongation at fracture are calculated from this data. The microhardness test and the tensile test measures material hardness at various places. This test uses a Vickers indenter with a 0.5 kg load for 15 seconds. The indentation is then carefully measured with an optical microscope. The microhardness test values reveal the material's microstructure, strength, and durability.

Microhardness was measured in the weld, HAZ, and base metal. The testing protocol followed ASTM E 384. Microhardness was tested at four equidistant sites per degree around the pipe's circumference – 0°, 90°, 180°, and 270° – for a complete evaluation. Not all parameter modifications were tested; a few were chosen as samples for the results. Both vertical and horizontal indentations were methodically done to reveal the material's hardness. An adequately measured 500-gram weight was applied for 15 seconds. The spacing between indentation points was maintained at 250 μm vertically and 500 μm horizontally, as shown in Fig. 4.

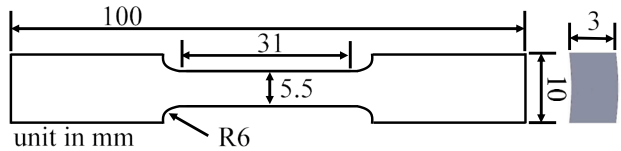


Fig. 3. Dimensions of tensile test specimens [14]

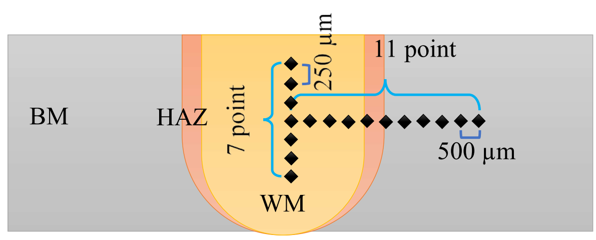


Fig. 4. Microhardness testing scheme [14]

The GTAW parameters utilized for the orbital pipe welding experiment play a crucial role in determining the quality of the resulting welds. The exact configurations of these parameters have a notable influence on the mechanical characteristics of the materials, encompassing their tensile strength and microhardness. In this study, the parameters were carefully chosen to ensure a thorough understanding of their impact on the welding process. The parameters are provided in Table 1, which outlines the variations in welding current and welding speed that will be tested. Three welding currents are being considered: 100 A, 110 A, and 120 A. These currents correspond to the electrical current levels used during the welding process. In the study, three different welding speeds have been considered: 1.3, 1.4, and 1.5 mm/s. These speeds represent the rate at which the welding tool moves along the pipe. The parameters cover a variety of current and speed values that are frequently employed in orbital pipe welding.

Table 1

Orbital pipe welding parameters

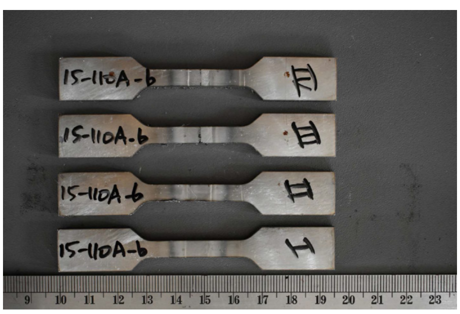
No.	Welding current (A)	Welding speed (mm/s)
1	100	1.3
2		1.4
3		1.5
4	110	1.3
5		1.4
6		1.5
7	120	1.3
8		1.4
9		1.5

5. Results of the experiment of tensile strength and break location, and microhardness testing

5. 1. Result of tensile strength and break location

Mechanical properties testing is essential in evaluating the quality and strength of welded joints. One mechanical properties of material testing method is tensile testing, which involves pulling a specimen until it breaks and measuring the force required. This test uses the ASTM E-8M standard, which outlines the procedures for performing tensile tests on metallic materials.

Fig. 5, *a,* shows a specimen before the pull test, which typically involves mounting the specimen onto a tensile testing machine using special grips. The device then applies a controlled load to the specimen until it breaks. The resulting force and elongation measurements are recorded and analyzed to determine the welded joint's tensile strength and other mechanical properties.



a

b

Fig. 5. Tensile test material: *a* – before testing; *b* – after testing at a welding current of 110A and a welding speed of 1.5 mm/s

Fig. 5, *b,* shows a specimen after a tensile test at welding current 110 A and a welding speed of 1.5 mm/s. This specimen has undergone deformation and necking, which is a reduction in the cross-sectional area of the specimen just before it breaks. This indicates that the welded joint has reached its maximum load-bearing capacity and is at the brink of failure.

Table 2 presents the findings of the study, which show that the highest tensile strength is achieved at parameter 13–100 A, 180° pipe position, with a value of 569.91 MPa. However, the results also reveal that the fault locations for this parameter are all in the weld area, which indicates that the weld joint is not of good quality. This finding is critical because it suggests that further improvements are necessary to enhance the quality of the weld joint to achieve better performance in terms of tensile strength.

