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Characterization of Rotary Friction Welded AISI 304 Steel Joints

Jwan Khalil Mohammed [a], Ramadan H. Gardi [b], Dlair O. Ramadan [c]

[a] Mechanical and Energy E gineering Techniques Department, Erbil Technical Engineering College, Erbil Polytechnic University, Erbil, Kurdistan Region, Iraq

[b] Mechanical and Mechatronics Engineering Department, Engineering College, Salahaddin University, Erbil, Kurdistan Region, Iraq

[c] Mechanical and Energy Engineering Techniques Department, Erbil Technical Engineering College, Erbil Polytechnic University, Erbil, Kurdistan Region, Iraq

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ABSTRACT

Friction welding method is one of the most efficient and effective techniques for joining similar and dissimilar materials. The AISI 304 austenitic stainless-steel is a most common type of austenitic stainless steel which is used in various practical applications like automotive, food manufacturing, chemical applications, etc. Therefore, the impact strength and microstructure behavior of friction welded AISI 304 austenitic stainless-steel joints were investigated. The specimens were divided into two groups, the surface of the first group was flat while the interface of the second group was designed by fabricating a pin and hole. The effect of different forging pressure (192.4, 240.5, 288.6 and 384.8 *MPa*) on impact toughness and microstructure behavior of AISI 304 were examined using Charpy impact tester and optical microscope, respectively. The minimum impact strength was observed at 240.5 *MPa* for flat interface samples whereas, the maximum impact strength value (0.5675 J/mm^2) was at 388.6 *MPa* forging pressure for pin interface samples. In addition, the ductile mode in pin type for all cases while both, brittle and ductile mode in the flat joint was noticed. Finally, it was concluded that the impact strength improved with designing a pin and hole shape at the joint interface.

Corresponding author: : Jwan Khalil Mohammed ; jwan.eng@hotmail.com ; +9647817812456

1. **Introduction**

Due to its high ductility, excellent drawing, forming properties, non-magnetic and low carbon content, the AISI 304 austenitic stainless steel is widely used in numerous applications like pressure vessels, chemical, cryogenic and hospital surgical equipment, cooking equipment and marine equipment [1]. When AISI 304 austenitic stainless steel is welded by fusion welding encountered some problems such as pores, internal strain, and slag sensitization phenomenon [2] and tender intermetallic phases which negatively influences the quality of welding [3]. Therefore, much more preferred that austenitic stainless steel is joined by friction welding types.

Rotary friction welding (RFW) is one of the solid-state techniques that utilized in joining similar and dissimilar materials [4]. In this process, the machinery components are brought into contact. Where one of them is rotated with the applied pressure while the other remains stationary [5-6]. Intimate contact between the parts are maintained which is causes the plastic deformation near the weld interface due to the application of an axial force. If sufficient frictional heat has been produced during softening, larger wear particles begin to expel from the interfaces and axial shortening of the components begin as a result of the expelled upsetting. In general, heat is conducted away from the interfaces, and a plastic zone develops. The plasticized layer is formed on the interfaces and the local stress system with the assistance of the rotary movement extrudes material from the interface into the flash [7–10].

