

Effect of Friction Pressure on Mechanical Properties of Austenitic Stainless-Steel Pipe Using Rotary Friction Welding

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ABSTRACT

Rotary friction welding (RFW) is one of the most effective and efficient methods of joining for welding similar and dissimilar materials in different industrial applications. In this study, the influence of friction pressure of Continuous Drive Rotary Friction Welding (CDRFW) was investigated for welding austenitic stainless-steel pipe (grade TP316L) at two different friction times, while other welding process parameters remained constant during the process. The results demonstrate a complex relationship between the friction welding parameters. For the first set of samples with a longer period of friction time of 45 seconds, increasing the friction pressure decreases the mechanical properties. In contrast, for a shorter period of friction time of 15 seconds, increasing the friction pressure increases the mechanical properties. The best result among the welded samples was achieved at the highest friction pressure and the shorter friction time, with the tensile strength reaching 457 MPa. However, for the longer period of friction time of 45 seconds, the tensile strength is dropped to a minimum of 171 MPa. The key parameter in this process is the heat input, which must be carefully controlled. Excessive or insufficient heat input can lead to improper bonding and poor weld quality. The findings of this study show that welded joints with the highest friction pressure combined with lower friction time give the best result of tensile strength and hardness profile. In contrast, the high friction pressure and friction time together need to be avoided to prevent degraded weld performance.

Keywords:

Friction Pressure, Friction Time, Austenitic Stainless-Steel Pipe, Mechanical Property, Microstructure.

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1. INTRODUCTION

Rotary friction welding is a solid-state welding process that utilizes the frictional heat produced at the rubbing surfaces. It raises the temperature at the interface to a point where high pressure causes the two surfaces to forge together. The technical and economic advantages of friction welding in comparison to other welding processes are significant [1-3]. In this process of welding, the values of the critical process parameters, including friction pressure, friction time, speed of rotation, forging pressure, and forging times have significant effects on the generated heat and joint formation. The microstructure of the welded joints can be affected by variations in each of these parameters, which in turn can change the mechanical properties of the welded joints. Therefore, the process parameters, microstructure,

and mechanical properties are strongly interrelated during rotary friction welding [4].

The main distinct feature of rotary friction welding, compared to other welding techniques, is that it can be used to weld similar and dissimilar metals. This capability is particularly advantageous to weld different grades of stainless steel, which can be used in various applications. It is widely regarded and considered as an effective method of welding to eliminate and overcome the limitations faced with traditional methods. Notably, it enables joining metals with different chemical, mechanical, and physical properties. The key advantages of this method of welding are significant cost savings, higher productivity, and elimination of consumable materials compared to traditional methods. So the difficulties faced during the selection of filler material can be eliminated [5-8].

Stainless steel is one of the most important and interesting materials in the field of engineering, due to its superior mechanical properties and excellent corrosion resistance. These characteristics establish it as a high-quality material. The material's widespread utilization in a broad range of applications demonstrates its high degree of importance and reliability [9-11]. The annual consumption of stainless steel in the last few decades has experienced significant growth, surpassing the growth rate of other metals [12]. This wide range of applications is because this material is available in a large variety of alloy compositions, resulting in a large variety of properties and manufacturability [13].

In the world of industry, and specifically in manufacturing process, welding can be considered as one of the main and crucial methods of joining various engineering components. Compared to other methods of joining, low fabrication cost, high efficiency, simple setup, and wide range of applicability are the most important features of this method of joining [14]. Stainless steel can be welded with many different types of welding processes. Each single technique has distinct advantages and limitations for the different types and grades of stainless steel. There has been a continuous study to improve the quality and weldability of stainless steel. Friction welding is one of the very efficient techniques that can be used to weld this material to eliminate common issues associated with melting and solidification and increase the quality and productivity. Austenitic stainless steel is one of the most common and famous types of stainless steel. It has the widest application because of its good features, such as easily formable, weldability, and good corrosion resistance, especially in the fields of oil and gas, petrochemical, power generating plants, and refineries.

Depending on the welding technique and process parameters for each method, including heat input and cooling rate, certain parts of the base metal experience peak or a range of temperature that is high enough to produce or develop microstructure changes, phase change, grain growth, or develop new phases in stainless steel. These can affect and degrade the mechanical properties, even corrosion resistance of the product, particularly in the heat-affected zone and weld area [15]. Rotary friction welding is a strong alternative method of welding to conventional welding techniques that can be used to join stainless steel materials which prevents material from melting and lowers heat input, making shorter heating and cooling cycles. This can reduce and eliminate the possibility of the formation of new and undesired phases [4]. Several researchers have

studied the effect of welding and welding parameters on the mechanical properties of the weld metal and the joint efficiency of stainless-steel materials.

