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RESEARCH PAPER

Investigation of the Microstructure and Wear Properties of AISI 304 Steel Friction Weldments

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A B S T R A C T:

In this study, a rotary friction welding technique was used to join austenitic stainless-steel grade AISI 304. The effect of different forging pressure (192.4, 240.5, 288.6 and 384.8 *MPa*) on wear resistance of AISI 304 were examined using a modified pin on disc tester. The microstructure of the AISI 304 was examined as well using an optical microscope. The wear resistance results of the welded specimens were reported better than as received. The variation of increasing wear loss was uniformly changed with sliding distance. Further, it was noted from the experiments that the wear rate increased with increasing forging pressure in which the minimum wear rate was 3 mm^3 at 192.4 *MPa* while a maximum wear rate (25.823 mm^3) occurs at a forging pressure of 384.8 *MPa*. This is due to the microstructure changes which is decreasing grain size and formation of twin grains and also precipitating carbides.

KEY WORDS*:* Rotary friction welding; Wear rate; Austenitic stainless steel 304; Microstructure; Surface roughness
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1.INTRODUCTION:

Stainless steels are widely used in various areas in practical applications such as nuclear, chemical and petrochemical industries (Ramirez et al., 2011). Stainless steels which are identified by iron-based alloys containing 8 to 25% nickel and 12 to 30% chromium (Barzinjy, 2016). Generally, there are several types of stainless steels including martensitic, ferritic, austenitic, duplex and precipitation hardening stainless steels (Kirik and Özdemýr, 2015). It is widely utilized in the liquid-handling system and hydraulic machinery due to excellent corrosion resistance, good machinability, low cost and weld-ability (Chiu et al., 2005; Samir A. and Gardi, 2017) and energy-absorption ability (Zhang et al., 2019).

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The AISI-304 is a most common steel among the austenitic stainless steels because of superior corrosion resistance in chemical environments and applicability in various areas, including automotive, food, chemical, nuclear power, energy source, marine transport, petrochemical, military (Hu et al., 2019; Naeem et al., 2019) and liquefied natural gas storage at cryogenic temperatures (Jia et al., 2020). Since, the wear is one of the most common industrial issues which encountered engineering assemblies and components. It diminishes the working efficiency by increasing the fuel usage, material losses and the rate of component replacement (Radhika et al., 2015). In addition, the welding is the other problem for joining materials due to changing the mechanical property of the materials internal strain, slag, pores, and sensitization phenomenon (Almanza-Casas et al., 2011) and tender intermetallic phases (Mercan et al., 2015). However, the 304 austenitic stainless steel (AISI 304 ASS) is a non-ferromagnetic alloy with high toughness and plasticity but owning poor wear resistance (Zhao et al., 2018) when it is welded. Due to formation of intergranular chromium carbides (Park et al., 2004). For the reason that friction welding is a much more preferable rout to join the austenitic stainless steel. Rotary friction welding is a solid-state welding process which used for joining the similar and dissimilar round bar materials. The joint is produced due to the generating heat between two contacted workpieces in which one is fixed and the other rotated with a certain speed. The plastic deformation is produced due to applying the axial force through the stationary side. Thereafter, applying the upset force when the sufficient heat is produced (Akbarimousavi and Goharikia, 2011).