In the last decades, many attempts have been made to improve the mechanical and metallurgical properties of friction welded AISI 304 stainless steel. For instance, Handa and Chawla, (2014) have joined AISI 304 with AISI 1021 steels. The researchers have conducted rotary friction welding at different friction pressures. In their results, they found out that the tensile strength and hardness at the center of the welded joints were increased with increasing the axial pressure while impact toughness decreased. The authors observed a maximum tensile strength at 135 *MPa* and 34 *s* [11]. Thereafter, Kirik and Özdemýr, (2015) determined the effect of friction welding process parameters of AISI 304L and AISI 1040 stainless steel sheets on the microstructure and mechanical properties. They found that the friction-welded AISI 1040 and AISI 304L steels were free of pores and cracks. Then, the authors indicated four different regions in the microstructural results including fully plasticized deformed zone, partially deformed zone, deformed zone, and base materials. The fully plasticized deformed zone and deformed zone were mainly affected by the frictional time and rotational speed. Although, this was suggested that the formation of a fully plasticized deformed zone due to the heat input and plastic deformation at the interface [12]. In addition, Li et al., (2018) evaluated the inhomogeneous interface structure and mechanical properties of rotary friction welded TC4 titanium alloy and 316L stainless steel joints. They observed the convex-shaped on TC4 titanium alloy side and concave-shaped on 316L stainless steel side. Furthermore, they noticed that the sliced samples were relatively weak even after post-weld heat treatment. Accordingly, suggested that this became surface crack sources after machining, caused stress concentration, sharply reduced the strength of samples and the elemental homogenization occurred in the joint after post-weld heat treatment [13]. However, many studies in the last ten years were attempted to investigate the austenitic stainless steels properties and the ability to improve the mechanical and metallurgical properties. Unfortunately, studying of similar joints for austenitic stainless steel by rotary friction welding is still limiting. Although, there is no study for improving the mechanical property of AISI 304 by designing the joint except the attempts which have been made by [14] for dissimilar joint between aluminum alloy to alumina and [15] for mild steel to austenite stainless steel. Therefore, the aim of this study is presenting the experimental investigation to evaluating the impact strength of friction welded austenitic stainless steel 304 with changing joint geometry.

2. Materials and methods

2.1. Material and specimen preparation

AISI 304 austenitic stainless-steel rod in diameter 15 *mm* was used as a base material, of which the chemical composition and mechanical properties are illustrated in

Table 1 and Table 2, respectively. The base material was cut to two different lengths including 60 *mm* which was kept on the stationary chuck and 40 *mm* on the rotating chuck of the lathe machine. The samples were divided into two groups each group included four samples. The surfaces of the first group remained flat while the second group was designed by producing a pin while at the opposing side the hole was drilled. The schematic diagram of the two groups of specimens are shown in **Error! Reference source not found.**(a and b).

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	18.2	8	-	0.1	Balance

Table 1. Nominal Chemical Composition

Table 2 Mechanical Properties of AISI 304 austenitic stainless steel.

	Yield Strength (MPa)	Ultimate Strength (MPa)	Impact Toughness Charpy (J)	Hardness		Modulus of Elasticity (GPa)	Melting Range (°C)
				HB	HVN		
AISI 304 Stainless Steel	215	505	138	123	202	129	1400-1450

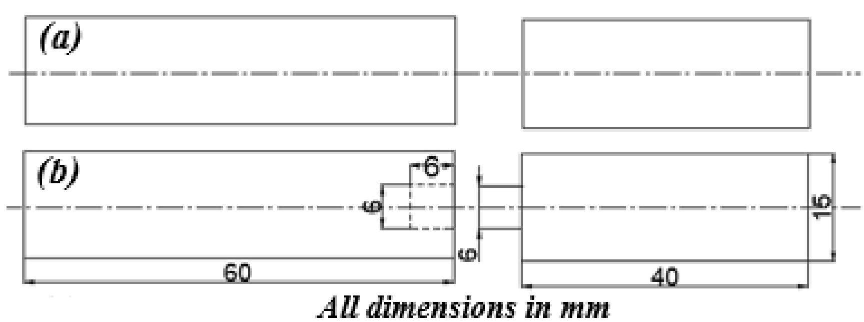

Figure 1 Scematic diagram of specimens (a) Flat interface, (b) Pin interface

2.2. Friction welding process

The welding process was performed on a lath machine. In this work, four different forging pressures (192.4, 240.5, 288.6 and 384.8 *MPa*) were examined. The process was conducted by adding friction pressure (192.4 *MPa*) gradually at the stationary side against the rotational side which rotate at 560 *RPM* frictional speed. When the two contacted interfaces were joined then the machine was stopped and the forging pressure (192.4 *MPa*) was added straight away. 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 constant friction time of 60 *s*. The appearances of the friction welded butt joint for both cases (flat and pin interface) at different forging pressure cases have been shown in **Error! Reference source not found.**. In the following sections, the investigations have been performed to evaluate the effect of forging pressure and designed joints on microstructure and impact toughness of friction welded samples.

