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Microstructure and mechanical properties of dissimilar joint of stainless steel pipes using rotary friction welding

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HIGHLIGHTS

- The mechanical properties of stainless steels were found to be highly sensitive to welding heat input.
- Fine-tuning parameters in rotary friction welding improved performance and joint microstructure.
- Joining austenitic and super duplex stainless steels was studied for offshore and energy uses.
- Microstructure was shown to predict the mechanical behavior and corrosion resistance of welds.

Keywords:
Dissimilar joint
Stainless steel pipe
Rotary friction welding
Mechanical property
Microstructure

ABSTRACT

Dissimilar welding joints of different grades of stainless-steel pipes using various welding processes and technologies have received special attention in the world of manufacturing in the last few years, due to the wide application of different grades of this material in different sectors, including refineries, chemical plants, heat exchangers, and power generation plants. The utilization of rotary friction welding has significantly increased, and more studies on it have been conducted to reduce the difficulties of joining similar and dissimilar materials in general and steel in specific, as it decreases the heat input and thermal cycle. This study investigated the effect of continuous drive rotary friction welding and process parameters on microstructure and mechanical properties of the dissimilar joint of austenitic and super duplex stainless steel. The result of the study shows a significant relation between the friction and forging parameters and the joint quality. The best result achieved in this study was when the process parameters were selected as 30MPa for friction pressure, 10 seconds for friction time, 20 MPa and 30 seconds for forging pressure and time, respectively, and the rotational speed of 1030 rpm. The result reveals that the effect of the process parameters that have the most effect on heat input is more significant. And heat input in this process is a key point in achieving a good or poor joint quality.

1. Introduction

Welding of dissimilar materials is an attractive method of joining and always receives special attention due to its extensive use and wide range of applications in the world of engineering. Applications in manufacturing and production sectors, including the automotive industry, oil and gas industries, refineries, heat exchangers, petrochemical, marine, and power generation plants. This wide demand and requirements on this type of welding are due to the advantages of very good mechanical properties, corrosion resistance, and economic benefits. And on the other side, it is also due to the difficulties faced during welding and selection of filling material for dissimilar materials due to the varieties of chemical, physical, and thermal properties that need to be studied and solved for better quality, efficiency, and more economic as well [1-4]. Austenitic stainless steel is the most popular and widely used grade of stainless steel due to its good mechanical properties and corrosion resistance. In some applications, this grade does not have sufficient strength and resistance to corrosion, so super duplex stainless steel is a very good alternative for this grade due to its very high mechanical properties and corrosion resistance. So, it can be considered as a good alternative in terms of technical and economic [4-6]. Super duplex stainless steel is one of the advanced and fastest-growing grades of stainless steel. which have both phases of austenitic and ferritic at room temperatures, so known as duplex stainless steel. This grade was discovered in the 1920s, but they were not fully optimized and utilized until recently. It exhibits excellent mechanical properties, including strength, toughness, and resistance to corrosion, as well as stress cracking corrosion, with exceptional resistance [7,8]. The mechanical properties and corrosion resistance of stainless steel depend on its structure, which can be explained by the precipitation rate of the phases produced during welding at high temperatures. And joining by welding is an effective and efficient method of joining. It is the only method in many applications and during welding this structure and the rate of ferrite and austenite

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changes and even may lead to precipitate of sigma and other chrome reach carbide phases due to heat input and residual stress that affect both the mechanical properties and corrosion properties[1,9]. This changes and degrading in properties is mainly depend on the heat input and the thermal cycle for each welding procedure and the effect, advantage and disadvantage of each welding procedure have been studied in many studies on different grades of steel and stainless steel for both similar and dissimilar. Friction welding is an effective welding method for both similar and dissimilar materials that improves mechanical properties, corrosion resistance, has lower heat input, no consumables, and lower working expenses [10-12].

Several studies exist to investigate the properties and efficiency of welded joints of stainless-steel material using different welding processes. Each of the welding methods and processes has special and distinct features and characteristics. Mohammed et al. [2], studied the effects of various filler materials on similar and dissimilar austenitic and duplex stainless steel using gas tungsten arc welding. The results showed a significant impact of filler materials on the mechanical properties and corrosion resistance. Wang et al. [13], studied the effect of metal inert gas (MIG) welding and tungsten inert gas (TIG) welding on welded joints of duplex stainless steel and low alloy steel. The mechanical performance of MIG welding joints, especially impact toughness, is superior to that of TIG welding. Çelik et al. [14], investigated the effect of heat input and inter-pass temperature on microstructure and mechanical characteristics of duplex stainless steel tubes using shielded metal and gas tungsten arc welding procedures. Sathiya et al. [15], in their investigation, the ferrite ratio for two distinct shielding gases, argon and helium, is applied to a joint duplex stainless steel plate UNS S31803 with gas tungsten arc welding, and the influence on mechanical characteristics and microstructure is evaluated. Zhang et al. [9], studied the effect of rotational friction welding on the structure of the welded metal and heat-affected zone for duplex stainless steel welded pipes. The study aims to prevent the formation of harmful phases, including sigma phase, in the weld area by investigating the microstructure and mechanical properties. The result demonstrates a rise in the ferrite content in the weld zone, grain refinement, and an increase in dislocation density. As a result, the hardness and tensile strength of the weld zone improved. Walter et al. [1], investigated the impact of linear friction welding process parameters on super duplex stainless steel plate jointing. The study examined microstructure, tensile strength, microhardness, and pitting corrosion, and the findings indicate that a combination of process factors can yield a defect-free and high-quality joint. Kumar et al. [16], investigated the characterization of rotary friction welding for austenitic stainless steel tube grade SS304, the experiment focused on key parameters. The weld strength improved at the maximum of heating and upset load. The maximum joint strength and hardness were achieved at an upset load of 143 MPa and an upset time of 4 seconds; however, a poor grain structure was observed in the welded region.