In 2018, Zhao *et al.* examined the wear resistance and corrosion resistance of resistance of the AISI 304 ASS using liquid nitrocarburization technique. Their results showed that both the wear and corrosion resistance of nitrocarburized 304 stainless steel were increased as compare to the non-nitrocarburized one (Zhao et al., 2018). In the same year, Krishna Kumar *et al.* investigated the wear resistance and hardness of AISI 304 by surface alloying process using heat generated gas tungsten arc source. They heated the surface of austenitic stainless samples for 6 *h* in the furnace. The authors revealed that the hardness was increased and wear resistance decreased after the heat treatment process (Krishna Kumar et al., 2018). In addition, Chattrakul and Sornsuwit, (2018) studied the effects of surface appearance, chemical composition and direction of AISI 304, AISI 304L stainless steel and nylon wire on wear resistance of polymer-metal interface. They realized that the sliding direction and surface roughness was more effective than chemical composition of AISI 304 and 304L stainless steel on wear rate. The authors considered that this result is referring to the amount of the contact area and displacement between austenitic stainless steel and nylon wire during the sliding. The authors concluded that the increase in roughness was increased wear rate in parallel direction but decreased it in perpendicular direction. However, in both directions the wear resistance of stainless steel 304 is less than 304L except in case of 1 μm surface roughness (Chattrakul and Sornsuwit, 2018). In 2019, Palanikumar *et al.* evaluated the effect of sliding speed and the temperasture change on the coefficient of friction at the contact interface of AISI 304 austenitic stainless-steel alloys in which subjected to full sliding. Their work was done using a rotatory type pin on disk tribometer. The authors found that the coefficient of friction decreased with increase in sliding speed at full sliding experiments. The sliding experiments results showed that the friction coefficient decreased with increase in sliding speed where the friction coefficient was in the range (0.15–0.28). They observed that during sliding the temperature at the contact interface was increased in the result of increasing in friction at the contact interface (Palanikumar et al., 2019).

During decades ago, a number of studies have been done on wear resistance for different welded methods and materials. However, the majority of attempts have been examined for friction stir welded materials. Unfortunately, there is no study on the literature into the investigation on wear resistance of rotary friction welded joints for the AISI 304 ASS. Therefore, the main aim of the current paper is evaluating the experimental investigation into the wear resistance of austenitic stainless steel AISI 304 with using rotary friction welding.

2.MATERIALS AND METHODS

2.1 Materials

The experiments were conducted on austenitic stainless steel (*AISI 304*) rod. To measure the wear, a duplex stainless steel (SAF 2205) with a hardness of (293 HB), which is higher than the hardness of AISI 304 (123 HB), was used. **Error! Reference source not found.** show the chemical composition. Whereas, **Error! Reference source not found.** provides the mechanical properties of both materials.

Material Type	Elements (wt.%)									
	C	Si	Mn	P	S	Cr	Ni	Mo	N	Fe
AISI 304 Stainless Steel	0.054	0.38	1.67	0.036	0.024	8.2	8	-	0.1	Balance
SAF 2205 Duplex Stainless Steel	0.03	1	2	0.03	0.015	22	5	3.2	0.18	Balance

Table (1) Nominal Chemical Composition

Table (2) Mechanical properties of the both materials

	Yield Strength (MPa)	Ultimate Strength (MPa)	Hardness (HB)	Modulus of Elasticity (GPa)	Melting Range (°C)
AISI 304 Stainless Steel	215	505	123	129	1400-1450
SAF 2205 Duplex Stainless Steel	450	655	293	200	1410-1465

2.2 Experimental Machine Setup and Procedure

The AISI 304 rod was machined to a 15 *mm* diameter using a lathe machine. Then the rod was cut to two different lengths including 60 *mm* and 40 *mm*. The larger workpiece length (60 *mm*) was kept on the stationary chuck of the lathe machine while the smaller length (40 *mm*) was kept on the rotating chuck. To achieve a good welding process, the contact faces of the two mate rods were pre-machined not only to get a smooth surface and to remove the oxide from the surfaces but also to avoid the bending by ensuring a perpendicular contact between the two mated rods.

2.3 Friction Welding Process

The welding process was conducted on a lathe machine. In the rotary friction welding, the most impacting parameters are friction pressure, rotational speed, friction time and forging pressure. In this work, four different forging pressures, (192.4, 240.5, 288.6 and 384.8 *MPa*) were employed to accomplish the welding process. The process was performed by adding a friction pressure of 192.4 *MPa* at the stationary side against the rotational side. Then the forging pressures 192.4 *MPa* was added straight away after stopping the machine. The same procedure was repeated for 240.5, 288.6 and 384.8 *MPa* forging pressures, respectively. It is worth to note that all the welding experiments were conducted at a constant rotation speed of 560 *RPM*, and a constant friction time of 60 *s*. The appearances of the friction welded butt joint of the specimens have been shown in **Error! Reference source not found.**.