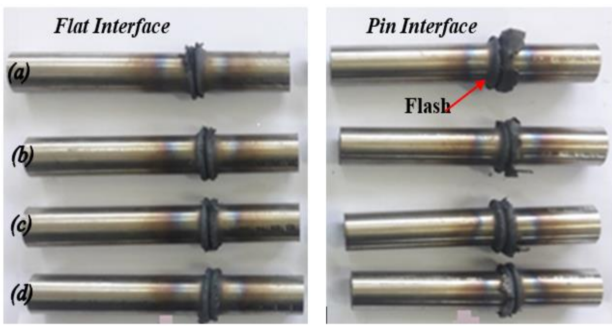

Figure 2 Friction Welded Specimens at Forging Pressure is (*a*) 192.4 MPa, (*b*) 240.5MPa, (*c*) 288.6 and (*d*) 384.8 MPa

3. Mechanical tests

3.1. Impact test

The welded specimens were machined according to the standard ASTM-E23. The dimensions of the sample were 55 *mm* long, 10 *mm* wide and 5 *mm* depth keeping the weld joint at the center of the specimen. In addition, a 'V' notch was made at the center of the specimen (weld joint) with 2 *mm* depth by 45° (see **Error! Reference source not found.**).

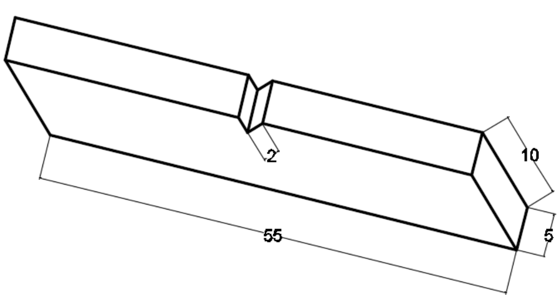

Figure 3 schematic diagram of the impact specimen

The Gunt impact tester pendulum type was used for investigating the Charpy impact behavior of the weld joints. The test was carried out at room temperature. Firstly, the work was done by supporting the two ends of the specimen. Then the amount of energy absorbed by air and the specimen was measured at room temperature separately. Thus, the impact strength was calculated by the following equation.

$$\text{Impact strength } (J/mm^{2}) = \frac{\text{Energy absorbed by specimen} - \text{Energy absorbed by air}}{\text{Cross section area without notch}}$$

3.2. Microstructure test

The microstructural features of friction welds were investigated using an optical microscope. The microstructure samples were first flattened using a disc and grinding/polishing machine. Then mechanically grind was applied using dry Al_2O_3 emery papers with different grades grit including 320, 800 and 1000 grits. For further surface finishing the grinded specimens were polished with a light cloth. Finally, the specimens were etched in a chemical solution which prepared according to the ASTM standard, with ($HCl + FeCl_3 + HNO_3 +$ distilled water) for 2.5 minutes.

4. Results

The Charpy impact test was conducted in order to investigate the impact toughness of friction welded AISI 304 austenitic stainless steels welded with different forging pressures. The relation between impact strength and forging force for the pin and flat interface specimens was plotted in **Error! Reference source not found.** andFigure **5** respectively. The microstructure of welded joints for pin and flat interface cases were presented in **Error! Reference source not found.** andFigure 7. The fracture results before and after the impact test were presented in Figure 8. In addition, the fracture morphology of all impact (pin and flat) specimens were demonstrated in **Error! Reference source not found.**.

5. Discussion

Error! Reference source not found. shows the minimum impact toughness was 0.165 J/mm^2 at 192.4 *MPa* forging pressure while this was reached to its maximum value 0.5675 J/mm^2 when forging pressure was 288.6 *MPa*. This result is related to the superior mixing, flow materials and generated sufficient heat during the welding. In addition, the formation of carbides between the grain boundaries (**Error! Reference source not**

found. *c*) compared to the microstructure of joints welded with lower forging pressures (**Error! Reference source not found.** *a* and *b*).

Consequently, the impact strength suddenly declined to 0.3775 J/mm^2 with the further increase in the forging force (384.8 *MPa*). This result is attributed to excessive heat due to highest forging pressure, created several phases which cannot be seen with optical microscope and fine-grained structures consisting of ferrite and graphite (**Error! Reference source not found.***d*). Accordingly, Asif et al., (2015) observed that the impact strength decreased when further increase in heat between the two contacted materials. Because under usual conditions in the friction welding, the two contacted surfaces will not melt but the contact edges will be heated and softened along the material flows and increasing ferrite content [16].