In the welding of stainless steel, the quality of the joint mainly depends on the heat input, thermal cycles, and the cooling rate because it affects the ferrite-to-austenite ratio and the period of time at high temperatures that may lead to the generation of new brittle phases. Rotary friction welding is a solid-state welding method that effectively reduces and prevents the formation of undesired and secondary phases due to lower heat input and higher cooling rate [17-19]. Therefore, this study describes the effect of rotary friction technique and process parameters, including friction and forging parameters, on the mechanical properties and microstructure of the dissimilar welded joint of austenitic and super duplex stainless steel pipe.

2. Experimental procedure

2.1 Material

In this study, austenitic and super duplex stainless-steel pipes were used. The pipes have an outer diameter of 33.4 mm, an inner diameter of 24.3 mm, and a wall thickness of 4.55 mm (Schedule 80). The chemical compositions and mechanical properties are tabulated in Tables 1 and 2. The microstructure of the Super Duplex Stainless Steel A790-S32750 and Austenitic stainless steel A312 TP316L is shown in Figures 1a and 1b, respectively.

The tabulated values for chemical analysis and mechanical properties in Tables 1 and 2 are provided by the stainless-steel material supplier in material test certificates. Both mechanical properties and chemical analysis were checked and verified.

Table 1: Chemical compositions of the received austenitic and super duplex stainless steel

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	-	-
		0.024	1.080	0.031	0.001	0.520	10.010	17.280	2.100	0.060	-
2	A790-S32750	0.030 Max.	1.20 Max.	0.035 Max.	0.020 Max.	0.800 Max.	6.00-8.00	24.00-26.00	3.00-5.00	0.240-0.320	0.500 Max
		0.021	0.412	0.016	0.005	0.362	6.104	24.422	3.435	0.267	0.302

Table 2: Mechanical properties of the received austenitic and super duplex stainless steel

SN	Material	Yield strength Rp0.2 (Mpa)	Ultimate tensile strength Rm (Mpa)	Elongation (A5%)	Hardness (HBW)
	A 312-TP316L	170 Min.	485 Min.	35 Min.	- Max.
1		301	613	53.5	155
	A790-S32750	550 Min.	800 Min.	15 Min.	300 Max.
2		610	855	35	266

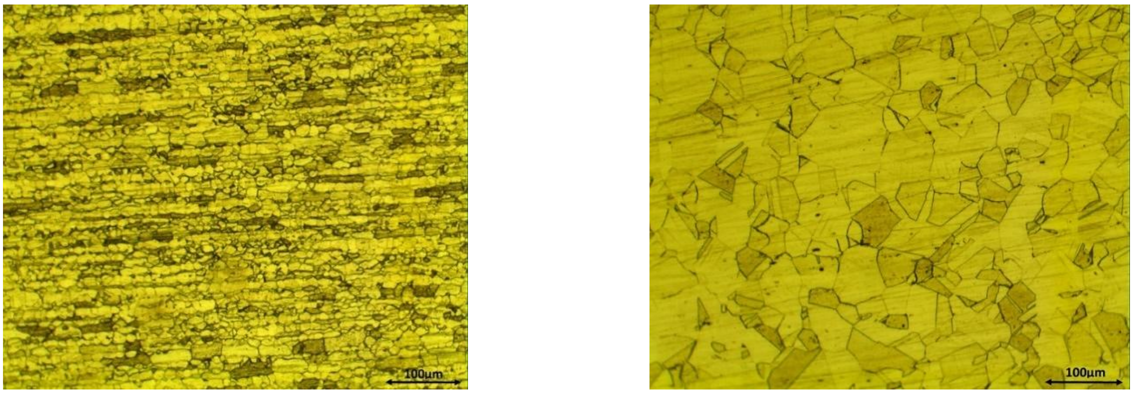


Figure 1: Microstructure of the as-received a) Super duplex b) Austenitic stainless steel

2.2 Rotary friction welding

The contentious drive rotary friction welding process is used to join the super duplex and austenitic stainless-steel pipes. for this purpose, a lathe machine, TSL-1000D, is used. The pipe was rotated on the chuck side of the lathe machine and fixed on the opposite side. The sliding movement was achieved by moving the tailstock towards the rotated pipe, and with the same mechanism, the applied force during friction and forging force was controlled. The stage change from the friction stage to the forging stage was achieved by a brake system of the machine that directly stopped the chuck and the pipe from rotation. And with modification and adding a pipe holder on the tail stock side to empower the machine to hold larger diameter tubes and pipes with a gap screw around it that guarantees and prevents slippage during the process of welding. The applied pressure was measured with a load cell that was installed 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 measured during the welding with a K-type thermometer, PK precision 710, with a range of -200 °C to 1370 °C, which was used for this purpose. The lathe machine, along with other mechanisms and instruments of measurement, is shown in Figure 2a, and a typical relationships diagram of rotary friction welding parameters at constant rotational speed is shown in Figure 2b.