For example, Mohammed et al. [16] conducted an investigation into the mechanical properties and corrosion resistance of similar and dissimilar stainless steel joints using the Gas Tungsten Arc Welding (GTAW) process employing two different types of filler materials. Their result showed that similar weld joints have better mechanical properties, and for dissimilar joints, the joints with 309L filler material have an optimum combination of mechanical properties and corrosion resistance compared to 2209 filler material.

Another work done by Unnikrishnan et al. [17] to study the effect of Shielded Metal Arc Welding (SMAW) and heat input on mechanical properties, microstructure, in addition to corrosion resistance and residual stress of austenitic stainless steel. Their findings showed that both ferrite content and grain size increased with an increase in heat input. Furthermore, shielded metal arc welding, even with high heat input, did not cause precipitation of carbides or intermetallic phases, but increasing heat input affected the density and size of pitting holes.

In 2014, Bhattacharya and Kumar. [18] investigated the impact of gas metal arc welding and process parameters like welding voltage, type of shielding gas, welding current, filler materials, and flow rate on tensile strength, microstructure, toughness, and joint distortion of austenitic stainless steel and duplex stainless steel. Their results confirmed that the quality of the joint is higher with a double shielding environment, and the tensile strength increased with voltage and the use of duplex filler material.

An important study by Udayakumar et al. [1], the mechanical properties and microstructure of super duplex stainless steel using rotary friction welding were examined. The study showed very good quality in terms of mechanical properties and all the weld joints had higher yield strength, and ultimate tensile strength compared to the base metal. Also the hardness was higher in the weld area and the failure occurred away from the weld zone.

To explore the efficiency of dissimilar weld joints, Gardi and Kako. [19] conducted a study on super duplex stainless steel SAF 2507 and mild steel using continuous drive rotary friction welding. The investigation showed that the highest efficiency of the welded joint could be obtained by using the lowest friction pressure and forging pressure.

In a different study, Khidhir and Baban. [20] investigated the effect of friction welding parameters on the mechanical properties and the microstructure of dissimilar steels, i.e., austenitic stainless steel and mild steel. The study showed the highest efficiency was 90% when the friction and forging pressure were 75 MPa and the lowest when forging pressure increased to 155 MPa.

In 2020, Kanan et al. [21] studied the girth friction welding to joint pipes. In addition to the good mechanical properties, the result showed that, using this method to joint super duplex stainless steel pipe, the rate of sigma phase decreased to less than 0.15% in the recrystallized zone for all process parameters. In comparison to other methods of welding, this can be considered as a very good feature in welding this type of material, that increases the toughness property in the heat-affected zone and the weld area.

In an updated investigation, Khidhir [22] studied the effect parameters of rotary friction welding on mechanical properties and microstructure of dissimilar steel materials, i.e., the duplex stainless steel, and the medium carbon steel. The joints have been produced with different friction pressures and reached the best result when the friction pressure was 75 MPa. The efficiency of the weld joint was 93%.

In another recent study, Zhang et al. [23] Studied the effect of rotary friction welding on mechanical properties and microstructure of the duplex stainless steel pipe. Their results the microstructure revealed that there is no deleterious phase in the weld area and tensile strength of the joint was very good.

Most reported works on rotary friction welding process focused on rotational speed,

friction pressure and forging pressure, and the friction and forging time, but not friction pressure and friction time together, specifically on austenitic stainless steel pipes. Such types of pipes have a significant impact on manufacturing industry, including oil and gas, refineries, and power generating plants, especially if the limitations of the process can be eliminated or reduced. In this study, therefore, continuous drive rotary friction welding was used to join austenitic stainless steel pipes grade TP316L, and the effect of friction pressure at two different friction times on microstructure and mechanical properties was investigated. In this process, the speed of the rotated part is constant while pressure is applied to generate the heat in alignment with the second part. To guarantee proper thermal and mechanical conditioning of the contact region, the friction pressure and speed are kept for a predetermined period. Then, the rotated part is stopped by the brake system, and forging pressure is applied for a predetermined period.

2. EXPERIMENTAL PROCEDURE

2.1 Material

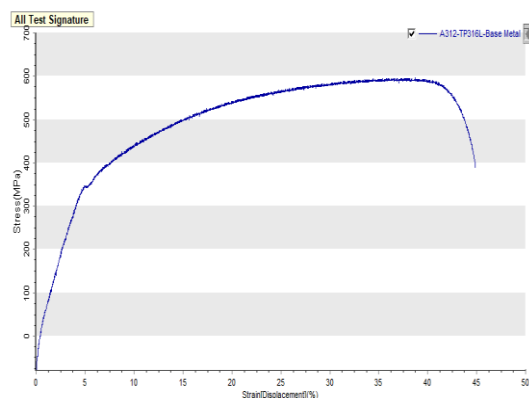
In present study, the pipe materials used were Austenitic Stainless Steel ASTM A312 TP316L. The dimensions of the test specimen are 1 inch in diameter and schedule 80, which is equal to 4.55 millimeters in thickness. The outer and inner diameters are 33.4mm and 24.3 mm, respectively. The chemical compositions and mechanical properties are tabulated in Table 1 and Table 2, respectively. The tensile strength test results and the microstructure of the received Austenitic Stainless-Steel A312-TP316L are shown in Figure 1.