In the case of flat interface specimens, the minimum impact strength was 0.1325 J/mm^2 at 240.5 *MPa* forging pressure. This is due to dynamic recrystallization in the welded joints (Figure 7*b*). This result is likely to be related to a low temperature and high strain rate. Increasing the forging pressure causes the material to flow plastically, which induces high strain rate. This phenomenon has restricted of grain growth and assisted to re-growth of new grains with a finer size [17]. Whereas, with increasing the forging pressure from 240.5 *MPa* to 288.6 *MPa* the impact strength raised to its maximum value (0.48 J/mm^2) as shown in Figure 5. This results attributed to increase the temperature and large amount of precipitated carbides in different shapes which can be seen in microstructure of the joint welded with 288.6 *MPa* (Figure 7*c*) compared to the microstructure of other joints for flat interfaces (Figure 7 *a*, *b* and *d*). This finding is consistent with that of Sammaiah et al., who examined 98 and 146 *MPa*. They reported that the impact strength is higher with the high forging in the result of higher deformation and failure occurred at the interface [18]. In comparison, the most interesting aspect of these graphs is the impact strength of designed pin interface significantly improved from 0.1325 J/mm^2 to 0.38 J/mm^2 at the 240.5 and from 0.48 J/mm^2 to 0.567J/mm^2 at 288.6 *MPa* forging pressures.

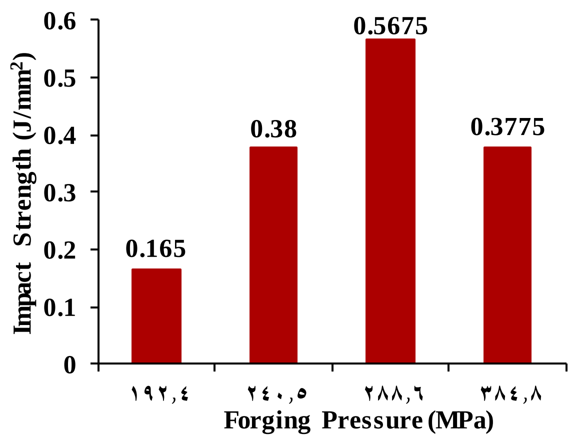

Figure 4 Impact Strength Under the Effect of Forging Force for Pin Interface Cases.

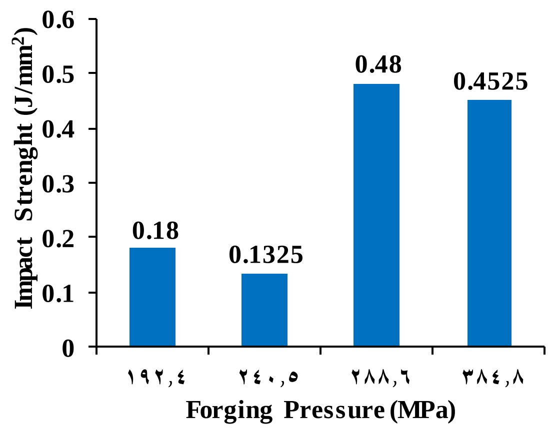

Figure 5 Impact Strength Under the Effect of Forging Force for Flat Interface Cases