Below are some investigations which have been performed to investigate the effects of the welding parameters on the wear, microstructure and the surface roughness of the welded joints.

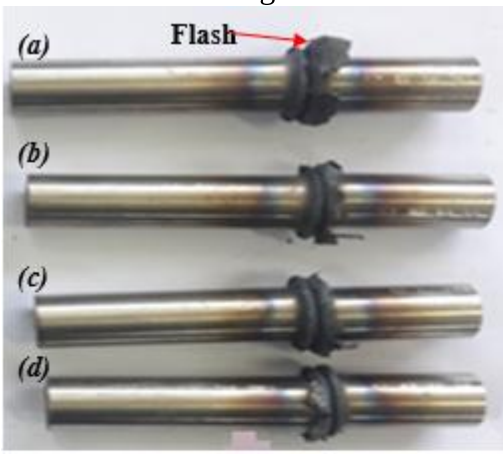


Figure 1: Friction Welded Specimens at Forging Pressure is (a) 192.4 MPa, (b) 240.5MPa, (c) 288.6 and (d) 384.8 MPa.

2.4 Microstructure

The microstructure of the welded joints was investigated using an optical microscope. The microstructure samples were prepared and flattened using a disc and grinding/polishing machine. The specimens were grinded dry using Al_2O_3 emery papers with a different grades grit including 320, 800 and 1000 grits. The grinded specimens were then polished with a light cloth. Finally, the polished samples were etched, using a solution which prepared according to the ASTM E407 standard, with (HCl +$FeCl_3$+ HNO_3+ distilled water) for 2.5 minutes.

2.5 Measuring Wear

Wear tests were performed using a modified pin-on-disc tester [Model: TE91/1, Pin on Disc Model, Serial No.: U 9259/3, TQ]. The pin was made from the *AISI 304* welded joints in the axial direction of the friction welded joint while the counter face rotating disc was made from the duplex stainless steel (SAF 2205). The wear samples were prepared according to the *ASTM: G99-05* standard. The dimension of the pin is 8 *mm* in diameter and 25 *mm* in length while the dimension of the disc is 65 *mm* in diameter. Figure 2 shows a schematic of the modified pin on disc tester. The pin was attached to the stationary side while the disc to the rotation part. The wear tests were conducted at room temperature in a dry condition. A load of 25 *N* was applied on the pin and the linear velocity was 12.5 *m/min*. Thereafter, different distance including 77, 154 and 232 *m* were considered, and wear rate were calculated. A digital scale, with a least count of 0.001*g*, was used to measure the weight of the samples. Thereafter, the surface roughness of disc has been evaluated using Tyler–Hobson surface roughness tester (Talysur-10) at different points with a 0.8 *mm* sensor sliding distance in which perpendicular on the wear track distance.

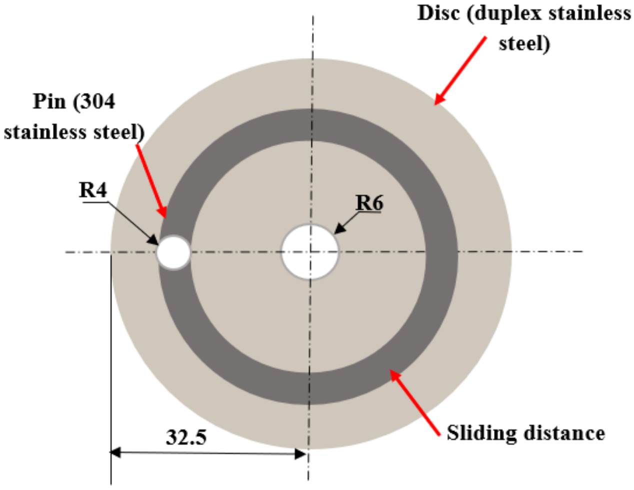


Figure 2: Schematic configuration of the modified pin-on-disk tribometer

1. RESULTS AND DISCUSSIONS

The wear rate of friction welded 304 AISI austenitic stainless steel was conducted for four forging pressure cases (192.4, 240.5, 288.6 and 384.8 *MPa*). The wear rate results were carried out after 2, 4- and 6-min. intervals of time. The wear rate with respect of sliding distance (77, 154 and 232 *m*) for as-received materials is shown in **Error! Reference source not found.**.