Table 1: Chemical compositions of the received stainless steels A 312-TP316L.

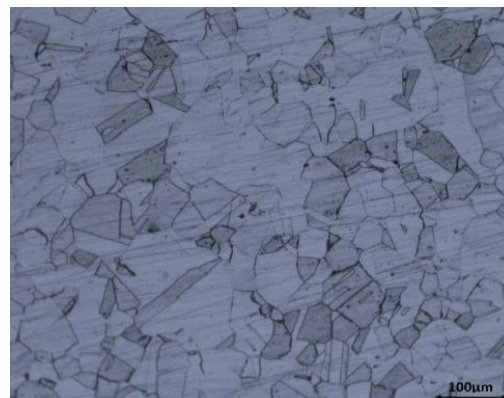
SN	Material	C %	Mn%	P%	S%	Si%	Ni%	Cr%	Mo%	N%	Cu%
1	A 312-TP316L	0.035 Max.	2.00 Max.	0.045 Max.	0.030 Max.	1.00 Max.	10.00- 14.00	16.00- 18.00	2.00- 3.00	-	-
	Heat No. A2002348	0.024	1.080	0.031	0.001	0.520	10.010	17.280	2.100	0.060	-

Table 2: Mechanical properties of the received stainless steels A 312-TP316L.

SN	Material	Yield Strength Rp0.2 (MPa)	Ultimate Tensile Strength Rm (MPa)	Elongation (A5%)	Hardness (HBW)
1	A 312-TP316L	170 Min.	485 Min.	35 Min.	- Max.
	MTC. Heat No. A2002348	301	613	53.5	155



(a)



(b)

Figure 1: a) Tensile test result, b) microstructure of the received austenitic stainless steel.

2.2 Rotary Friction Welding Process

The continuous drive rotary friction welding process is implemented using a lathe machine.

The pipe was rotated on one side, while the other one was fixed on the opposite side. The pipe on the chuck side was rotated at the speed of the lathe machine, and the pipe on the tail side was fixed from rotation. The sliding movement was achieved by moving the tailstock towards the rotated pipe, and simultaneously controlling the applied force during friction and forging force. Changing the welding process stages, from the friction stage to the forging stage, was achieved by a clutch and brake system equipped within the machine, which directly separates the chuck from the motor, resulting in stopping the chuck and the pipe from rotating. By adding a pipe holder on the tail stock side, the machine is empowered to hold a larger diameter of tubes and pipes. These test picemen are held in place with screws around them, to guarantee and prevent slippage during the rotation and welding process. The applied pressure was measured via a load cell that was installed in a specific way to measure the applied force during the friction and forging stages. In addition, a digital torque adaptor is used to prevent excessive load and also to control and maintain a steady load on the pipe. The temperature was also measured during the welding. The lathe machine, along with other mechanisms and instruments of measurement, is shown in Figure 2. The temperature of the rotary friction welding process was measured using Voltcraft IR1600, an infrared thermometer capable of measuring temperature ranging from -50 °C to 1600 °C. This device can be connected to a computer to record the temperature variations over time, and allows

simultaneously recording of both IR and K-type thermocouple temperatures.



Figure 2: RFW machine and arrangement.

Another K-type thermometer, PK precession 710, with a range of -200 °C to 1370 °C, was also used to verify the measurement of the IR thermometer. The selection of the emissivity factor is a key point for an accurate measurement of surface temperature by an infrared thermometer. 0.82 was selected for this study to get the most accurate values. For this study, the number and value of the friction welding parameters for each test are shown in Table 3. And the repeatability of the process was verified by repeating the process and the tensile strength test up to three sample tests for the selected samples. The result showed the repeatability of the process, the standard deviation of the strength test result for all samples was less than 5% only for sample numbers three and seven were 5.2% and 7.7% respectively.

Table 3: Rotary friction welding process parameters

Sample No.	Sample Name	Material	Rotational Speed RPM	Friction Pressure Mpa	Friction Time Sec	Forging Pressure Mpa	Forging Time Sec
01	ASS.-ASS. P.T.-01	TP316L-TP316L	1030	10	45	20	5
02	ASS.-ASS. P.T.-02	TP316L-TP316L	1030	12.5	45	20	5
03	ASS.-ASS. P.T.-03	TP316L-TP316L	1030	15	45	20	5
04	ASS.-ASS. P.T.-04	TP316L-TP316L	1030	17.5	45	20	5
05	ASS.-ASS. P.T.-05	TP316L-TP316L	1030	10	15	20	5
06	ASS.-ASS. P.T.-06	TP316L-TP316L	1030	12.5	15	20	5
07	ASS.-ASS. P.T.-07	TP316L-TP316L	1030	15	15	20	5
08	ASS.-ASS. P.T.-08	TP316L-TP316L	1030	17.5	15	20	5

2.3 Mechanical Tests

2.3.1 Tensile Test

To evaluate mechanical properties after completing the friction welding, all the samples of the welded pipes were tested by a tensile test. Welded pipes were cut into samples for the tensile test, which were prepared according to ASTM A370 with a gauge length of 25mm, as in Figure 3, and the requirements of the machine test were taken into consideration.