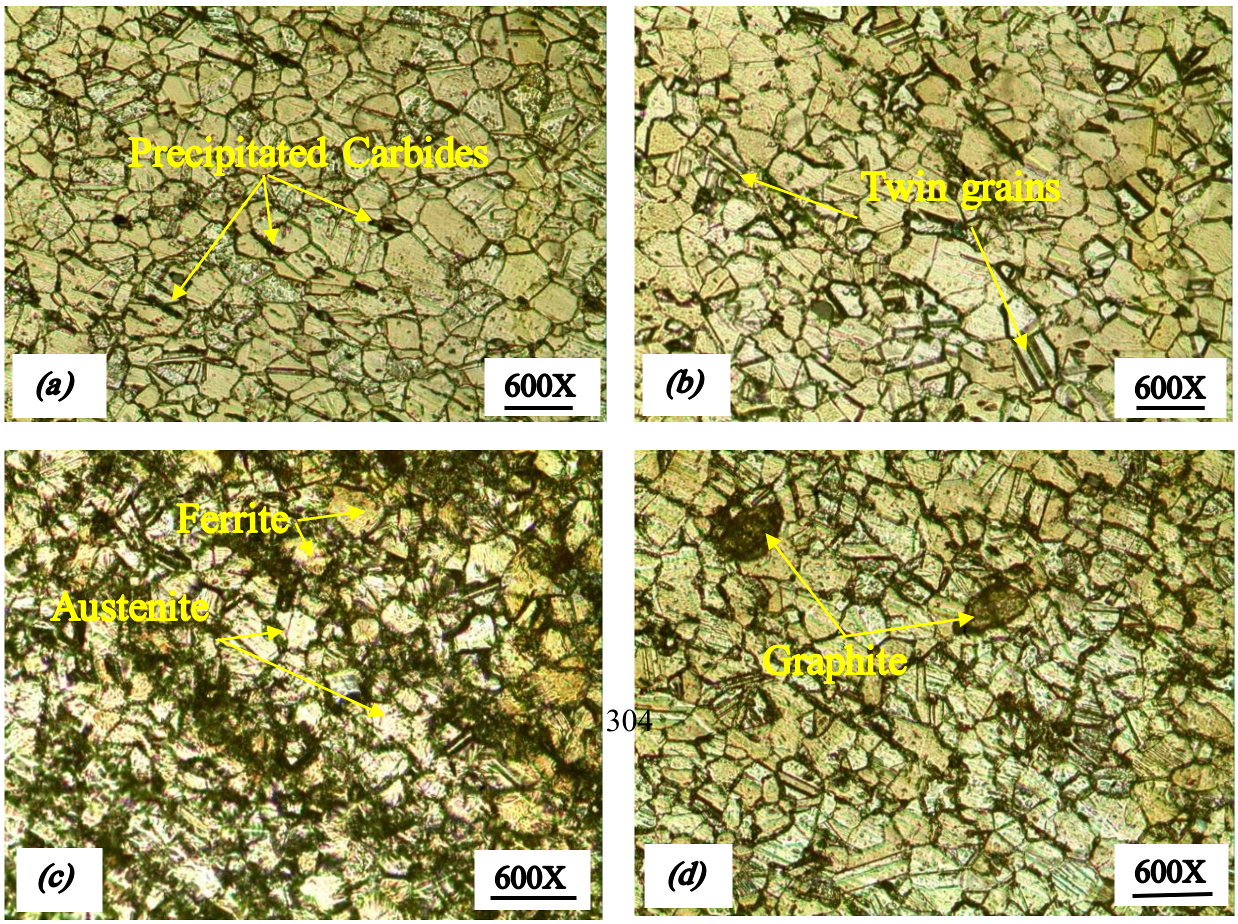

Figure 6 Optical micrographs of friction welded (Pin interface) at forging pressures (*a*)192.4 *MPa*, (*b*) 240.5 *MPa*, (*c*) 288.6 *MPa* and (*d*) 384.8 *MPa*.