For this study, the number and value of the friction welding parameters for each test are shown in Table 3.

Table 3: Rotary friction welding process parameters for this study

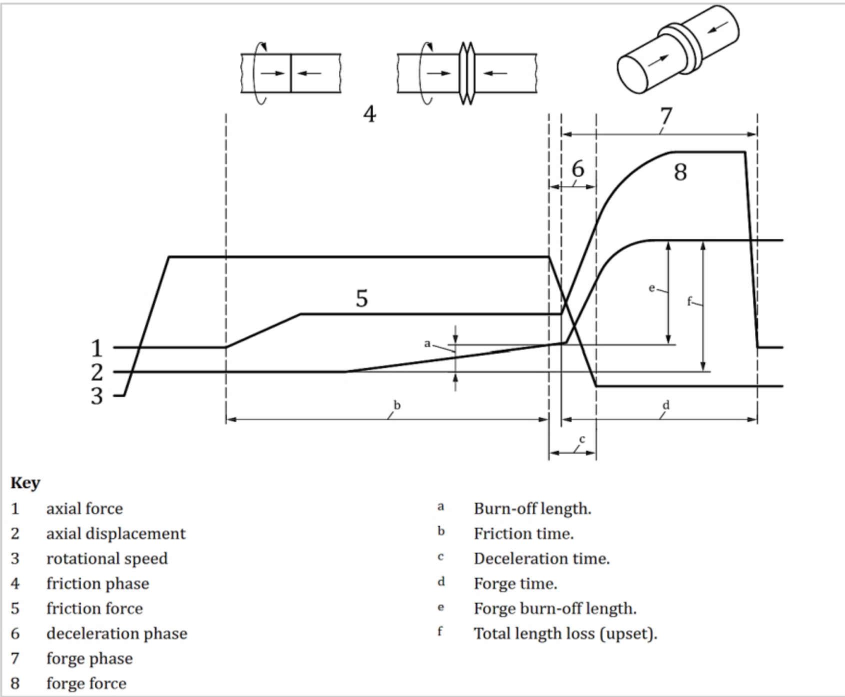
Sample No.	Sample material	Rotational speed RPM	Friction pressure (MPa)	Friction time (sec)	Forging pressure (MPa)	Forging time (sec)
1	ASS-SDSS	1030	15	15	20	5
2	ASS-SDSS	1030	20	15	20	5
3	ASS-SDSS	1030	25	15	20	5
4	ASS-SDSS	1030	15	20	20	5
5	ASS-SDSS	1030	20	20	20	5
6	ASS-SDSS	1030	25	20	20	5
7	ASS-SDSS	1030	30	10	20	15
8	ASS-SDSS	1030	30	10	30	15
9	ASS-SDSS	1030	30	10	20	30
10	ASS-SDSS	1030	30	10	30	30

This study aims to investigate the effect of rotary friction welding process parameters, including the impact of friction pressure, friction time, forging pressure, and forging time on the mechanical properties and microstructural evolution this has been implemented in two stages at first stage the effect of friction parameters was studied then after finalizing the optimum value for the friction parameters then forging parameters increased to reveal their effect on the weld quality. The repeatability of the process was verified by repeating the process and achieving the same result. After implementing the process, the welded pipes were prepared and cut into predefined lengths and dimensions for different mechanical and microstructure tests. Milling and turning machines were used for the cutting process, and water is used as a cooling fluid during cutting to prevent high temperatures from affecting the properties of the welded samples. The cutting process for welded pipes for test samples is shown in Figure 3.

2.3 Mechanical tests and microstructure analysis

The mechanical properties of the welded pipes after completing the rotary friction welding were tested with the tensile strength test. Tensile strength specimens were prepared according to the requirements of ASTM A370 for the tensile strength specimen dimension of the tubular product specimen, as in Figure 4, and the requirement of the machine test was taken into consideration. The tensile test for this study was performed in the Material Testing Solutions Lab. The model of the machine used for testing was the UNIVER 600, with a capacity of 600 kN. The test was implemented with a rate of 5 mm/minute at a room temperature of 25 °C.