Figure 3: Tensile test specimens.

The tensile test for this study was performed in the Material Testing Solutions Lab. The model of the machine test was UNIVER 600, used with a capacity of 600 KN. The test was implemented with a rate of 5mm/minute at a room temperature 25C°.

2.3.2. Microhardness Test

The hardness of the welded samples and the hardness profile across the base metal to the heat-affected zone to the thermomechanical-affected zone to the weld area then to the opposite side of the welded metal according to ASTM E92 were evaluated with a Digital Microhardness

Tester that has a load range from 0.1Kg to 1 Kg for this study the HV01 has used the load of 1 Kg for 15 seconds as dwell time.

2.4 Microstructure Characterization

Microstructure analyses were performed on the welded joints for the welded samples in addition to the base material. To find out the effect of the rotary friction welding and welding process parameters on the weld area, heat-affected zone, the thermomechanical affected zone, and the base metal away from the welding area. If any precipitations and other undesired and new phases have been formed. Optical microscopy was used to examine the weld joints and the base materials. The samples of the microstructure were ground to a flat face with different abrasive papers with grit numbers of P120 to P2500. Then the samples were polished in three stages as per Table 5 of the referenced guideline ASTM E3 with nap cloth and 6-micron to 1-micron diamond suspension solution. The polished samples were etched with a chemical solution that consisted of five different chemicals to reveal the microstructures, named carpenter etchant, a very effective etchant for austenitic stainless steel.

3. RESULTS AND DISCUSSIONS

3.1. Tensile Strength

The results of the tensile strength test for the welded samples are presented in Figures 4 and 5. And the ultimate tensile strength of the welded samples is compared in Figure 6. The result shows the influence of friction pressure on the strength of both sets. The tensile strength test of the welded pipes for the lower friction time increases with friction pressure, but in higher friction time

strength decreases as the friction pressure increases.

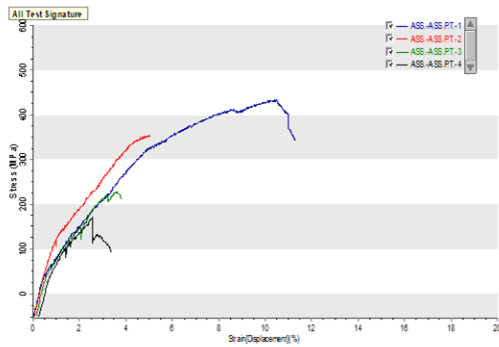


Figure 4: Tensile strength curve of the welded sample 1-4.

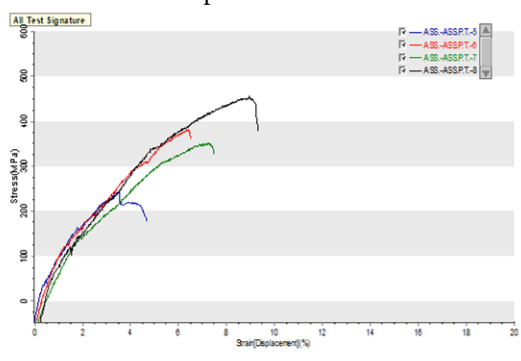


Figure 5: Tensile strength curve of the welded sample 5-8.

The results show that the heat generated during rotary friction welding has a significant and main role in the quality of the joint. Low-generated heat results in low quality and improper bonding between the two faces, and excessive heat results in low quality and low mechanical properties due to the generation of brittle phases. So, it is recommended to avoid combining high friction pressure and friction time together for rotary friction welding process, and the selection of the process parameters needs to be carefully controlled. This result shows that there is a significant relationship between friction time and friction pressure with the mechanical property. The same has been achieved by Khidhir. [22] the joint efficiency increased with increasing friction pressure and reducing friction time in dissimilar welding of carbon steel and super duplex stainless steel solid road. Increasing friction pressure from 35MPa to 75MPa and reducing friction time from 50sec to 38sec increased the joint efficiency from 76% to 93%. These results are also in agreement with the results of Alza. [24] for welding low-carbon steel by rotary friction welding. When the friction time is 8Sec increasing the friction pressure from 0.8MPa to 1MPa increases the tensile strength value from 682MPa to 829MPa But the result of dissimilar welds between low and medium-carbon steel is different for the same