Table 2

Results of a tensile test performed at a 1.3 mm/s welding speed

No.	Parameter	Position (degrees)	Tensile strength (MPa)	Standard deviation	Fracture location
1	13–100 A	0	540.19	4.51	Weld metal area
		90	557.14	7.17	Weld metal area
		180	569.19	0.14	Weld metal area
		270	546.91	4.18	Weld metal area
2	13–110 A	0	528.80	8.55	Weld metal area
		90	534.80	20.63	Weld metal area
		180	548.17	6.86	Weld metal area
		270	468.10	6.67	Weld metal area
3	13–120 A	0	524.62	20.56	Weld metal area
		90	540.54	16.23	Weld metal area
		180	554.41	3.85	Weld metal area
		270	489.45	30.44	Weld metal area

Fig. 6 displays the outcomes of the distribution of tensile strength data to elongation that occurs at a welding speed of 1.3 mm/s with a welding current of 100 A (*a*), 110 A (*b*), and 120 A (*c*). The results indicate that the maximum tensile strength data falls within 600–670 MPa. Furthermore, each welding current variation data exhibits a different degree of welding, and the point of ultimate tensile strength reaches the highest point with varying degrees of welding. Specifically, in data (*a*), the end of maximum tensile strength is reached at 180°; in data (*b*), 180° is also the point of ultimate tensile strength, and in data (*c*), the maximum tensile strength point is attained at 180° as well. This finding implies that the degree of welding and welding current significantly impact the tensile strength of the weld joint.

The findings presented in Table 3 indicate that the welding parameter with the highest tensile strength is parameter 14, which involves a welding current of 120 A and a pipe position of 90°, resulting in tensile strength of 662.58 MPa with an error of 5.81 %. However, it is noteworthy that all the fault locations for these welding parameters are located in the weld area, which suggests that the welding joint is still not adequately connected. Therefore, further improvements in the welding process are necessary to enhance the quality and strength of the joint.

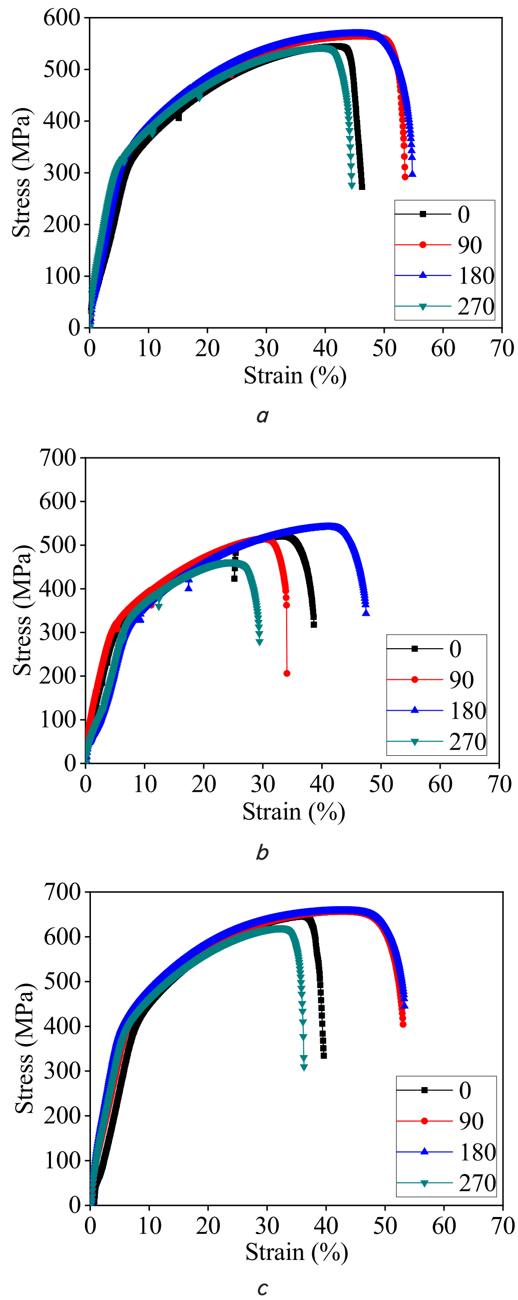


Fig. 6. Stress vs strain chart at a welding speed of 1.3 mm/s with welding currents: *a* – 100 A; *b* – 110 A; *c* – 120 A

The data analysis of tensile strength and elongation at various welding currents is presented in Fig. 7. The experiment was conducted at a welding speed of 1.4 mm/s, and the welding current was varied at 100 A (*a*), 110 A (*b*), and 120 A (*c*). The data shows that the maximum tensile strength is in the range of 600–670 MPa. Furthermore, it is observed that the point of ultimate tensile strength varies with the degree of welding and current variation. For instance, in data (*a*), the maximum end of tensile strength is observed at 180°, and the same is observed for data (*b*). However, in data (*c*), the maximum point of tensile strength is observed at 180° as well.