(a)



(b)

Figure 2: a) The RFW machine, b) Typical relation of rotary friction welded parameters [source ISO 15620]

Figure 3: Cutting process for the welded pipes during sample preparation

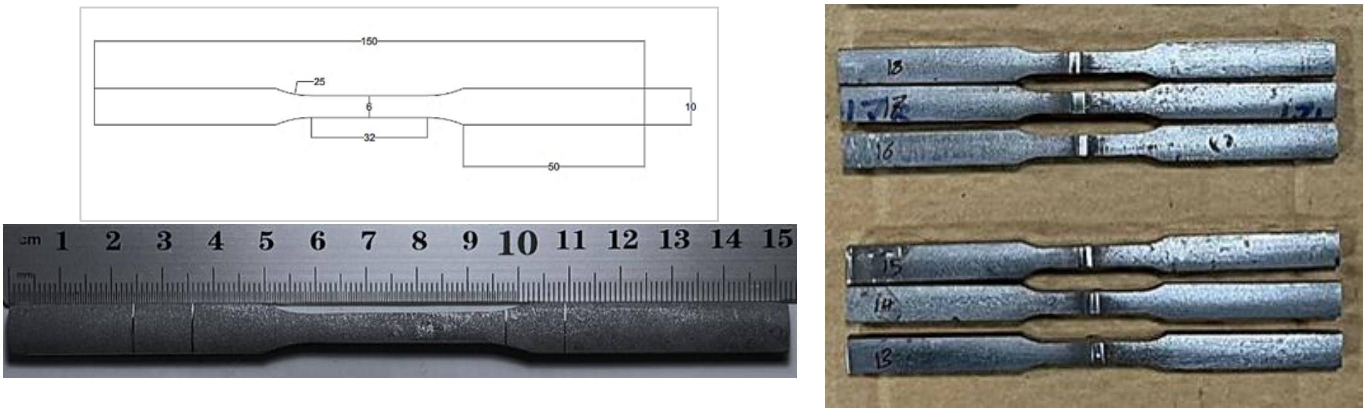


Figure 4: Tensile test specimen dimension as per ASTM A8E

The hardness of the welded samples was measured using a digital microhardness and a hardness tester under indentation loads of 1 kg and 10 kg, respectively. The hardness profile obtained covered the assembled part, including the welded zone, bonding zones, heat-affected zones, and the base metal of both types of steel. The microstructure analysis of the welded joints of the samples was performed using an optical microscope. To achieve this, the samples initially underwent mechanical polishing using abrasive papers ranging from 120 to 2500 grits/cm². To achieve highly specular surfaces, the polished surfaces were then finished using diamond pastes ranging from 6 to 1 microns. Finally, the polished surfaces of the samples were chemically etched using a chemical solution called Carpenter, composed of five different chemicals, which is used to reveal the microstructures of austenitic and super duplex stainless steel.

3. Results and discussion

3.1 Visual examination

The welded pipes with the rotary friction welding process were examined visually externally and internally after cutting the specimens for mechanical and microstructure tests. For most of the samples, no cracks or weld defects were observed visually. The total burn-off length for the welded pipes is shown in Figure 5. An increase in friction pressure and time increases the burn-off length, and the same result is achieved by Makava et al., [19]. A similar relationship with forging pressure was observed, consistent with the findings reported by Matti et al. [20].

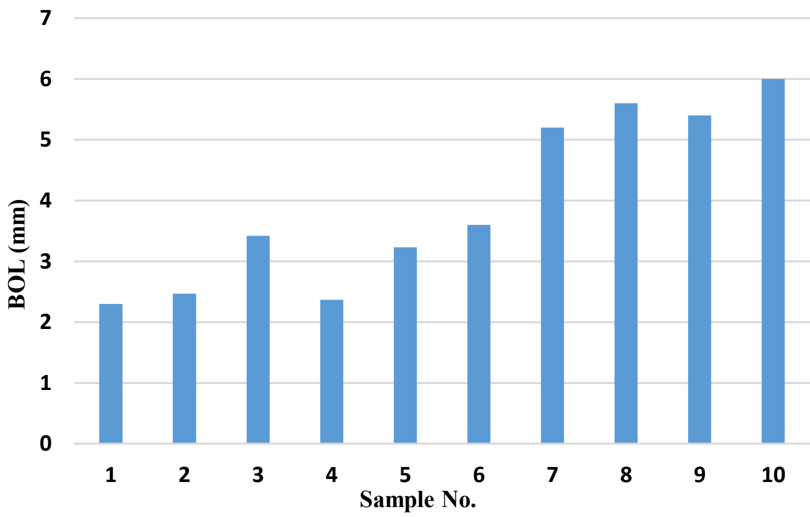


Figure 5: Total burn off length for the welded samples

The length of the flash for the super duplex stainless steel is much larger than that of the austenitic stainless steel. This is due to the lower melting temperature for duplex stainless steel, as shown in Figure 6. The visual inspection of the tested samples after the tensile strength test also made the elongation for the austenitic side higher, almost for all the samples, as a result of the higher ductility of this grade. The surface fracture of the samples with higher heat input shows better bonding between the two surfaces of the pipes. The macrostructure of the welded samples shows different areas on both sides of the steel pipes, the weld area, and the heat-affected zone. And the different grain size and structure can be seen without any magnification and with a few times magnification, especially for the heat-affected zone, the elongated grains near the thermo-mechanical affected zone, and the flash area.