In addition, the comparison of wear rate as a function of sliding distance for four pins are shown in the sequence of **Error! Reference source not found.** (a-d), respectively. In addition, the microstructure for welded joints are presented in **Error! Reference source not found.**. Thereafter, the surface roughness of duplex stainless steel SAF 2205 disk for friction welded pins after 6 *min* wear and as-received materials were presented in **Error! Reference source not found.**.

In general, the obtained results revealed that the wear rate are increased with increasing siding distance for both as-received and welded joints. **Error! Reference source not found.** a-d shows the minimum wear rate values (3 mm^3) at 77 *m* sliding distance and maximum was at (25.823 mm^3) 232 *m* sliding distance for all forging pressure cases. This was revealed that the wear rate trends up with increasing sliding distance (from 77 to 154 then 232 *m*). These results are attributed to that at final stage the hard and denies layer of chromium oxide were removed which leads to increasing wear rate. Consistent with this results the previous researcher argued that this was due to the duration of rubbing surface and the reduction of shear strength of the material, which increased the true area of contact between contacting surfaces (Chowdhury et al., 2013) and increasing coefficient of friction (Rana et al., 2016). Furthermore, the study by Naplocha and Kaczmar, (2011) suggested that at dry sliding condition, when the wear rate is changed slowly, the surface layer will produce with changed microstructure and chemical composition. This is due to the formation wear debris from the counterparts, the reinforcing phases, oxides and atmosphere gases.

This study revealed that the wear rate is increased with increasing the forging pressure with constant sliding distance. For instance, the minimum wear rate was recorded (3 mm^3) at a forging pressure of 192.4 *MPa* and a sliding distance of 77 *m* (see **Error! Reference source not found.** a) and this rate increased to its maximum value (9 mm^3) at a forging pressure of 384.8 *MPa* at the same sliding distance. These values were significantly less than the as-received materials which is 23 mm^3 as seen in **Error! Reference**

source not found. at the same sliding distance. This reduction of wear resistance under the effect of forging pressure is attributed to the producing a finer grain size by slicing the grains (twin grains). Further, reducing the hardness in these regions due to the formation carbides in the grain boundaries (**Error! Reference source not found.**). In accordance with this concept the researchers, Thangarasu, Murugan and Dinaharan, in 2014 reported that when the hardness of materials are higher hardness, the lower wear rate will happen, due to increasing the resistance to remove material during sliding.

What is interesting about the data in this study is the friction welding has a significant effect on wear rate. As it can be seen that an excellent improvement of wear resistance was revealed for welded joint compared to as received materials. This improvement is related to microstructure changes at the weld joints such as a great number of twins, the finer grain size at the joints, occurring the two phases (austenitic and ferritic), recrystallizations and large amount of carbides at the grain boundaries as shown in **Error! Reference source not found.** a-d.

The surface roughness of the wear track on the *SAF 2205* duplex stainless steel for as received condition (304 austenitic stainless-steel pin) is measured separately which is $0.9\mu m$. As it can be seen from the graph (**Error! Reference source not found.**), the surface roughness of the disc at a sliding distance of 232 *m*, except the samples at 240.5 *MPa*, are higher as compare to the surface roughness of as-received materials. The surface roughness increased with increasing forging pressure. These results are referring to microstructural changes including creation of different carbides that occurs at joint during welding during heat and plastic deformation. Thus, these results are shows that the correlation between the surface roughness with forging pressure were negatively associated.