According to the findings presented in Table 4, the welding parameter with the highest tensile strength was achieved at parameter 15–120 A with a 90° pipe position, resulting in 676.19 MPa with an error of 2.03 %. During the tensile test, the fracture location was generally observed to be in the weld area. However, there was one parameter where the fracture occurred in the base metal area, suggesting that the welded joint was sufficiently strong for that particular parameter.

The graph in Fig. 8. presents the outcomes of the distribution of data on tensile strength and elongation that occurred when welding at a speed of 1.5 mm/s and using a welding current of 100 A (*a*), 110 A (*b*), and 120 A (*c*). The highest tensile strength recorded was around 660 MPa. For each variation of the welding current, the point of maximum tensile strength reached the highest point at different welding angles. Specifically, in data (*a*), the maximum point of tensile strength was reached at 270°. In data (*b*), the ultimate point of tensile strength was reached at 270°, and in data (*c*), the maximum point of tensile strength was reached at 270°.

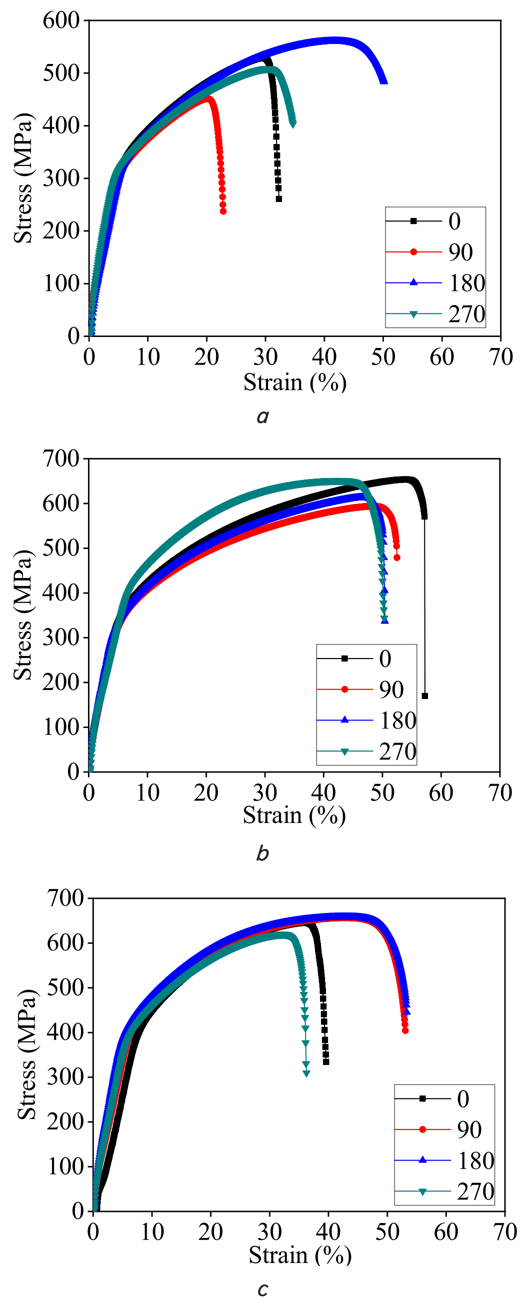


Fig. 7. Stress vs. strain diagram for 1.4 mm/s welding, with welding currents: *a* – 10 0A; *b* – 110 A, *c* – 120 A

The fracture surfaces of the specimen were examined using SEM, and the SEM images are presented in Fig. 9. The highest and lowest tensile strength parameters were tested and compared to the base metal fracture.

