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Design and Analysis of Orbital Pipe Welding Prototype for Piping System Welding Applications

Agus Widyianto[1*], Ario Sunar Baskoro[2], Gandjar Kiswanto[2]

[1]Automotive Engineering and Manufacturing Research Group, Department of Mechanical and Automotive Engineering, Faculty of Vocational, Universitas Negeri Yogyakarta, Kampus Wates, 55652, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI Depok, 16424, Indonesia

*Corresponding author: aguswidyianto@uny.ac.id

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ABSTRACT

Welding the joints of pipes is often required for maintenance and repairs in industrial applications, where pipes are frequently used. A prototype of an orbital pipe welding machine was constructed, and its design, analysis, and construction were carried out. The goal of this endeavor was to improve the quality of the welding process as well as overall productivity. The design study was carried out with the assistance of the SolidWorks program, which allowed for the determination of the stress, strain, displacement, and factor of safety imposed on the gear section throughout the welding and pipe installation process. During pipe installation, the gear section experiences maximum stresses of 3.920e+12 MPa, 5.029e+05 MPa, and 2.239e+06 MPa, respectively. These stresses are a result of the pipe being installed. When the pipe is installed, the highest strain in the gear section is 1.802e+01%, 3.030e-06%, and 8.439e-06%, respectively. This strain happens when the pipe is installed. In addition, the maximum displacement in the gear section is 3.074e+09 mm, 3.215e+04 mm, and 6.312e-03 mm, respectively, when the pipe is mounted and the pipe is installed. With a value of 1.5, the analysis results demonstrated that the maximum stresses, strains, and displacements in the gear section during the welding process are sufficient to fulfill the requirements for the critical safety factor. This demonstrates that the orbital pipe welding equipment may be utilized to generate welds of superior quality while simultaneously enhancing both productivity and efficiency through its utilization.

1. Introduction

Welding is an essential process in construction and manufacturing, and it plays a crucial role in the industry. As time passes, welding techniques are continually evolving, and technology is constantly advancing in this field. The development of these technologies is primarily focused on enhancing the quality of welding results. Advancements in welding technology have led to improved welding techniques and equipment that offer greater accuracy, efficiency, and safety. This progress has enabled industries to produce high-quality welding results with greater precision and speed, resulting in improved productivity and profitability [1]. In summary, the development of welding technology is an ongoing process that aims to improve the quality and efficiency of welding and enable industries to stay competitive in a rapidly evolving market.

Pipe welding is a crucial process in various engineering applications such as the oil and gas industry, automotive industry, nuclear and thermal power plants, petrochemicals, food processing, pharmaceuticals, and more. The use of SS316L stainless steel pipes is prevalent in petrochemical, pharmaceutical, and food processing industries due to their corrosion resistance, high-temperature strength, and durability [2, 3]. As the use of natural gas is expected to increase in the next two decades, there will be a rising demand for pipe welding in the petrochemical industry [4].

The demand for high-pressure gas transmission pipes has also increased, and to meet this demand, it is essential to have pipes with high strength, toughness, and ductility at a lower cost. The selection of appropriate materials for such pipes is crucial to ensure their quality and safety. Therefore, there is a need to invest in the development of new technologies and innovative designs that can produce high-quality, cost-effective pipe welding solutions [5]. The advancements in welding technology have led to the development of various welding techniques, such as orbital welding, which provides a more precise and efficient way of welding pipes. By using such techniques, the quality of the welding results can be improved, leading to safer and more reliable pipeline transmission systems [6].

The use of automatic welding machines in pipeline construction has greatly improved the efficiency and quality of the welding process. With the help of these machines, welding can be done at a much faster pace and with greater precision than manual welding. Moreover, the use of automatic welding machines has reduced the amount of labor needed for welding, which in turn reduces the cost of pipeline construction. In the case of the pipeline automatic welding machines, the rigid pneumatic clamping apparatus and double driving slewing mechanism allow for the precise alignment and rotation of two pipe tubes during the welding process [7]. This results in a uniform and high-quality weld that meets industry standards. The ability of these machines to operate in harsh environments and handle large diameter pipelines makes them suitable for a wide range of pipeline construction projects [8].

The article [9] studied the difficulty of ship pipeline welding in tight and narrow spaces and proposed a novel auxiliary device to assist with the welding process. The article explored the design and analysis of the device and provided experimental results showing its effectiveness in improving welding quality. However, the article did not investigate other potential factors that may affect ship pipeline welding, such as welding techniques or material properties, and did not discuss potential limitations or drawbacks of the proposed device. The article by Mehrdad et al. [10] is focused on the design and analysis of a welding robot for arc welding. The article studies the design of the robot's mechanical structure, control system, and trajectory planning algorithm, as well as the analysis of its welding performance. However, the article does not address the impact of welding environment factors such as temperature, humidity, and contaminants on the performance of the robot, and the reason for this omission is not clear.