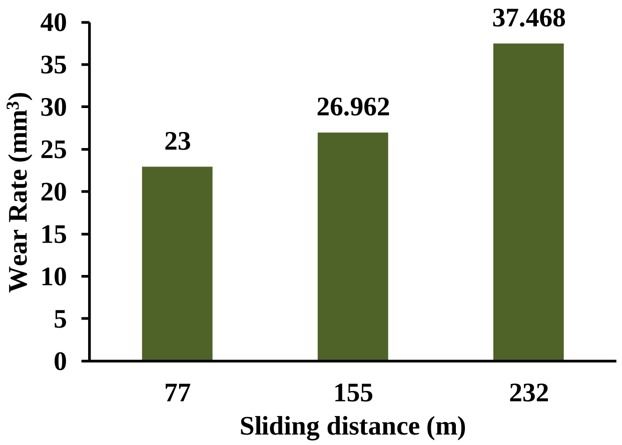
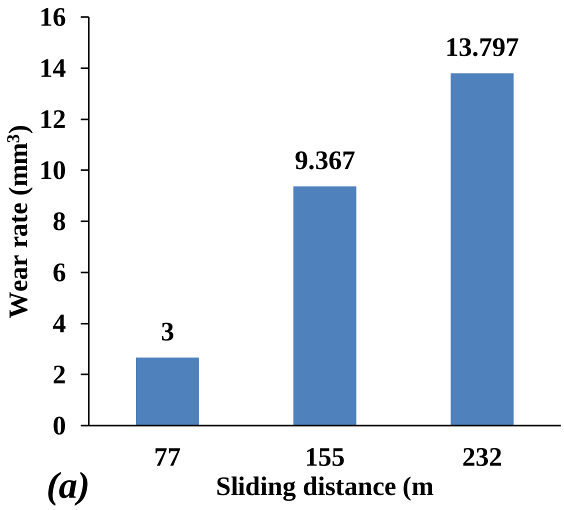
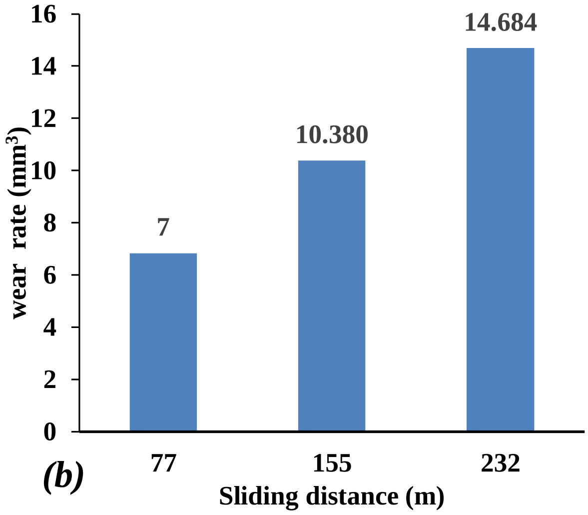


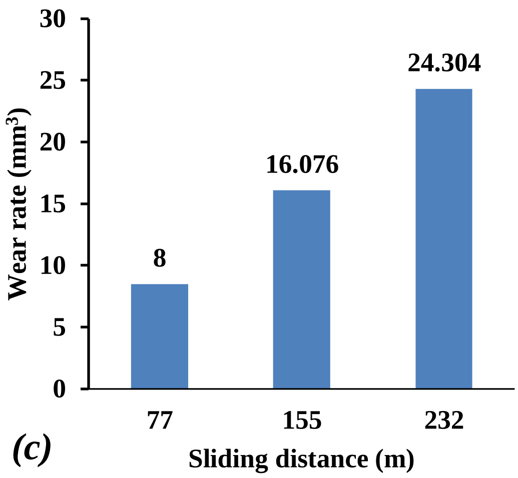
Figure 3: Variation of Wear Rate with Sliding Distance for As-Received Materia



(a)



(b)