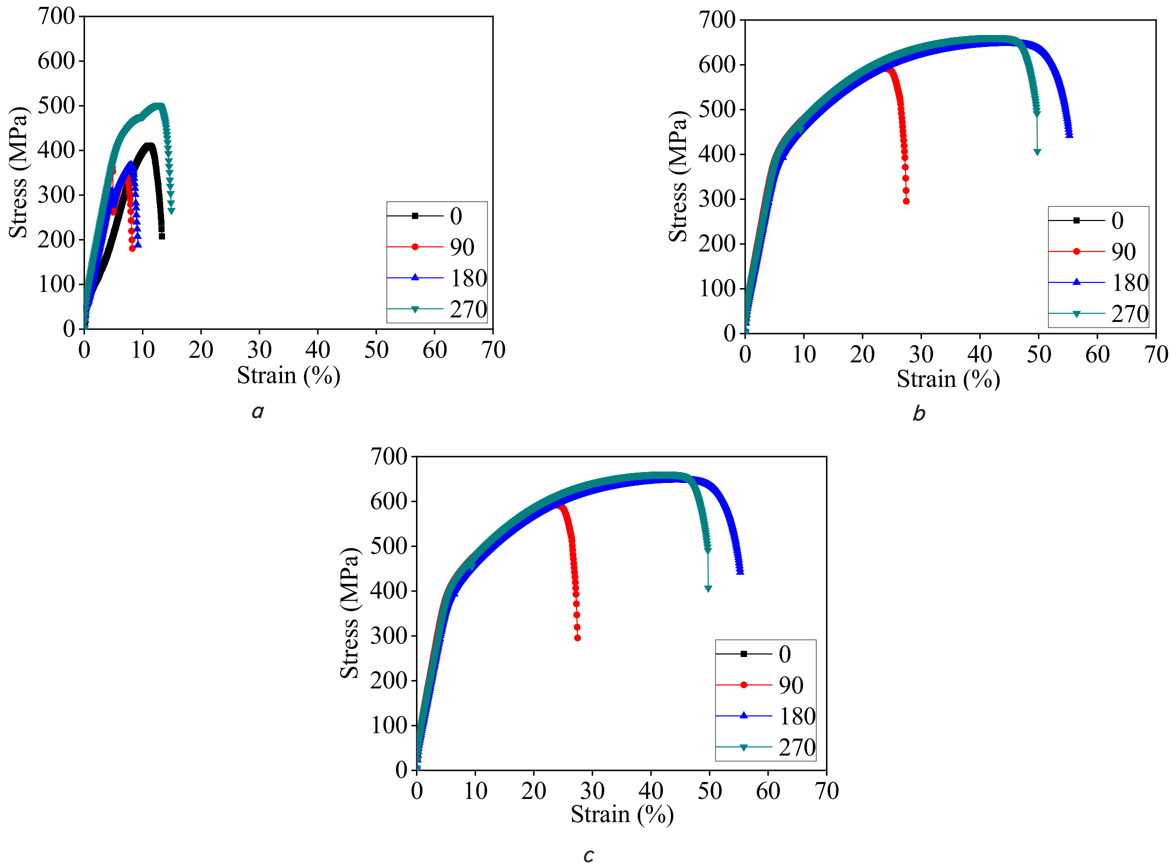


Fig. 8. Stress vs strain chart at a welding speed of 1.5 mm/s, with welding currents: *a* – 100 A; *b* – 110 A; *c* – 120 A