The study conducted by Mariam et al [11] aimed to design and analyze a soft crawling robot, with a particular focus on optimizing the robot's design parameters for efficient crawling motion. The study explored various design aspects, including material properties, geometry, and actuation mechanism to identify the optimal configuration that would produce the desired crawling motion. On the other hand, Ridzuan and Jagan [12] investigated the design and analysis of a monorack arm made of carbon fiber composite material for a motorcycle. The study primarily focused on analyzing the stress and deformation behavior of the monorack arm under different loading conditions using finite element analysis (FEA) software. Additionally, the study aimed to optimize the monorack arm's design for minimum weight and maximum strength.

Manual welding has been the traditional method of welding, but it has several weaknesses, such as a lack of precision, inconsistency in the final product, and the high skill level required of the welder. As a solution, welding orbital machines have been developed and are already available on the market. These machines offer a higher level of precision, consistency, and efficiency in the welding process. However, some of these machines are expensive and may not be customizable to the specific needs of different industries [13].

This research addresses these concerns by developing an orbital pipe welding prototype that is cost-effective and customizable to industry needs. The design of the prototype incorporates features that make it efficient and reliable in producing high-quality welds on SS316L stainless steel pipes. Additionally, the prototype can be customized to fit pipes with different diameters and thicknesses, making it a versatile tool for a range of industries. The economic aspect of the prototype is also an important consideration. Building a pipeline transmission system requires a sizable investment, and a cost-effective tool for welding the pipes can help reduce overall project costs. This makes the orbital pipe welding prototype an attractive option for companies looking to reduce costs while maintaining high standards of quality and safety. Overall, this research presents a promising solution to the challenges of pipe welding. By developing a cost-effective and customizable orbital pipe welding prototype, the industry can benefit from increased efficiency, precision, and safety in the welding process.

2. Methodology

The analysis of the orbital pipe welding prototypes was carried out using SolidWorks software, which is a computer-aided design (CAD) tool that allows for the simulation of static and dynamic load tests. The software was used to generate a three-dimensional model of the prototypes, and the design was analyzed for Von Mises stresses. This approach allowed for a detailed examination of the prototypes and helped to identify potential stress points or weak areas. To ensure that the experimental design approach was effective, a range of different materials and sizes were used in the orbital pipe welding prototypes. The prototypes were tested under various loading conditions, and the resulting stresses were analyzed to determine the most effective design for the prototypes. To conduct the analysis of the orbital pipe welding prototype, the geometry of the prototype was redesigned using SolidWorks software to suit the required shape. The new design was then modelled into three dimensions to facilitate the analysis process. The use of SolidWorks software helped to generate a 3D model of the prototype, which enabled the analysis to be conducted more accurately.

The analysis process involved subjecting the prototype to various static and dynamic load tests, and the software was able to generate output data that described the stress, strain, displacement, and factor of safety. By analyzing the output data, it was possible to determine how the prototype would perform under different loading conditions and identify any areas of weakness that needed to be addressed. The use of this experimental design approach enabled the researchers to simulate the behaviour of the prototype under a variety of different conditions, without the need for costly physical testing. This approach allowed for the exploration of multiple design alternatives and helped to optimize the design of the orbital pipe welding prototype. Overall, the use of SolidWorks software and the experimental design approach provided a powerful tool for designing and analyzing complex engineering systems like the orbital pipe welding prototype.