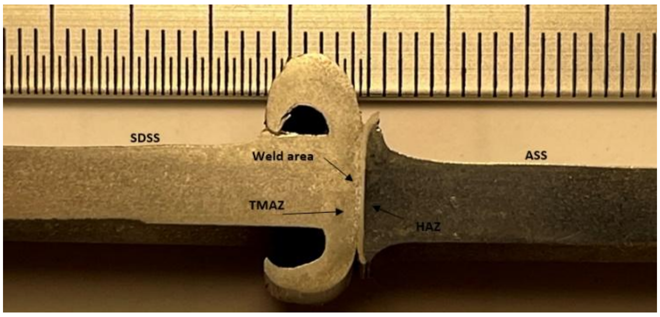


Figure 6: Macrostructure of the welded pipe for sample no.9

3.2 Tensile strength

The result of the tensile strength tests of the welded samples reveals that an increase in friction pressure has a positive and significant effect on tensile strength. While the effect of friction time has a negative effect, as is clear in Figures 7a and 7b, the friction pressure increases the heat input to the pipe surface and enhances a better fusion and covalence between the faces, the same result achieved by Khidhir [21]. The fracture surfaces of the welded samples after the tensile strength test show better covalence for those samples with higher input, as shown in Figures 8a to 8c. For the second part of the experiment, it is clear that the effect of forging pressure is negative in the selected range of work; meanwhile, the effect of the forging time is positive. In rotary friction welding, the parameters that increase the heat input, including friction pressure, friction time, and rotational speed, have a significant effect on the heat input during the process and define the quality of the weld. Insufficient heat or excessive heat input can lead to poor quality of the welded joint, as low heat input will result in a low-quality bond between the two faces of the pipes. Excessive heat input will lead to the formation of chrome carbides and new brittle sigma phases that will result in low mechanical properties, a brittle joint, and low corrosion resistance as well. For this reason, there is no direct relationship between these parameters and the quality of the joint; changing each of these parameters is interconnected to the others and to the joint quality. Increasing one of them increases the quality to a limit, then decreases the quality again after this limit. It's crucial to control the heat input to achieve the best result. And for the interpretation of the effect of forging parameter, which does not affect the heat input, it is related to the density of the dislocation-induced stress during this period. Increasing pressure more than the required value on the pipes will cause stress and affect the welded area during cooling. The forging time significantly increases the quality of the joint, as it allows the surfaces to have greater fusion and better covalence. The same has been achieved by Asif et al., [22]. The joint efficiency increased with increasing friction pressure and reducing friction time in dissimilar welding of carbon steel and super duplex stainless steel. Increasing friction pressure from 35 to 75 MPa and reducing friction time from 50 to 38 sec increased the joint efficiency from 76 to 93%. These results are also in agreement with the results of Alza. [23], for welding low-carbon steel by rotary friction welding. When the friction time is 8 seconds, increasing the friction pressure from 0.8 to 1 MPa increases the tensile strength value from 682 to 829 MPa. But the result of dissimilar welds between low and medium-carbon steel is different for the same welding process parameters. At the same time, the result of Gardi and Kako [24], reveals that in comparatively high constant friction time for dissimilar joints of super duplex stainless steel and mild steel, a small-diameter road, increasing friction pressure from 33 to 80 MPa decreases the joint efficiency from 79 to 66%. 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. [25]. For welding austenitic stainless steel bars, grade 304 shows that increasing friction time improves the tensile strength at low friction pressure. However, for higher friction pressure, increasing friction time does not yield the same results, and instead, it decreases the quality and strength.