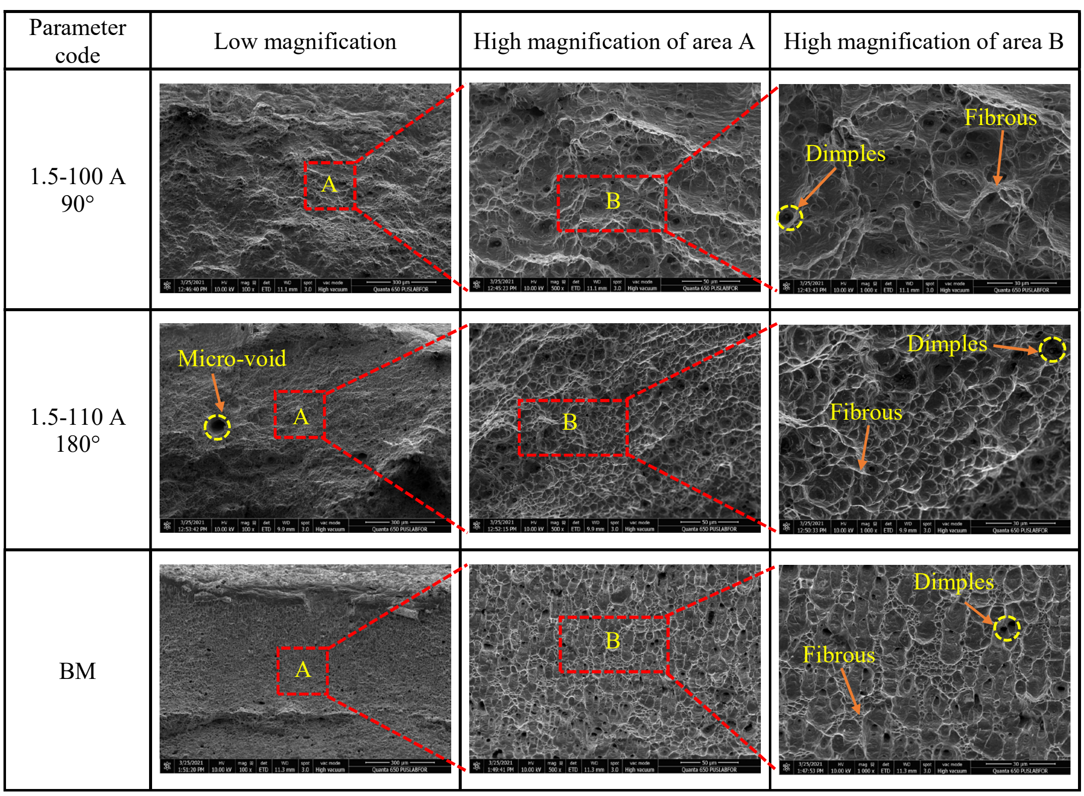


Fig. 9. Fault surface profile of tensile test results on several parameters with low magnification and high magnification

Table 3

Results of the pull test at 1.4 mm/s of welding speed

No.	Parameter	Position (degrees)	Tensile strength (MPa)	Standard deviation	Fracture location
1	14–100 A	0	565.15	26.44	Weld metal area
		90	497.56	26.30	Weld metal area
		180	531.79	28.89	Weld metal area
		270	500.18	8.55	Weld metal area
2	14–110 A	0	614.19	39.42	Weld metal area
		90	574.66	19.22	Weld metal area
		180	584.27	29.24	Weld metal area
		270	659.99	8.46	Weld metal area
3	14–120 A	0	632.09	13.09	Weld metal area
		90	662.58	5.81	Weld metal area
		180	659.33	1.07	Weld metal area
		270	632.82	12.93	Weld metal area

Table 4

Results of tensile tests at 1.5 mm/s of welding speed

No	Parameter	Position (degrees)	Tensile strength (MPa)	Standard deviation	Fracture location
1	15–100 A	0	400.19	10.56	Weld metal area
		90	351.33	10.30	Weld metal area
		180	383.57	16.06	Weld metal area
		270	480,51	20.69	Weld metal area
2	15–110 A	0	556.63	3.02	Weld metal area
		90	592.92	0.96	Weld metal area
		180	630.72	17.21	Base metal Area
		270	656.29	4.76	Weld metal area
3	15–120 A	0	574.84	13.21	Weld metal area
		90	676.19	2.03	Weld metal area
		180	644.56	3.45	Weld metal area
		270	565.77	9.01	Weld metal area

Fig. 9 shows that the welding speed used was 1.5 mm/s with a welding current of 100 A and a pipe position of 90°, which resulted in the lowest tensile strength and a brittle fracture surface with many large dimples and untidy fibers. On the other hand, the welding speed parameter of 1.5 mm/s with a welding current of 110 A and a pipe position of 180° produced the highest tensile strength and a more ductile fracture surface, showing large micro-voids with many dimples and large sizes. Moreover, the fracture results at the welding speed parameter of 1.5 mm/s with a welding current of 110 A and a pipe position of 180° were nearly identical to those of the base metal.

5. 2. Results of microhardness testing

The Vickers test is a method used to determine the microhardness of metallurgical specimens. In this study, microhardness testing was carried out only at a welding current parameter of 110 A because a welding current of 110 A produces the highest tensile strength, and the fracture surface is more malleable. Approaching the fracture results in the base metal.

The microhardness test results for this parameter are shown in Fig. 10, which displays the microhardness values at a welding current of 110 A with horizontal distribution at four different pipe positions 0° (*a*), 90° (*b*), 180° (*c*), and 270° (*d*). Micro hardness test points are carried out from the WM, HAZ, and BM areas along a horizontal distribution.

The microhardness testing results indicate that the welding speed of 1.4 mm/s has the highest microhardness value, but this parameter produces poor-quality welds. Conversely, the welding speed of 1.3 mm/s made the best quality welds based on the smallest microhardness value among all the parameters tested. The highest and lowest microhardness values were found at the welding speed of 1.4 mm/s, with 252 HV at the WM area in the 90° pipe position and 160.7 HV at the HAZ area in the same position. Furthermore, the horizontal distribution of the microhardness test showed that the microhardness value decreased at welding speeds of 1.3 mm/s and 1.5 mm/s. These results suggest that a microhardness test is a useful tool for assessing the quality of the welds, and the welding speed parameter is a critical factor in determining the microhardness value.

Below is a picture of the microhardness value at a welding current of 110 A with a vertical distribution in the WM area (Fig. 11).