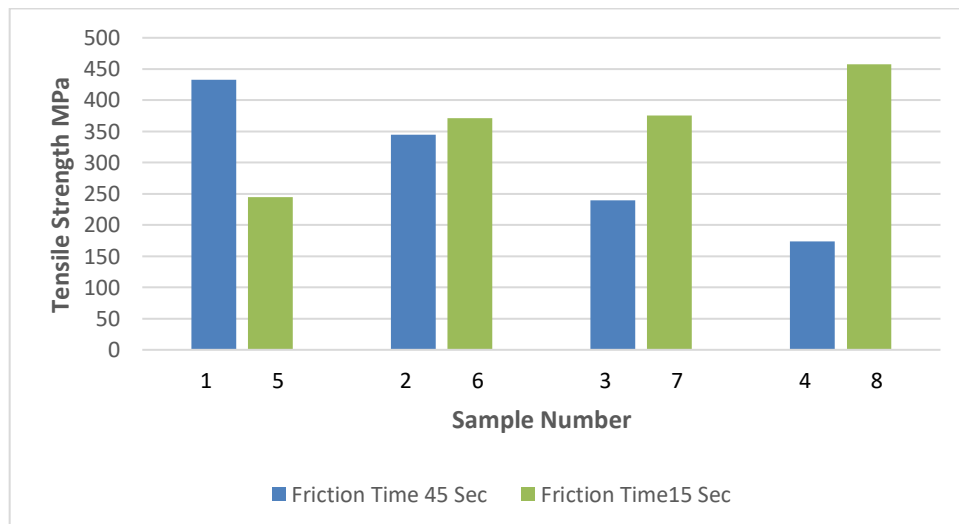


Figure 6: Tensile strength of the welded sample with different friction times.

welding process parameters. while the result of Gardi and Kako.[19] reveals that in comparatively high constant friction time for dissimilar joints of super duplex stainless steel and mild steel, small-diameter road, increasing friction pressure from 33MPa to 80MPa decreases the joint efficiency from 79% to 66% and this reduction is attributed to the accelerated formation of brittle sigma (σ)

intermetallic phase. This is due to the possibility of producing undesired phases in stainless steel, like the sigma phase, which increases the brittleness of the welding interface. and results from Firmanto et al. [4] for welding austenitic stainless steel bars grade 304 shows that for low friction pressure, increasing friction time improves the tensile strength, but for higher friction pressure,

increasing friction time is not the same and decreases the quality and strength.

3.2. Hardness Test

The microhardness of the welded samples after friction welding in the weld area and weld interfaces mainly depends on the generated heat during the process and the cooling rate, which affects the microstructure evolution, grain refinement, and new phase formation. but the difference in generated heat from the center to the surface of the pipe does not have the same effect as in welding of shafts, as achieved by Alza. [24] The hardness of the welded samples mainly depends on the grain refinement and secondary phase precipitation. The microstructure of most of the samples does not show any precipitation phases, but the result of the hardness profile of sample number 4 clearly shows both factors grain refinement and new phase formation in the weld area, which increased the hardness in the weld area and the hardness profile as shown in Figure 8. This is due to the increase in the heat generated during

welding, as both the friction pressure and time are maximum in this case of welding. So, the changes in the hardness profile from the first set of welding to the next are not related to the grain refinement only, precipitated phases also matter. Due to the short time of heating and cooling cycles for samples 5 to 8, the hardness profile of the samples is lower compared to the first set of welded samples and can be used to predict the microstructure and new phase formation. Comparing the result of the hardness for both sets of welding in Figures 8 and 9 shows that the effect of friction pressure on the hardness in the middle of the pipe is not as significant as the friction time, and it has more effect in higher friction times. Figure 7 shows the same that the hardness of the weld area is much higher for the first set of samples 1-4, and the effect of friction pressure is higher in this group compared to the next four samples in the second group. The hardness profiles in Figure 10 on the surface of the pipe show little change, a little higher compared to the hardness at the middle of the pipe and this is due to the higher cooling rate.