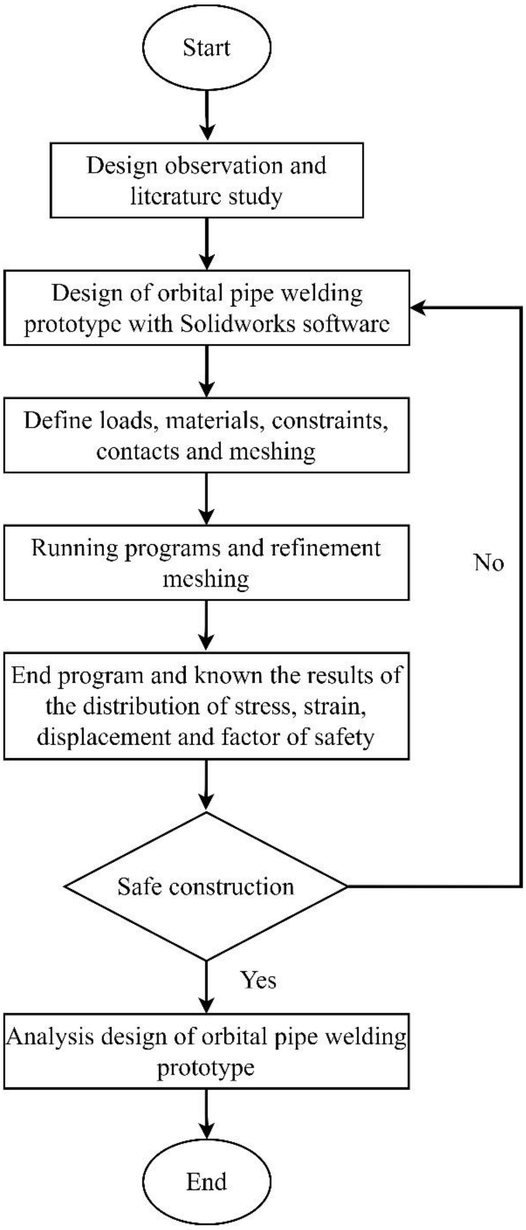


Figure 1. Schematic flow chart design of orbital pipe welding prototype

The process of designing the orbital pipe welding prototype using SolidWorks software is presented in a flowchart in Fig. 1. The study began by gathering geometry data and other relevant information necessary for analyzing the prototype. Then, the prototype was designed from the fabrication of its parts to its final assembly. This process involved inputting material properties, constraints, and contact details, followed by meshing and load determination. The program was run, and the meshing was refined to obtain information on the distribution of stress, strain, displacement, and factor of safety on the prototype. This information was then used to evaluate the safety of the prototype. If the construction was found to be unsafe, the design phase was repeated, and if it was determined to be safe, the analysis of the orbital pipe welding prototype design proceeded.

3. Result and Discussion

The design analysis process involves subjecting the prototype design to various simulations and tests to evaluate its performance under different operating conditions. The stress analysis is carried out to determine the distribution of forces and stresses within the gear section and the pipe when subjected to different loads. The strain analysis helps to determine the deformation of the materials under load, while the displacement analysis assesses the deflection of the pipe and the gear section. The factor of safety is an important consideration during the design analysis process. It is a measure of the safety margin built into the design to ensure that the prototype can withstand the maximum load without failure. If the factor of safety is too low, it indicates that the prototype is not strong enough to withstand the required load and modifications need to be made to the design. The design analysis process plays a critical role in determining whether the orbital pipe welding prototype can be made into a production-ready tool. By evaluating the design's performance and durability under different operating conditions, engineers can optimize the design to ensure it meets the required specifications and standards. Ultimately, the success of the design analysis process will determine whether the prototype can progress to the manufacturing stage and be successfully commercialized.

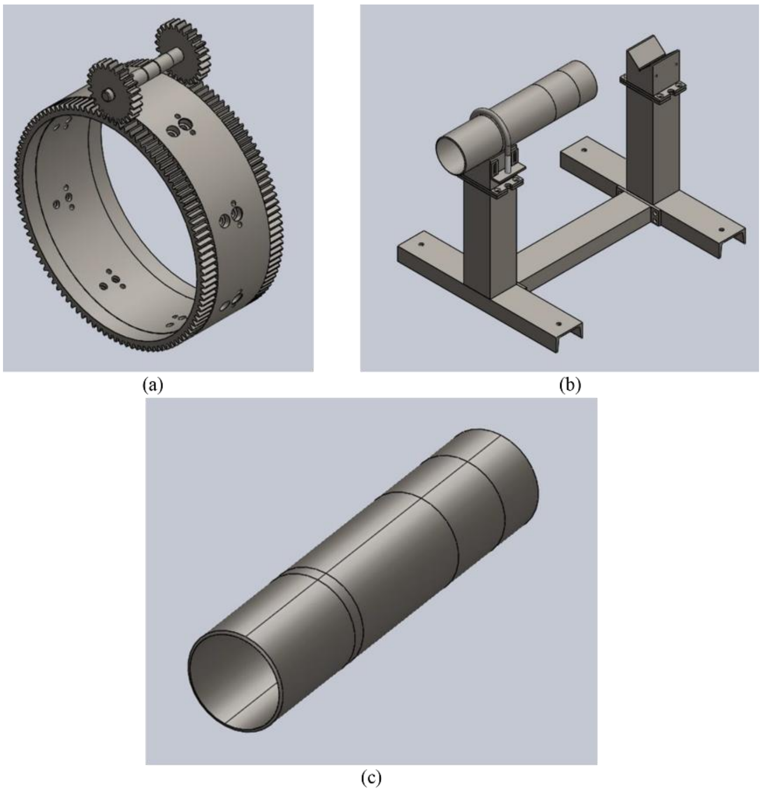


Figure 2. Base design part of (a) gear, (b) when the pipe is installed and (c) the pipe

The basic design of the orbital pipe welding prototype shown in Fig. 2 is well-suited for its intended application and has been carefully designed to ensure the safety and stability of the welding process. The gear-to-gear mechanism shown in Fig. 2a is designed to transfer the rotational movement from the motor to the pipe holder. The small gear and large gear are connected by a shaft to transmit the rotational force. The small gear rotates with a speed of 1000 rpm (107 teeth), while the large gear rotates with a speed of 237 rpm (25 teeth). The number of teeth in the gears is chosen to provide the necessary torque to hold the pipe and rotate it during welding.