The microhardness values at pipe positions 0° (*a*), 90° (*b*), 180° (*c*), and 270° (*d*) for a welding current of 110 A are presented in Fig. 11. The microhardness test points were conducted from the middle area of the weld metal (WM) in the vertical distribution. The microhardness test results indicate that welding with a welding speed of 1.4 mm/s produced the most considerable microhardness value. However, the microhardness value decreased when welding at 1.3 mm/s and 1.5 mm/s.

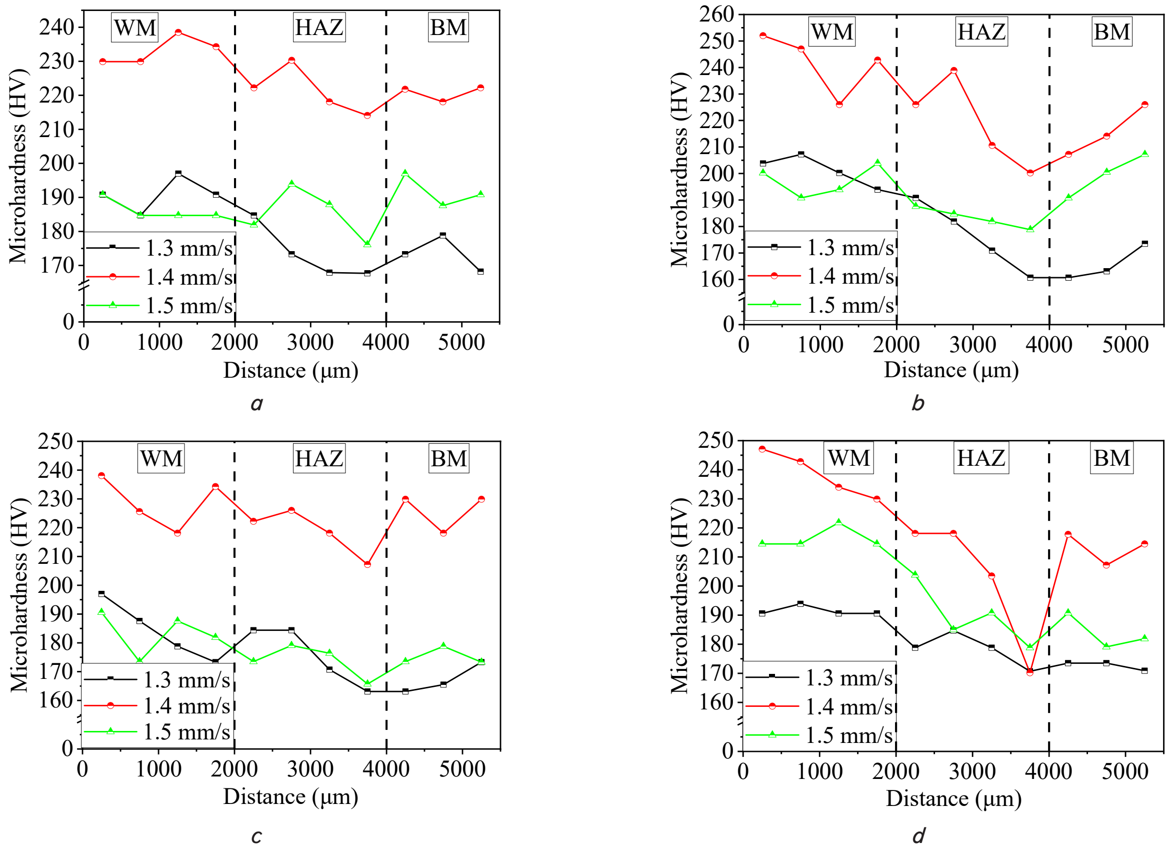


Fig. 10. Microhardness values on welding current 110 A with horizontal distribution at pipe position:
a – 0°; *b* – 90°; *c* – 180°; *d* – 270°