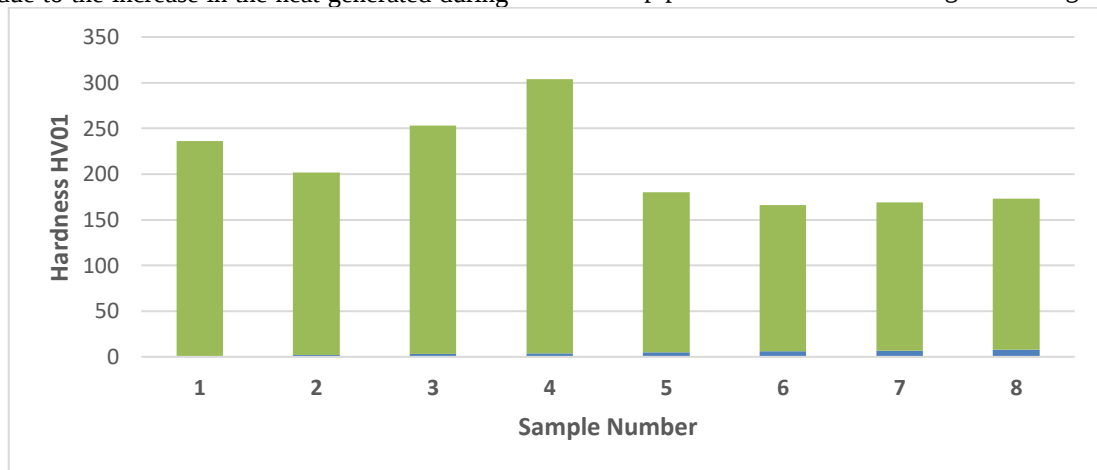


Figure 7: Average hardness of weld area of the welded sample 1-8.

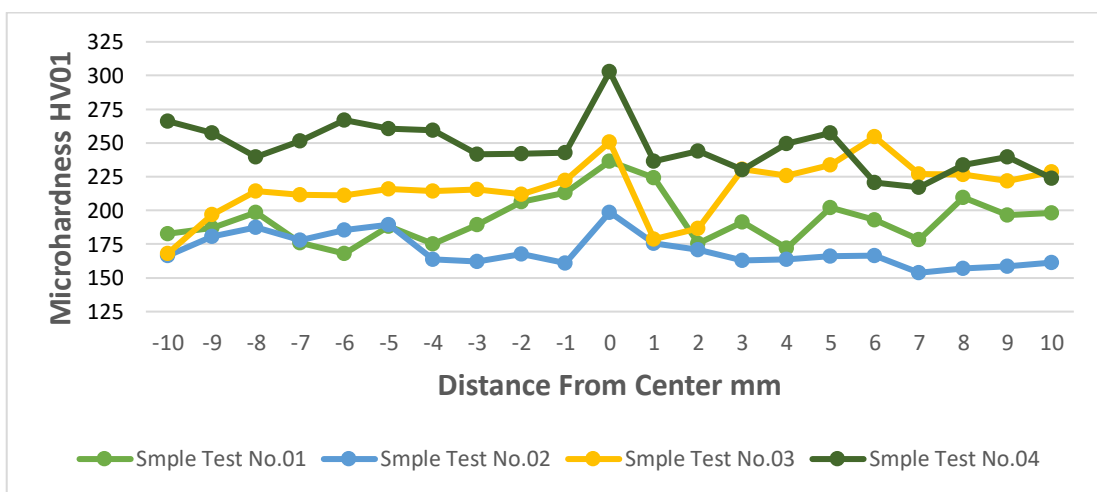


Figure 8: Hardness profile of the welded sample 1-4.

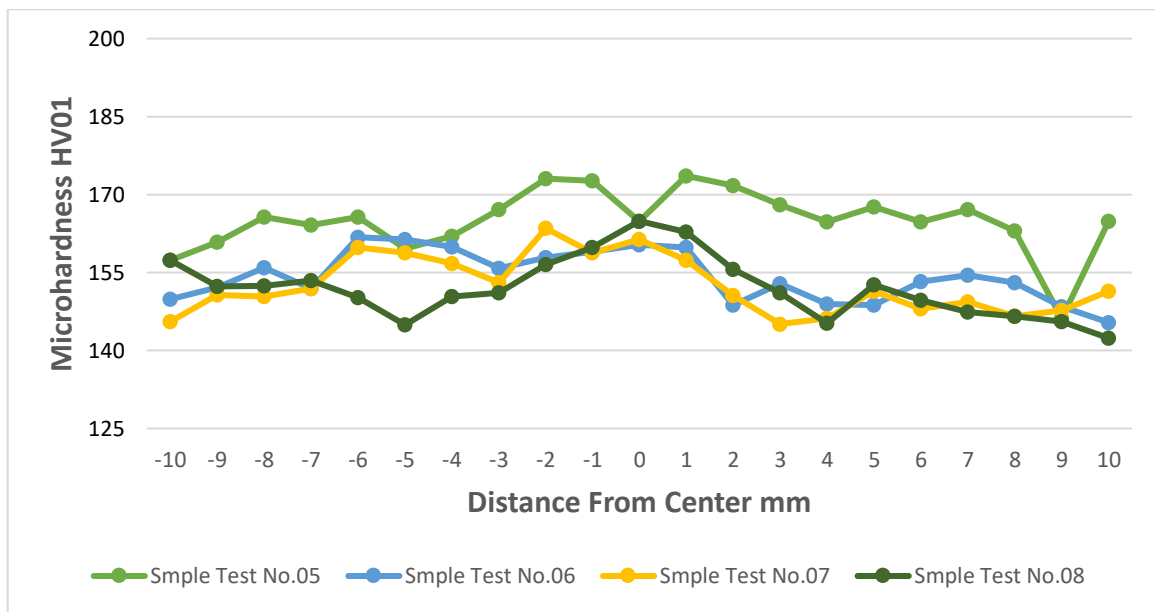


Figure 9: Hardness profile of the welded sample 5-8.