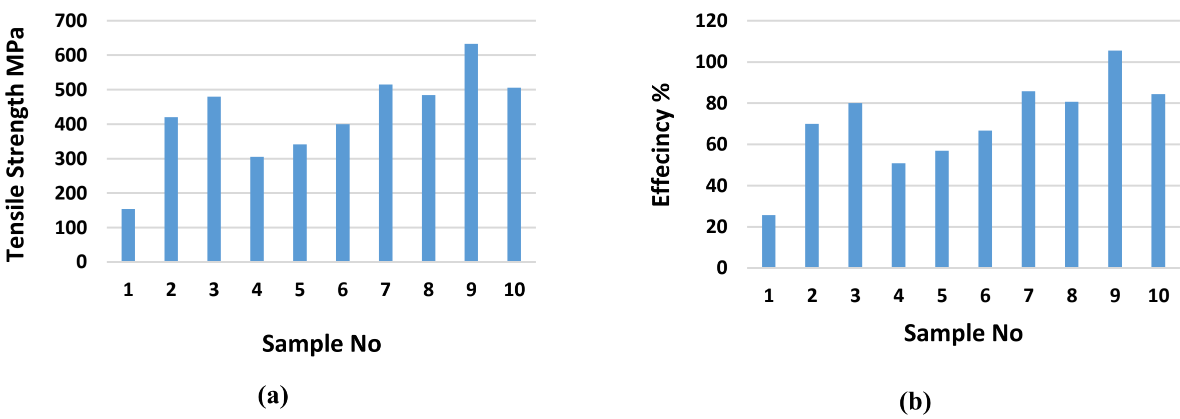


Figure 7: a) Tensile strength test and b) Joint efficiency

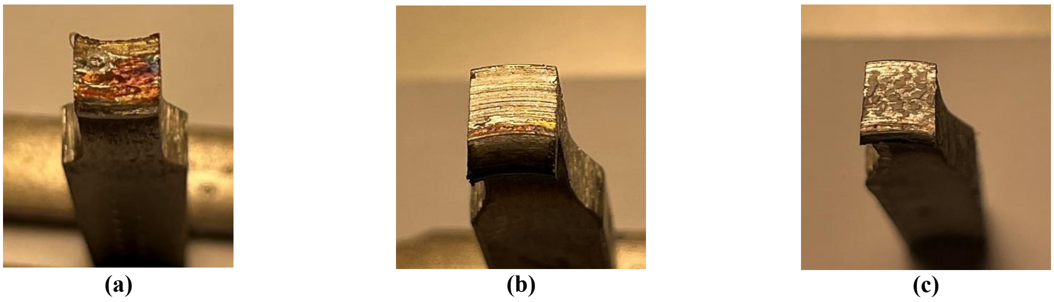


Figure 8: Fracture surface of the welded samples: a) Sample no. 1, b) Sample no. 3, c) Sample no.9

3.3 Hardness and hardness profile

The hardness profiles of the samples coming from both tests of measurement under loads of 1 kg and 10 kg are presented, respectively, in Figures 9 and 10. The indentation marks in the profile corresponding to sample no.09 are illustrated in Figure 11. The results demonstrate the effect of friction welding parameters on the welded area of the samples and the hardness of the base metals. The hardness and hardness profile of the welded pipes with any process of welding and any process parameters mainly depend on heat input, thermal cycle, generating the secondary phases, increase of dislocation density, and grain refinement [25]. Any process parameter that has a greater effect on these factors will have a more significant impact on the hardness. This can be considered an interpretation of the effect of friction parameters, specifically friction time, as it increases the heat input. Titouche et al. [26], confirmed the change in the microhardness. Another aspect of this change in the microhardness is the formation of the new precipitated phases, including the sigma phase, in addition to the grain refinement, which was confirmed and mentioned by [26].