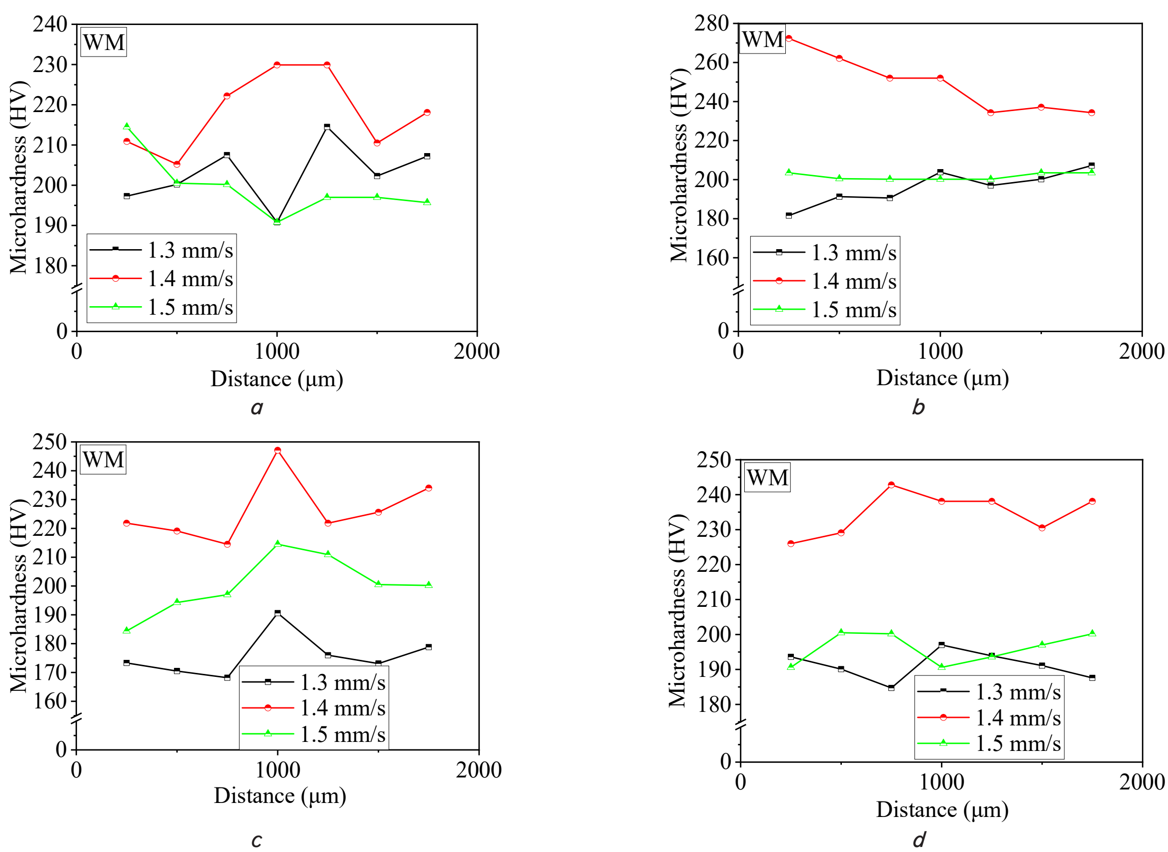


Fig.11. Microhardness values on welding current 110 A with vertical distribution at pipe position:
a – 0°; *b* – 90°; *c* – 180°; *d* – 270°

In the vertical distribution, the highest microhardness value was observed at a welding speed of 1.4 mm/s with 272.3 HV at a pipe position 90°. On the other hand, the smallest microhardness value was honored at a welding speed of 1.3 mm/s with a value of 170.5 HV at a pipe position of 270°. Thus, the high microhardness value for a welding speed of 1.4 mm/s indicates that the welding quality in this parameter is not good. On the other hand, the welding quality is better for a welding speed of 1.3 mm/s, as it has the smallest microhardness value compared to other parameters.

6. Discussion of the experimental results of tensile strength and microhardness

The research discussion has provided valuable insights into the various challenges faced during the orbital pipe welding process, particularly concerning the significant influence of gravity and the characteristics of SS 316L material. There is a noticeable contrast in the impact when welding in the 0° position compared to the 180° position. Ovality distortion may occur due to the higher density of SS316L and the heat generated during welding. This distortion can result in inconsistent spacing between the tungsten electrode and the base metal. The different positions along the weld are affected by the variations in weld penetration and nugget profiles, which directly impact the material's strength and hardness. A suggested approach to address this issue is using a sequential welding method, as discussed in a referenced paper [4]. This method effectively controls heat input and minimizes temperature variations in the material during the welding process. According to the research data, the optimal combination for achieving the highest tensile strength was a welding speed of 1.5 mm/s and a welding current of 120 A. This information can be found in Table 4 and Fig. 8. This parameter combination resulted in a comprehensive weld penetration, which led to a satisfactory weld bead width and a smoother surface finish.

In addition, a thorough examination of the grain size and microstructure was conducted, as evident from the SEM results illustrated in Fig. 9. The findings have significant implications. By meticulously managing welding parameters, one can surmount obstacles like distortion caused by gravity and attain the highest level of weld quality. The SEM results visually represent the material's microstructure, providing valuable insights into the grain size and morphology that arise from specific parameter combinations. This helps comprehend the correlation between parameters and weld quality and offers valuable insights for enhancing the orbital pipe welding process involving SS316L pipes.