Table 1. Material properties of SS 316

Material	Modulus of elasticity (MPa)	Yield strength (MPa)	Ultimate strength (MPa)	Poisson's ratio	Density (kg/m^3)
SS 316	192999.99	172.37	580	0.27	8000

In the pipe support section shown in Fig. 2b, the v block model is used to hold the pipe in place, while the U pipe lock is used to clamp the pipe firmly. This design ensures that the pipe remains stable during welding and prevents any unwanted movement. The pipe to be analyzed in Figure 2c is a 304L stainless steel pipe with a diameter of 4 inches. This type of pipe is commonly used in the food, beverage, and pharmaceutical industries due to its high corrosion resistance and excellent mechanical properties. The wall thickness of the pipe is chosen based on the requirements of the application and is usually thicker for higher pressure applications. Table 1 shows the material properties of orbital pipe welding prototype used in the analysis.

3.1 Stress analysis on orbital pipe welding prototype

The von Mises stress type is a commonly used method in stress analysis to evaluate the maximum stress that a material can endure before yielding. By applying this method to the gear part of the orbital pipe welding prototype, engineers can determine the strength of the gear to withstand static loads and rotational forces. The stress analysis involves applying loads to the gear in different directions and simulating the effects of these loads on the material. The load on the gear is indicated by the red arrows in the analysis, with the assumption that the total weight of the orbital pipe welding prototype is 250 N. This allows engineers to evaluate the stress distribution within the gear and identify any areas that are susceptible to failure.

The aim of the stress analysis is to ensure that the gear is strong enough to withstand the loads it will be subjected to during operation. This includes not only the weight of the prototype but also the forces generated during welding. By ensuring that the gear is strong enough, engineers can minimize the risk of gear failure and ensure that the orbital pipe welding prototype is safe to use.

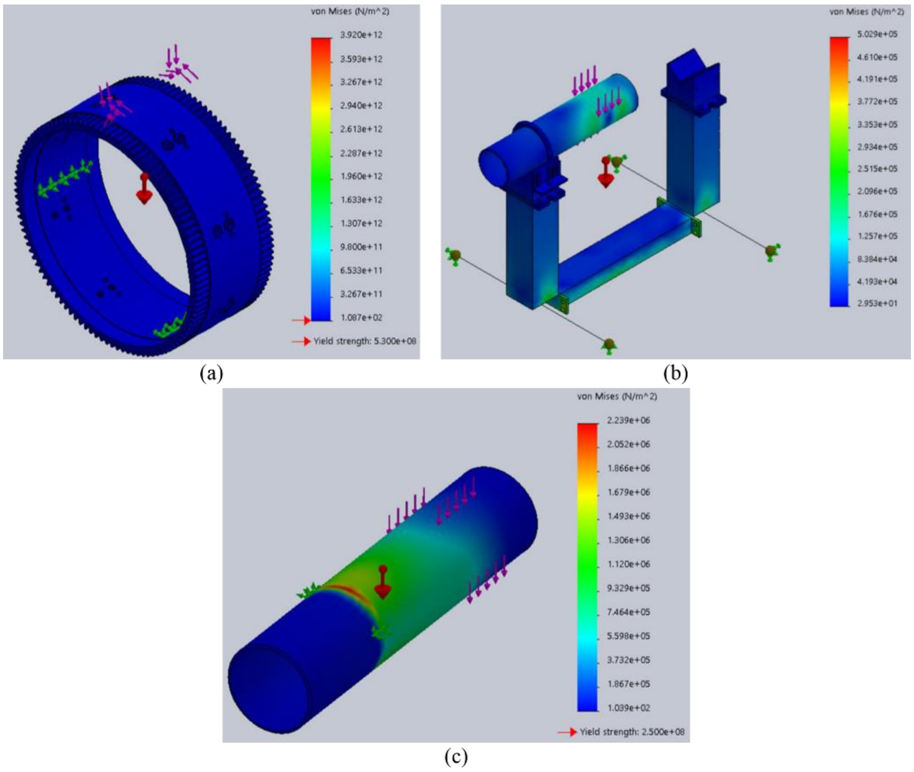


Figure 3. Stress analysis on (a) gear, (b) when the pipe is installed and (c) the pipe

The results of the von Mises stress analysis are crucial in determining the strength and durability of the orbital pipe welding prototype during operation. As depicted in Fig. 3, the stress distribution analysis highlights the maximum and minimum stresses using Solidworks software. The gear section was subjected to the stress analysis, as shown in Fig. 3a. The results of this analysis show that the gear can endure a maximum stress of 3.920e+12 MPa, a minimum stress of 1.087e+02 MPa and has a yield strength of 5.300e+08 MPa. These outcomes are vital in determining the reliability of the gear during operation.