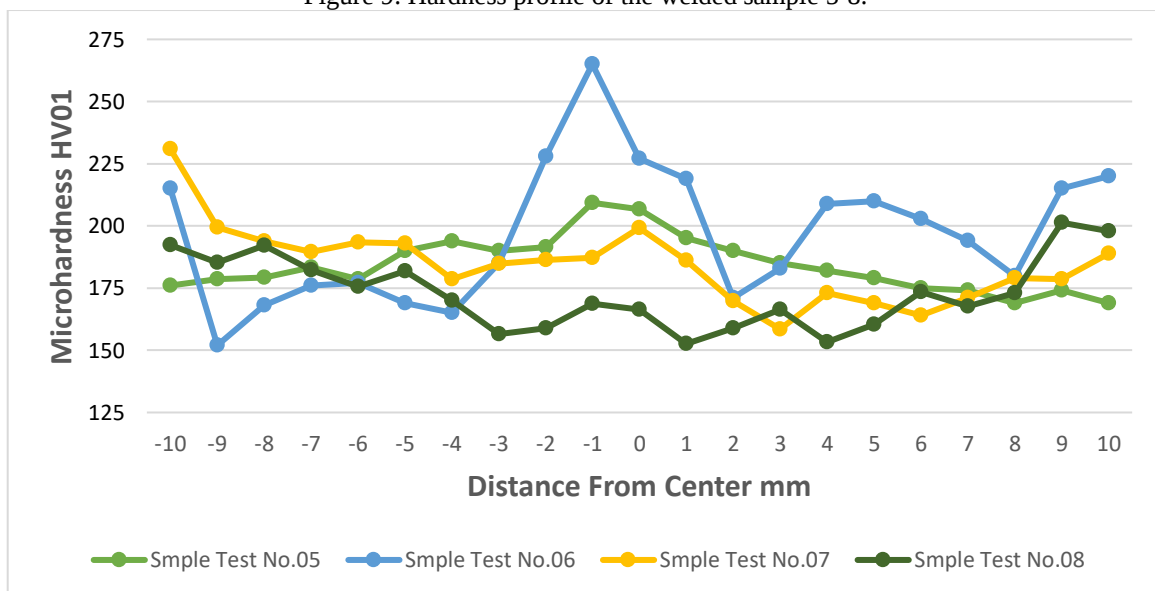


Figure 10: Hardness profile of the welded sample 5-8.

The hardness in the weld and TMAZ is higher due to the finer grain, and in the first set of welding. In addition to this, due to a higher rate of ferrite and finer grains, the same result was also observed by Walter et al. [25].

3.3. Microstructure

The mechanical properties of friction welding can be significantly affected by the microstructure and the grain structure. Figure 11 shows the effect of friction pressure and friction time on the microstructure of the different welded

samples. The grain size of samples 3 and 4 compared to samples 7 and 8 is much smaller, and this is due to the higher friction time and temperature, and the hardness of the first two samples is much higher. and the newly formed brittle intermetallic phases for sample no 4 exist at a higher rate compared to samples, which can be interpreted to the lower mechanical property for this sample and lower corrosion resistance expected specially on the samples that cr carbides formed on the grain boundaries it will initiate the intergranular corrosion and then pitting corrosion.