This research paper highlights a crucial aspect of orbital pipe welding, specifically focusing on the continuous welding method. It is important to note that there is a potential risk of excessive heat generation on the inner side of the pipe during the welding process. Extreme heat during welding can result in over-penetration, which may cause the formation of holes in the final section of the SS316L material. Experiments conducted at various current levels, such as 100 A, 110 A, and 120 A, occasionally faced challenges, leading to the need for multiple welding attempts. These challenges can significantly affect the strength and hardness of the material. Based on the research, two potential solutions have been identified to tackle this issue.

One method involves a sequential welding approach to maintain consistent heat input and effectively control the material's temperature. This method efficiently retains the heat to prevent excessive penetration and damage to the material. In the second solution, argon gas is introduced into the pipe to regulate temperature and ensure a stable welding environment. This approach aligns with the findings presented in a referenced paper [8], which highlights the importance of certain factors, such as achieving the correct penetration depth and grain width, to gain maximum tensile strength. Increasing the welding current raises the temperature and heat input, which leads to a deeper weld penetration. Thus, it is crucial to meticulously regulate welding parameters to prevent problems such as excessive heat and penetration, which can impact the material's strength and hardness. These findings emphasize the significance of precise parameter control in orbital pipe welding. They emphasize the importance of implementing strategies like sequential welding and gas regulation to optimize the welding process and guarantee consistent, high-quality welds with SS316L material.

The size of grains that develop in different areas, such as the weld metal, heat-affected zone, and base metal, significantly impacts the microhardness of a weld. The temperature and heat input mainly influence the size of these grains the material is exposed to during the welding process, as extensively discussed in the literature [3]. After carefully analyzing the Weld Metal (WM), it becomes clear that a smaller grain size corresponds to a higher microhardness value. However, it is worth noting that the microhardness values in the Heat-Affected Zone (HAZ) tend to be lower in comparison to both the Weld Metal (WM) and Base Metal (BM) regions (refer to Fig. 10).

This is primarily because the HAZ area usually shows larger grain sizes and faster grain growth rates. It's important to note that in the context of this study, a welding speed of 1.3 mm/s results in higher heat input and a broader temperature distribution when accounting for different current fluctuations. Alternatively, setting the welding speed at 1.5 mm/s yields a decreased heat input and a more accurate temperature distribution, especially when compared to other welding parameters. Understanding temperature variation is crucial for accurately predicting grain growth. When welding at speeds of 1.3 mm/s and 1.5 mm/s, it is observed that grain structures tend to become coarser, which may lead to a decrease in microhardness values (refer to Fig. 10, *d*). After careful examination, it is clear that a welding speed of 1.3 mm/s yields superior weld quality in terms of microhardness values. This can be attributed to the promotion of smaller grain sizes. This information provides a thorough understanding of the complex connection between welding parameters, heat input, and grain size, which all play a role in determining the microhardness of the weld.

One crucial aspect to consider in this study is the continuous welding technique, which results in higher temperatures on the pipe's inner surface during welding. Due to the thermal effect, deformities may occur during welding in the challenging transition zone from 270° to 0° pipe position. As part of future research developments, it would be beneficial to explore the adoption of a sequential welding method. The welding process is carried out step-by-step, sequentially progressing from one position to another. For example, the process could begin at 0° and advance to position 90°. At this point, the welding process would temporarily pause to allow the material to cool down. After that, welding would resume, progressing from 90° to 180°, and so on. This sequential welding strategy helps address the difficulties that arise when welding in the final position from 270° to 0°, which can be quite challenging. Potential flaws and issues related to temperature-induced deformities at the critical 270° to 0° can be significantly minimized or even eradicated using a sequential welding approach. This approach implements a systematic and precise welding process, improving weld quality and reliability. Further research can explore the feasibility and effectiveness of this sequential welding method to address the limitations observed in this study.

7. Conclusion

1. A recent study has examined the relationship between welding speed, current, and tensile strength. At particular pipe places, faster welding rates and currents produce higher tensile strengths than lower ones. At a pipe angle of 90°, 1.5 mm/s, and 120 A generate the highest tensile strength of 676.19 MPa, whereas 100 A produces 480.51 MPa and 351.33 MPa. Depending on welding settings, the base metal's maximum tensile strength is lowered by 1.1 % to 48.6 %. Orbital pipe welding requires careful parameter selection to obtain the required tensile strength.

2. A deeper investigation shows that 1.4 mm/s and 110 A welding current produce the maximum microhardness value in the weld metal area and finer grains in the middle region. This indicates that this combination of factors improves weld quality. However, increasing the welding speed to 1.5 mm/s decreases microhardness and coarsens grains in the center weld metal area. However, reducing the welding speed to 1.3 mm/s increases microhardness but coarsens middle grains. In conclusion, a welding speed of 1.4 mm/s and a welding current of 110 A produce the highest microhardness and finer grain structure, indicating a better weld.

Conflict of interest

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

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Data availability

The manuscript has no associated data.

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