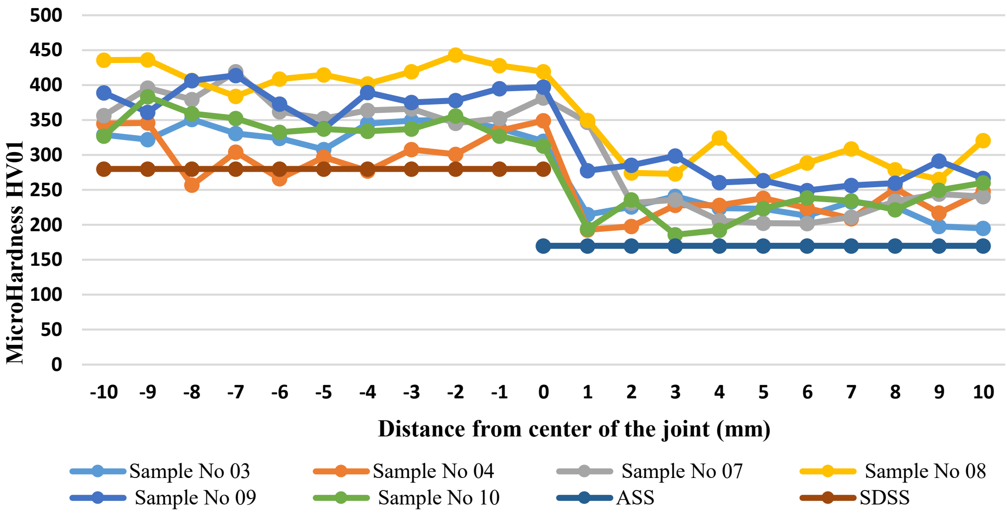


Figure 9: Microhardness profile at the middle of the pipe

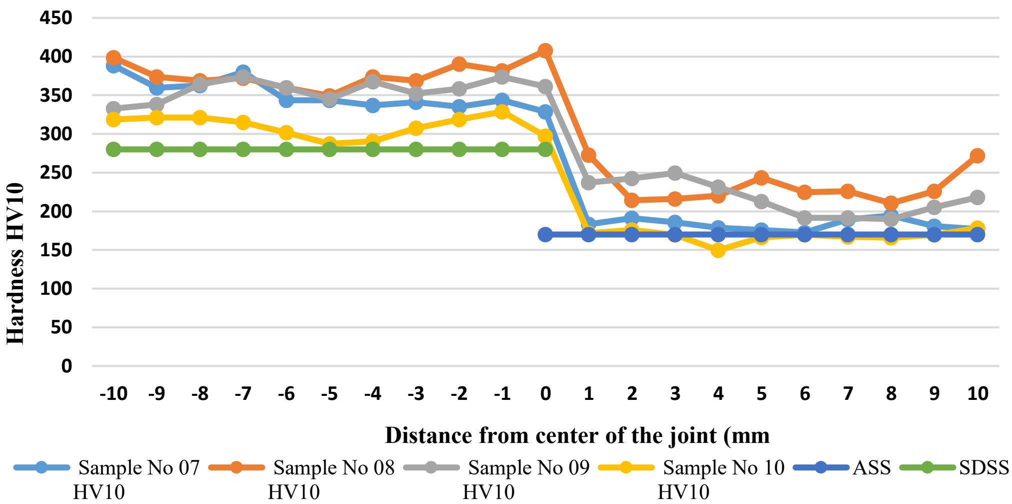


Figure 10: Hardness profile at the middle of the pipe

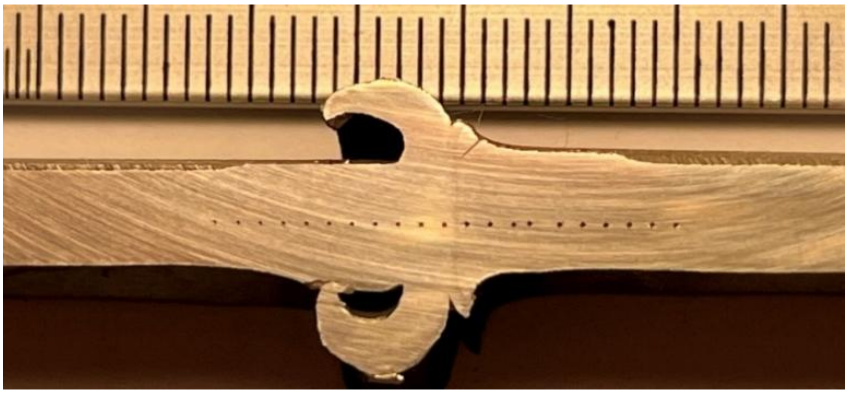
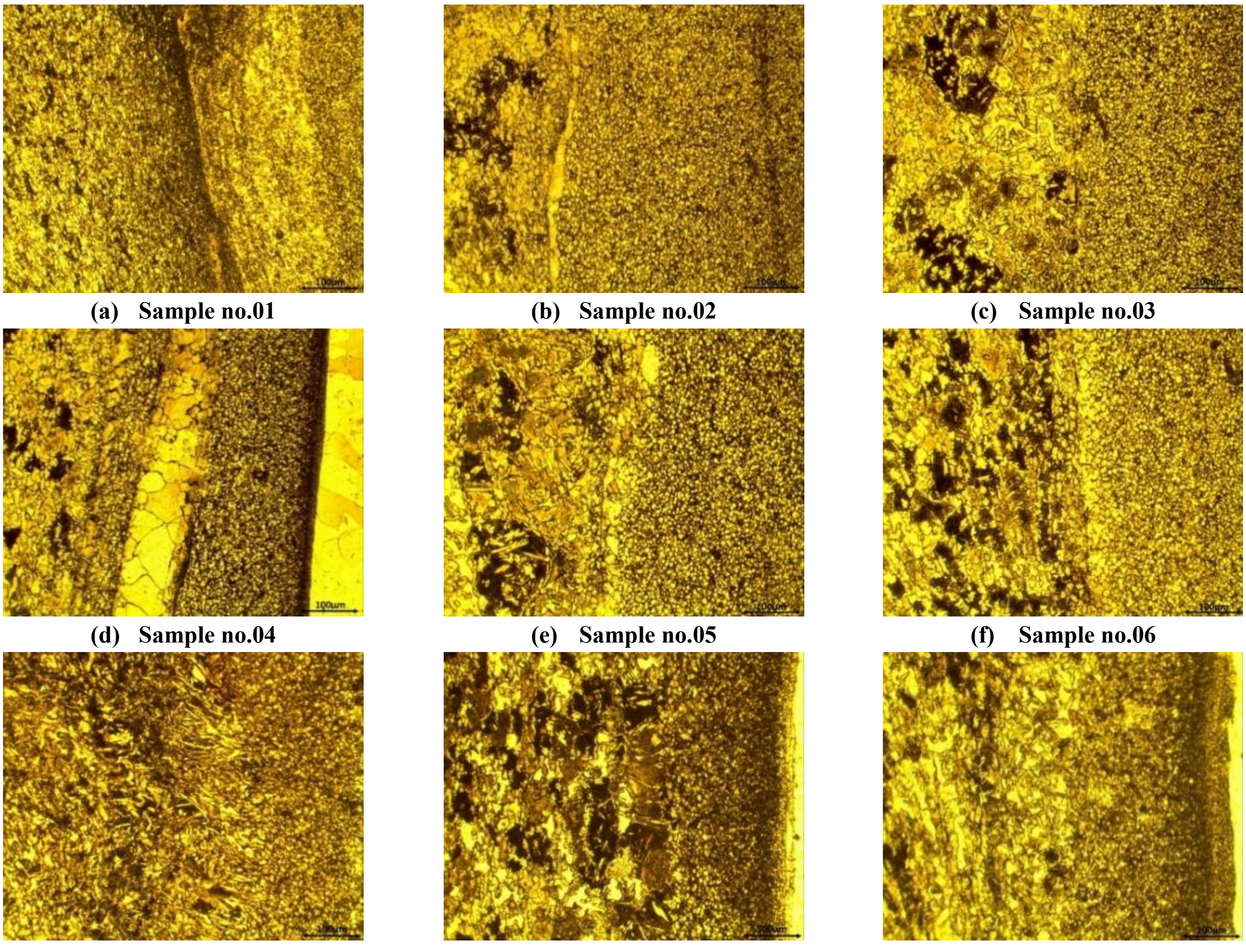