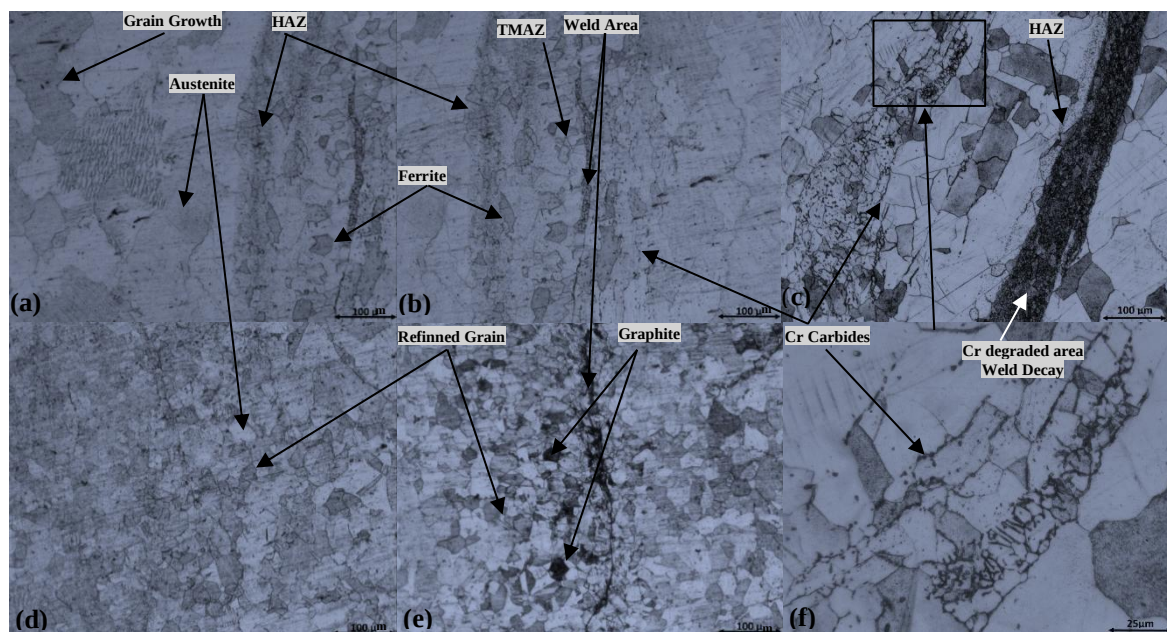


Figure 11: a) HAZ of sample no. 8, b) weld area of sample no. 8, c&f) weld area of sample no. 7, d) weld area of sample no. 3, e) weld area of sample no. 4.

4. CONCLUSION

In this study, the mechanical and microstructure of continuous drive rotary friction welding of austenitic stainless-steel grade 316L were investigated, and conclusions are drawn as follows.

- 1- The mechanical properties of the joints welded with a friction time of 15 seconds are better and have fewer weld defects compared to the joints welded with a friction time of 45 seconds.
- 2- The friction pressure is a significant parameter and can affect the joint property of the welded joint. In our case, for the second set, the strength of the sample 8 is 457 MPa, considering the minimum required strength for this grade as 485 MPa, the joint efficiency is around 94%.
- 3- The hardness of the first set, with 45 seconds of friction time, is much higher than the second set, with 15 seconds of friction time.
- 4- The microstructure of the weld zone shows the effect of the friction pressure and time on both the heat-affected zone and the thermomechanical affected zone.
- 5- A weld joint with better quality can be reached with more studies on this topic by controlling the variable parameters.

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تأثير ضغط الاحتكاك على الخواص الميكانيكية لأنبوب الفولاذ المقاوم للصدأ الأوستنيتي باستخدام اللحام الاحتكاكي الدوراني

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الملخص

اللحام بالاحتكاك الدوراني (RFW) هو أحد أكثر الطرق فعالية وكفاءة للربط بين المواد المتشابهة وغير المتشابهة لأغراض مختلفة في التطبيقات الصناعية. في هذه الدراسة، تم التحقيق في تأثير ضغط الاحتكاك اللحام الاحتكاك الدوراني المستمر (CDRFW) للحام أنابيب الفولاذ المقاوم للصدأ الأوستنيتي (الدرجة TP316L) في وقتي احتكاك مختلفين. بينما ظلت معلمات عملية اللحام الأخرى ثابتة أثناء العملية. توضح النتائج وجود علاقة معقدة بين معلمات اللحام بالاحتكاك. بالنسبة للمجموعة الأولى من العينات ذات فترة احتكاك أطول تبلغ 45 ثانية، فإن زيادة ضغط الاحتكاك تقلل من الخصائص الميكانيكية، ومع ذلك، لفترة أقصر من وقت الاحتكاك تبلغ 15 ثانية، فإن زيادة ضغط الاحتكاك تزيد من الخصائص الميكانيكية. تم تحقيق أفضل نتيجة للعينات الملحومة بأعلى ضغط احتكاك عند وقت احتكاك أقصر، وقوة الشد هي 457 ميغا باسكال. ولكن لفترة أطول من وقت الاحتكاك، 45 ثانية، تكون قوة الشد 171 ميغا باسكال على الأقل. المعيار الأساسي في هذه العملية هو ضرورة التحكم الدقيق في مدخلات الحرارة أثناء هذه العملية، إذ قد يؤدي ارتفاع أو انخفاض مدخلات الحرارة إلى خلل في الالتصاق ورداءة جودة اللحام. تُظهر نتائج هذه الدراسة أن الوصلات الملحومة ذات ضغط الاحتكاك العالي مع زمن احتكاك أقل تُعطي أفضل نتيجة لقوة الشد وخصائص الصلابة. في حين يجب تجنب ضغط الاحتكاك العالي وزمن الاحتكاك معاً لمنع تدهور أداء اللحام.

الكلمات الدالة :

ضغط الاحتكاك، زمن الاحتكاك، أنبوب الفولاذ المقاوم للصدأ الأوستنيتي، الخاصية الميكانيكية، البنية المجهرية.