Additionally, Fig. 3b presents the stress analysis of the welding prototype when the pipe is installed. The results show that the pipe installation causes a maximum stress of 5.029e+05 MPa and a minimum stress of 2.953e+01 MPa. This analysis is useful in determining the load-bearing capacity of the welding prototype when the pipe is installed. Furthermore, the stress analysis of a 4-inch diameter pipe section is shown in Fig. 3c. The results show that the maximum stress the pipe can withstand is 2.239e+06 MPa, the minimum stress is 1.039e+02 MPa, and the yield strength is 2.500e+08 MPa. These results are critical in ensuring that the welding prototype can withstand the stress caused during welding operations and can safely perform its function without compromising the integrity of the pipe section [14].

Overall, the stress analysis is a critical step in the design process for the orbital pipe welding prototype. By evaluating the strength and durability of the gear, engineers can optimize the design and ensure that the prototype can withstand the demands of real-world welding applications. This will help to ensure the successful commercialization of the prototype and its widespread adoption in the welding industry. The von Mises stress type static load analysis is essential in evaluating the strength and reliability of the orbital pipe welding prototype. The results of this analysis provide valuable insights into the performance of the prototype, and help engineers optimize the design for safe and effective operation.

3.2 Strain analysis on orbital pipe welding prototype

The strain analysis provides crucial information about the deformation of the material under stress, which can affect the overall performance of the welding prototype. In particular, the strain analysis helps to identify the regions of the gear section that are most susceptible to deformation, which can guide engineers in optimizing the design for maximum strength and durability. The results of the strain analysis are important in ensuring the welding prototype ability to withstand the high-stress conditions experienced during welding operations. By analyzing the strain values, engineers can identify any areas of weakness and make necessary design modifications to enhance the prototype performance. Overall, the strain analysis provides valuable insights into the structural behavior of the welding prototype and helps engineers optimize the design for optimal performance and safety.

The strain analysis is an important aspect of determining the performance and reliability of the orbital pipe welding prototype. The strain analysis test results using SolidWorks software are presented in Fig. 4. The figure displays the strain analysis on the gear section, shown in Fig. 4a. The maximum change in strain is indicated by the red color, and its value is 1.802e+01%. The minimum change in strain, represented by the blue color, has a value of 2.774e-10%. Fig. 4b shows the results of the strain analysis when the pipe is installed. The maximum strain observed in this case was 3.030e-06%, while the minimum strain was 0%. Additionally, the strain analysis was performed on the pipe section, and the results are presented in Fig. 4c. It was observed that the maximum strain on the pipe section was 8.439e-06%, while the minimum strain was 3.863e-09%. The results of the tests indicate that the design of the gear section of the welding prototype experiences only very small strains when subjected to loading [15].

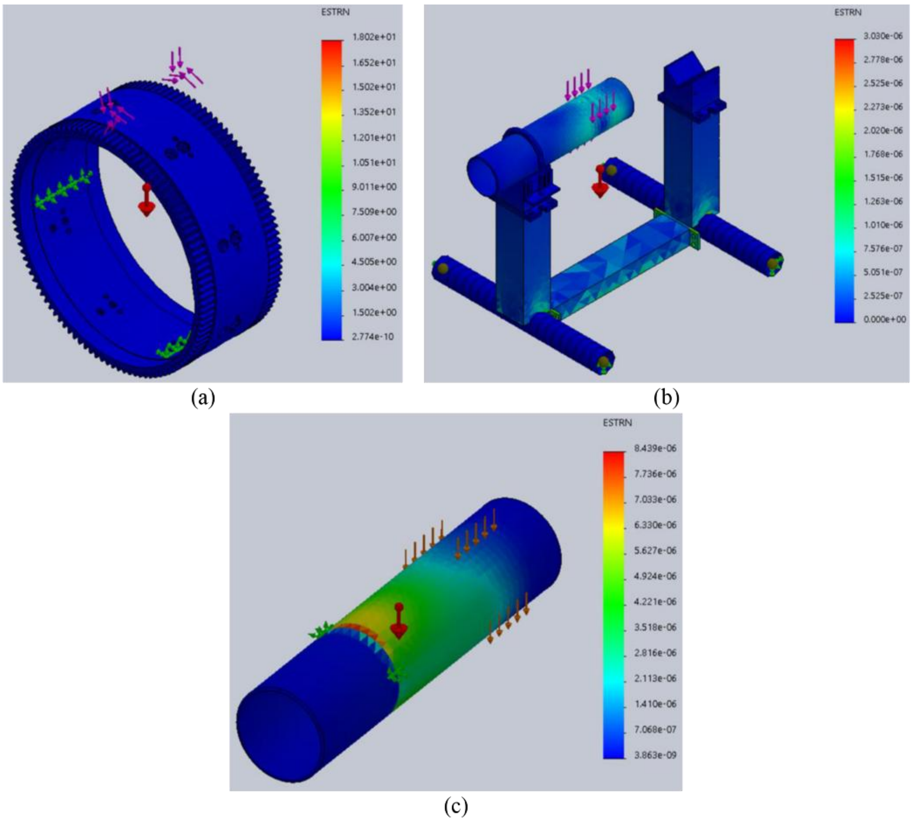


Figure 4. Strain analysis on (a) gear, (b) when the pipe is installed and (c) the pipe