Figure 11: Hardness indentation at the middle of the pipe sample no. 9

3.4 Microstructure

Mechanical properties and corrosion resistance of the austenitic and super duplex stainless steel are strongly related to the microstructure and the austenite to ferrite ratio; any change in the structure and the austenite to ferrite ratio directly affects the mechanical properties and the quality of the product. This change can be due to any process of forming, welding, or heat treatment. During rotary friction welding, the structure of stainless steel is affected by the heat input and the duration of this process at the elevated temperature, so the process of friction welding and friction parameters have a significant effect on the microstructure and the properties. The microstructure of the welded samples is shown in Figures 12 a to 12 i. It demonstrates the effect of the welding parameters on the rate of the newly formed phases, grain size, and the structures. The samples with more heat input have more chrome carbides and brittle phases, including the sigma phase. The detail of the welded sample shown in Figure 13 shows the weld area to the thermo-mechanical affected zone and the heat-affected zone for sample no. 7.



(a) Sample no.01 **(b) Sample no.02** **(c) Sample no.03**

(d) Sample no.04 **(e) Sample no.05** **(f) Sample no.06**

(g) Sample no.07 **(h) Sample no.08** **(i) Sample no.09**

Figure 12: Microstructure of welded samples at the weld area a) Sample no.01, b) Sample no.02, c) Sample no.03, d) Sample no.04, e) Sample no.05, f) Sample no.06, g) Sample no.07, h) Sample no.08, i) Sample no.09

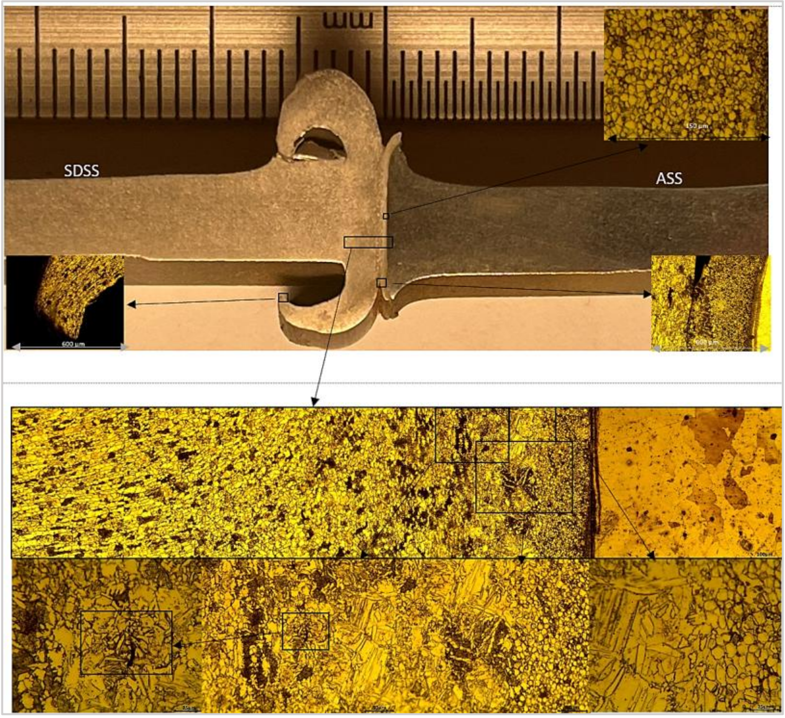


Figure 13: Microstructure of welded sample no.07

4. Conclusion

In this study, the mechanical and microstructure of the dissimilar joint for austenitic stainless steel and super duplex stainless steel A312 TP316L and A790 SS32750 by using continuous drive rotary friction welding was investigated. And the conclusions are as follows.

1) The continuous drive rotary friction welding can be used to join austenitic and super duplex stainless steel with good mechanical properties and acceptable microstructure.
2) The mechanical properties of the welded joint by this process are significantly affected by the friction and forging parameters, both pressure and time.
3) The heat input for this process is the key parameter in defining the mechanical properties and microstructure.
4) The welded joint quality and the process parameters are interconnected and any change in any parameter can significantly change the quality, especially the parameters that increase the heat input.
5) The best result for dissimilar joints between austenitic and super duplex stainless steel was achieved by using rotary friction welding with the following parameters. 30 MPa as friction pressure, 10 seconds for friction time, 20 MPa for forging pressure, 30 seconds for forging time, and 1030 rpm for rotational speed.
6) More study is required on this topic to join steel pipes to investigate more on both mechanical and corrosion resistance of the welded pipes and to overcome the related issues of this process and use it in the manufacturing process in different industries, as the benefits of this process compared to the traditional methods of welding are significant.

Author contributions

Conceptualization, **Z. Tawfeeq** and **R. Gardi**; data curation, **Z. Tawfeeq**; formal analysis, **Z. Tawfeeq**; investigation, **Z. Tawfeeq**; methodology, **Z. Tawfeeq** and **R. Gardi**.; project administration, **Z. Tawfeeq** and **R. Gardi**; resources, **Z. Tawfeeq**; software, **Z. Tawfeeq**; supervision, **R. Gardi**; validation, **Z. Tawfeeq** and **R. Gardi**; visualization, **Z. Tawfeeq**; writing—original draft preparation, **Z. Tawfeeq**; writing—review and editing, **Z. Tawfeeq**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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