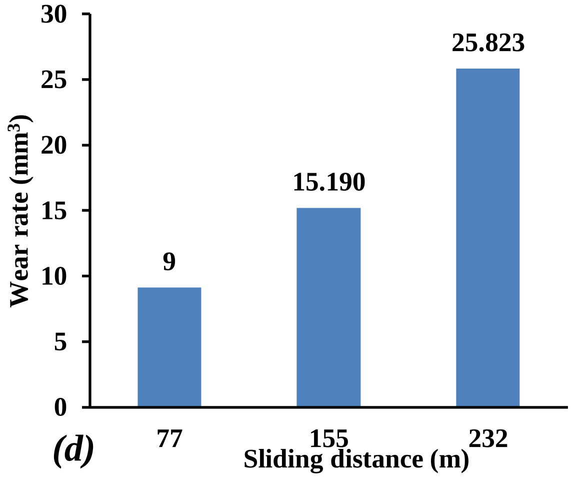
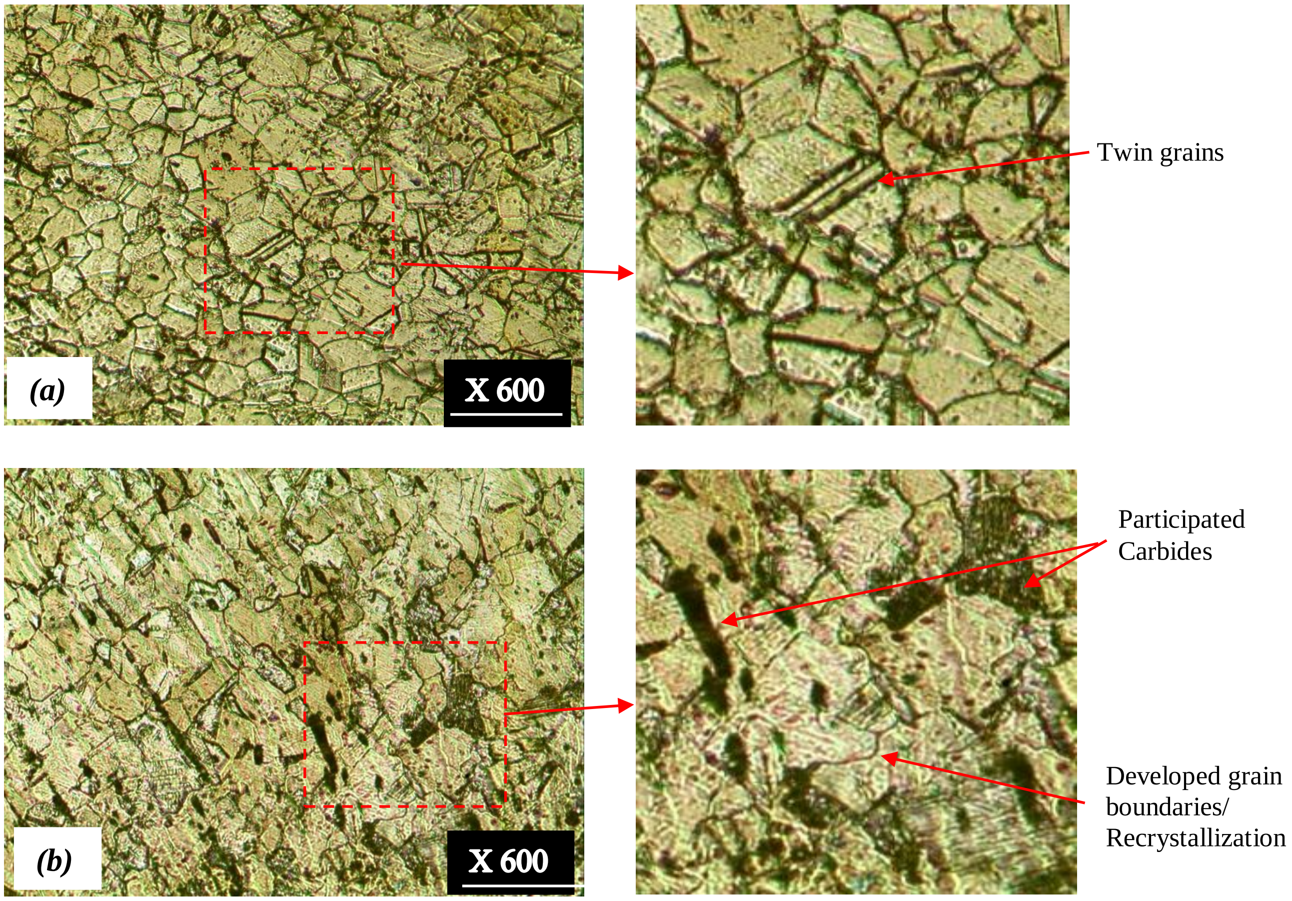


Figure 4: Variation of Wear Rate with Sliding Distance at (a) 192.4 MPa, (b) 240.5 MPa, (c) 288.6 MPa and (d) 384.8 MPa.