This is a positive indication that the welding prototype is structurally sound and can withstand the stresses associated with welding operations. However, it is important to note that the strain analysis provides only a snapshot of the prototype's behavior under a specific set of conditions. It is necessary to conduct further tests to verify the prototype's performance under different loading conditions to ensure its overall reliability and safety. The strain analysis results provide valuable insights into the deformation behavior of the welding prototype. By analyzing the strain values, engineers can identify potential weaknesses in the design and make necessary modifications to optimize the prototype's performance and safety. Overall, the strain analysis is a critical component of the testing process for the welding prototype and helps ensure its reliability and durability.

3.3 Displacement analysis on orbital pipe welding prototype

The displacement analysis is critical in evaluating the performance of the orbital pipe welding tool prototype because it enables the identification of areas that may be prone to failure due to excessive deformation or displacement. Moreover, the displacement analysis can help engineers optimize the design to achieve maximum stability and rigidity while minimizing weight and material usage [16]. Overall, the results of the displacement analysis help to ensure that the final product is safe, reliable, and able to perform its intended function without failure.

The displacement analysis performed on the orbital pipe welding tool prototype design indicates that the amount of displacement is within safe limits. The maximum and minimum displacement values for the gear section, shown in Fig. 5a, are 3.074e+09 mm and 1,000e-30 mm, respectively. Similarly, Fig. 5b illustrates that the maximum and minimum displacements for the installed pipe are 3.215e+04 mm and 1,000e-30 mm, respectively. Moreover, the displacement analysis of the pipe section, depicted in Fig. 5c, indicates that the maximum and minimum displacements are 6.312e-03 mm and 1,000e-30 mm, respectively. These values are well within the safe limits, as changes exceeding 1 mm can result in material failure.

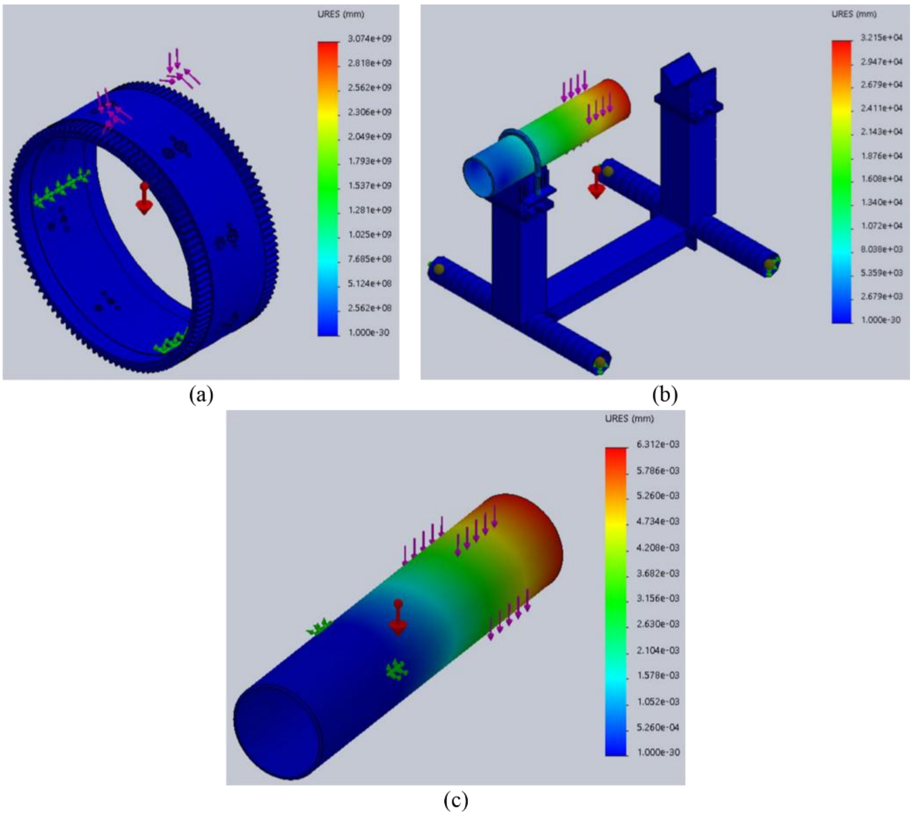


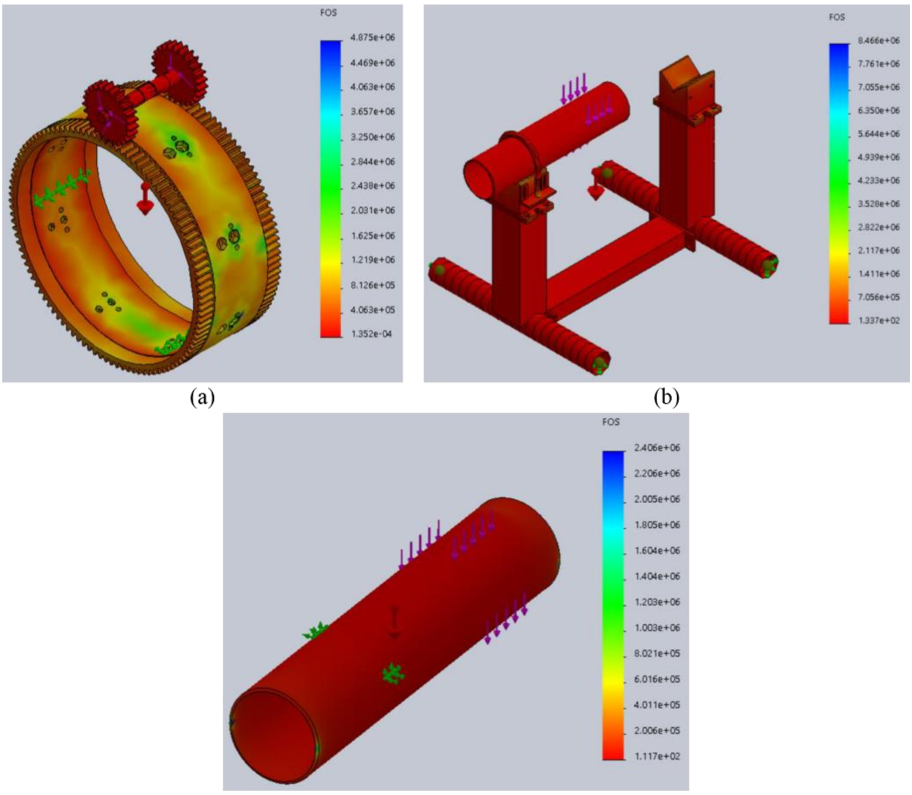
Figure 5. Displacement analysis on (a) gear, (b) when the pipe is installed and (c) the pipe

Overall, the results of the displacement analysis suggest that the gear frame's shape and material used in the orbital pipe welding tool's prototype design are safe for use under load. Fig. 5 visually presents the amount of displacement in the tool, providing a clear understanding of how much movement occurs due to load.

3.4 Factor of safety analysis on orbital pipe welding prototype

The factor of safety (FOS) is a measure of the safety margin of a structure or component against failure due to the applied loads. The FOS is calculated by dividing the yield strength of the material by the maximum stress experienced by the structure or component. In this case, the FOS analysis was carried out on the gear section of the orbital pipe welding prototype to ensure that it can withstand the static loads it will be subjected to during operation.

Fig. 6a shows the loading on the gear, which is indicated by the red arrow. The maximum and minimum FOS values for the gear section are 4.875e+06 and 1.352e-04 respectively. These values indicate that the gear section has a high margin of safety and is capable of withstanding the load. Fig. 6b shows the FOS analysis when the pipe is installed. The maximum and minimum FOS values are 8.466e+06 and 1.337e+02 respectively. These values indicate that the pipe section has a high margin of safety and is capable of withstanding the load. Fig. 6c shows the FOS analysis on the pipe section. The maximum and minimum FOS values are 2.406e+06 and 1.117e+02 respectively. These values also indicate that the pipe section has a high margin of safety and is capable of withstanding the load [17].



(a) (b)

(c)

Figure 6. Factor of safety analysis on (a) gear, (b) when the pipe is installed and (c) the pipe

Based on the calculations, it can be concluded that the material used on the gear and pipe sections of the orbital pipe welding prototype is strong enough to withstand the load. The FOS values are greater than 1.5, which is the minimum value recommended for safe operation. If the FOS value were to be 1.5 or less, it would indicate that the material has been deformed or broken, as the maximum stress is comparable or greater than the yield strength of the material. Therefore, the FOS analysis confirms the reliability and safety of the orbital pipe welding prototype.

3.5 The results of the work test of the orbital pipe welding prototype

The design of the orbital pipe welding prototype is presented in Fig. 7, providing a comprehensive depiction of the design. In Fig. 7a, the design of the pipe support system is showcased, which is suitable for fitting pipes with a 4-inch diameter. The gear-to-gear mechanism design for orbital pipe welding is presented in Fig. 7b, which includes 8 locks that securely hold the pipe in place during the welding process. Fig. 7c depicts the insertion of the gear-to-gear mechanism into the pipe. Lastly, the fabrication results of the orbital pipe welding prototype can be seen in Fig. 7d, which provides a visual representation of the finished product, allowing for a better understanding of the overall design.