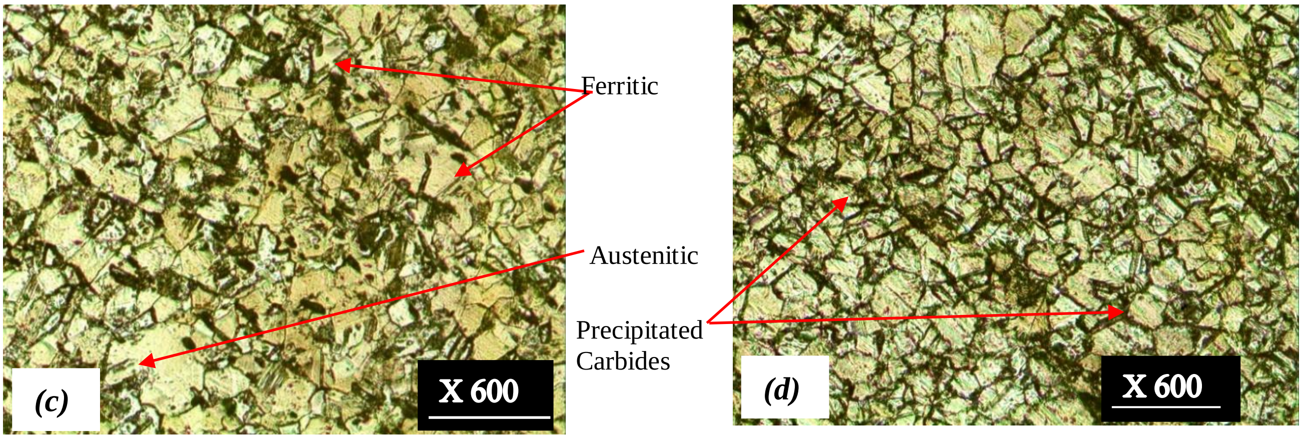


Figure 5: Optical image showing the microstructure of AISI 304 at different forging pressure (a) 192.4 MPa, (b) 240.5 MPa, (c) 288.6 MPa and (d) 384.8 MPa.

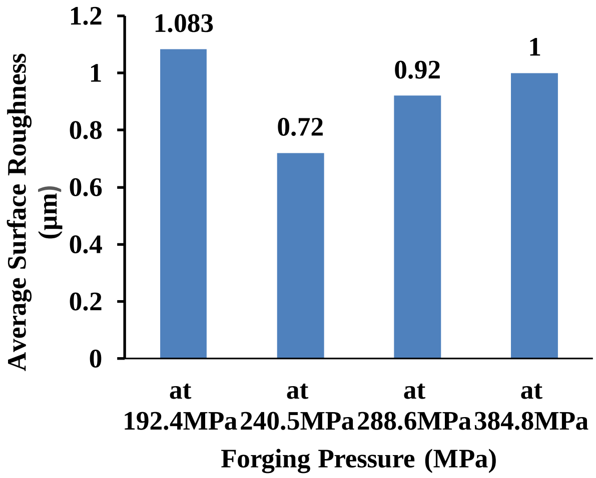


Figure 6: Average Surface Roughness of Disk at Different Forging Pressure Cases.

2. CONCLUSIONS

The aim of the present research was to examine the wear resistance of friction welded joints of AISI 304 ASS. The following conclusions can be drawn from the present study:

1. The friction welding of *AISI 304* austenitic stainless steel improves the wear resistance.
2. The minimum wear rate was 3 mm^3 at 192.4*MPa* forging pressure, while the maximum wear rate was 25.823 mm^3 at 384.8 *MPa* forging pressure.
3. The lowest surface roughness on *SAF 2205 DSS* disc can be obtained when *304 ASS* pin friction welded with 240.5 *MPa* forging pressure.

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