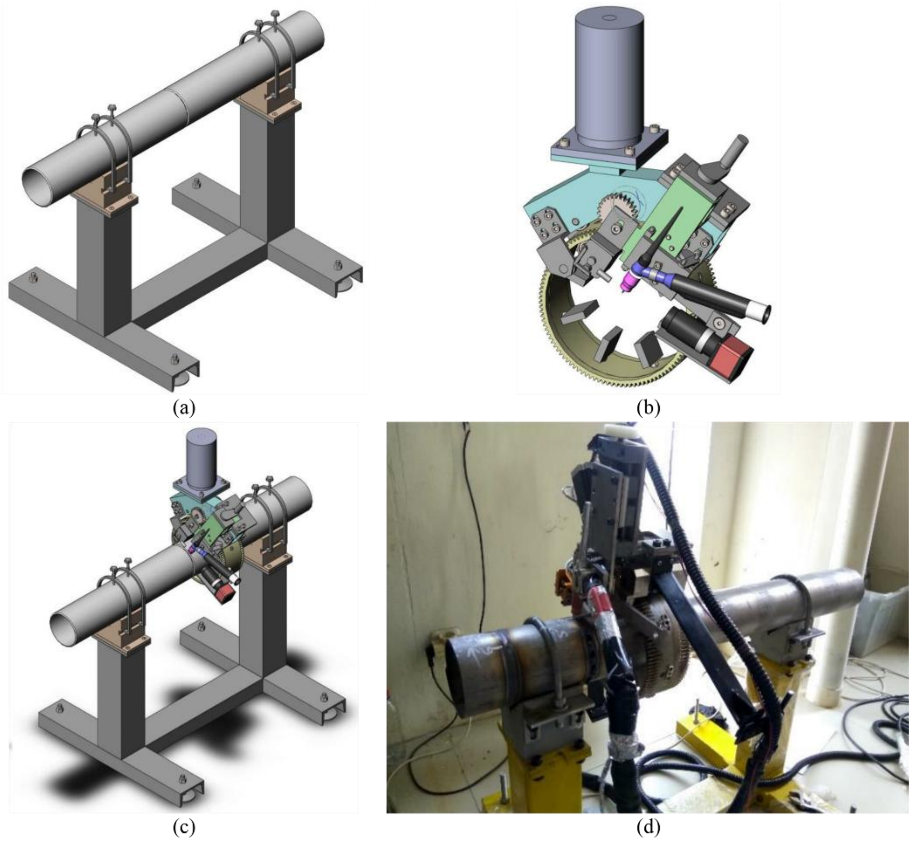


Figure 7. Design of (a) pipe support system, (b) gear-to-gear mechanism, (c) assembly of pipe support and gear-to-gear mechanism and (d) prototype of orbital pipe welding [18]

After successfully designing the orbital pipe welding prototype, the next step was to test its functionality using a welding tool. SS316L pipes with a thickness of 3 mm and a butt joint connection were selected for testing. The welding process was carried out using a welding current parameter of 110 A and a welding speed of 1.4 mm/s. The results of the welding process were highly satisfactory, with no issues or problems encountered during the welding process.

Figure 8. The results of the weld using the orbital pipe welding prototype

To further evaluate the effectiveness of the prototype, the pipe welding results were cut and labelled from an angle of 0 to 360 degrees, providing a comprehensive overview of the quality of the welds. This data is presented in Fig. 8, which serves as an important reference for analyzing the performance of the orbital pipe welding prototype. Overall, the successful results of the welding test indicate that the design and implementation of the orbital pipe welding prototype was a success and has the potential to be a valuable tool for welding applications in the future.

4. Conclusion

The study described in this paper focuses on the design and analysis of an orbital pipe welding prototype that utilizes AISI 316 stainless steel. The design was analyzed using SolidWorks software to determine stress, strain, displacement, and factor of safety on the gear section during the installation and welding of the pipe. The maximum stresses, strains, and displacements that occur in the gear section were found to be 3.920e+12 MPa, 5.029e+05 MPa, and 2.239e+06 MPa respectively, for when the pipe is installed and welded. Additionally, the maximum strain was found to be 1.802e+01%, 3.030e-06%, and 8.439e-06% respectively, and the maximum displacement was found to be 3.074e+09 mm, 3.215e+04 mm, and 6.312e-03 mm respectively. The analysis of the factor of safety on the static stress distribution of the welding equipment showed that it meets the required critical factor of safety with a value of 1.5. The welding prototype was successfully tested on pipes without any issues, and the welds produced were of good quality but require further analysis with other welding parameters. Overall, this study provides a solid foundation for the use of orbital pipe welding as a reliable and efficient method for joining pipes in industry.

Conflict of interest

The authors declare no conflict of interest.

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