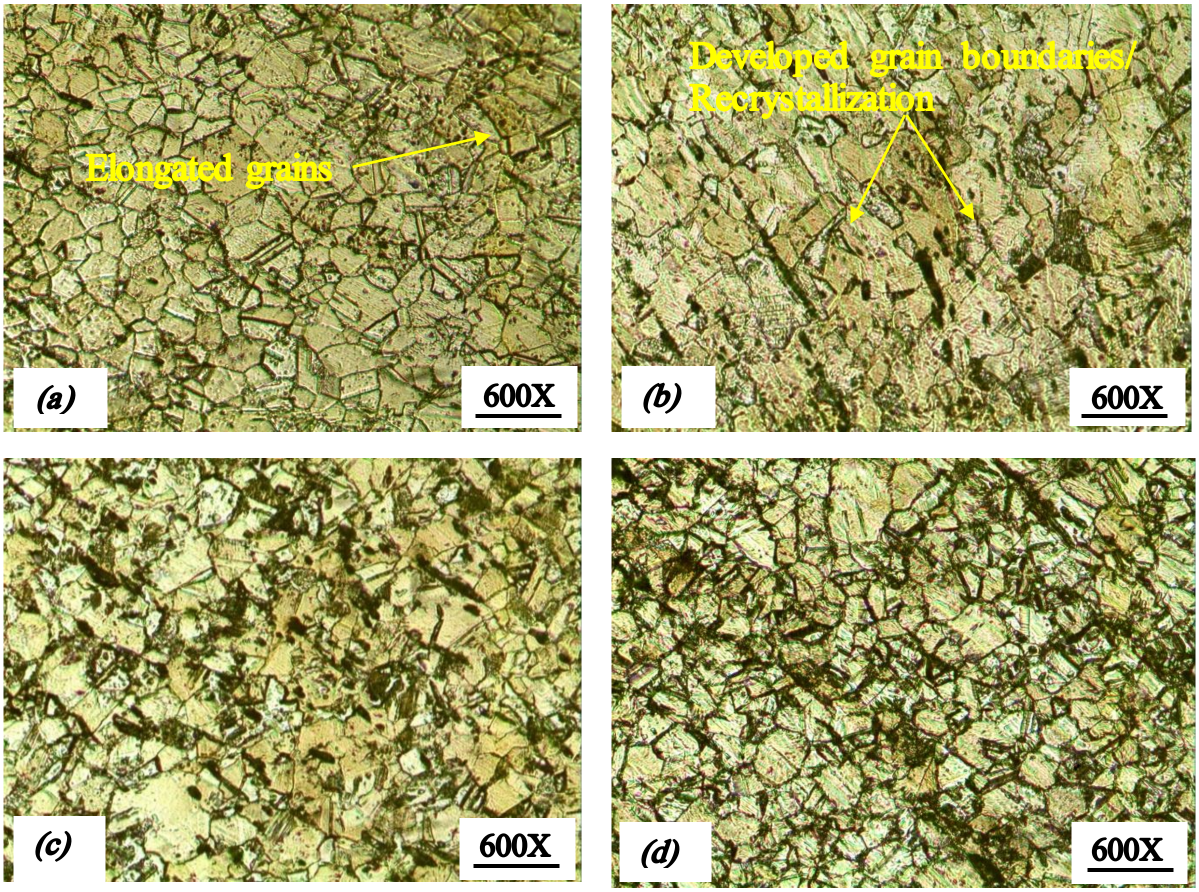

Figure 7 Optical micrographs of friction welded (Flat interface) at forging pressures (*a*)192.4 *MPa*, (*b*) 240.5 *MPa*, (*c*) 288.6 *MPa* and (*d*) 384.8 *MPa.*

The ductile mode can be seen for pin interface cases (**Error! Reference source not found.***a-c*) this is due to exhibiting the ductile cleavages in the joint interface. These results are evidence on an increasing the strength of impact samples with producing a pin. Whereas, in the **Error! Reference source not found.** *d*, the transition of ductile to brittle is observed. Zhu and Xuan (2010) showed that this transition is related to temperature and the multi- layer welding process [19].

The brittle fracture can be seen for the joints welded with 192.4 *MPa*, 288.6 *MPa* and 384.8 *MPa* for flat case (**Error! Reference source not found.***e, g* and *h*) this is due to exhibiting the brittle dimples in the joint.

Figure 8 Specimens after completion of impact tests

6. CONCLUSIONS

In the present study, the friction welding was successfully done on AISI 304 stainless steel and Charpy impact test of friction welded joints of *AISI* 304 austenitic stainless steel performed for pin and flat joints. The findings led to state the following conclusions:

1. The friction welded joints with 288.6 *MPa* exhibited the maximum impact strength for pin and flat interface case.
2. The friction welded joints with 192.4 *MPa* exhibited the minimum impact strength for pin while minimum impact strength in flat

interface at the joint welded at 240.5 *MPa*.

3. The fracture mode in pin type for all cases was ductile while in flat joint both brittle and ductile mode.

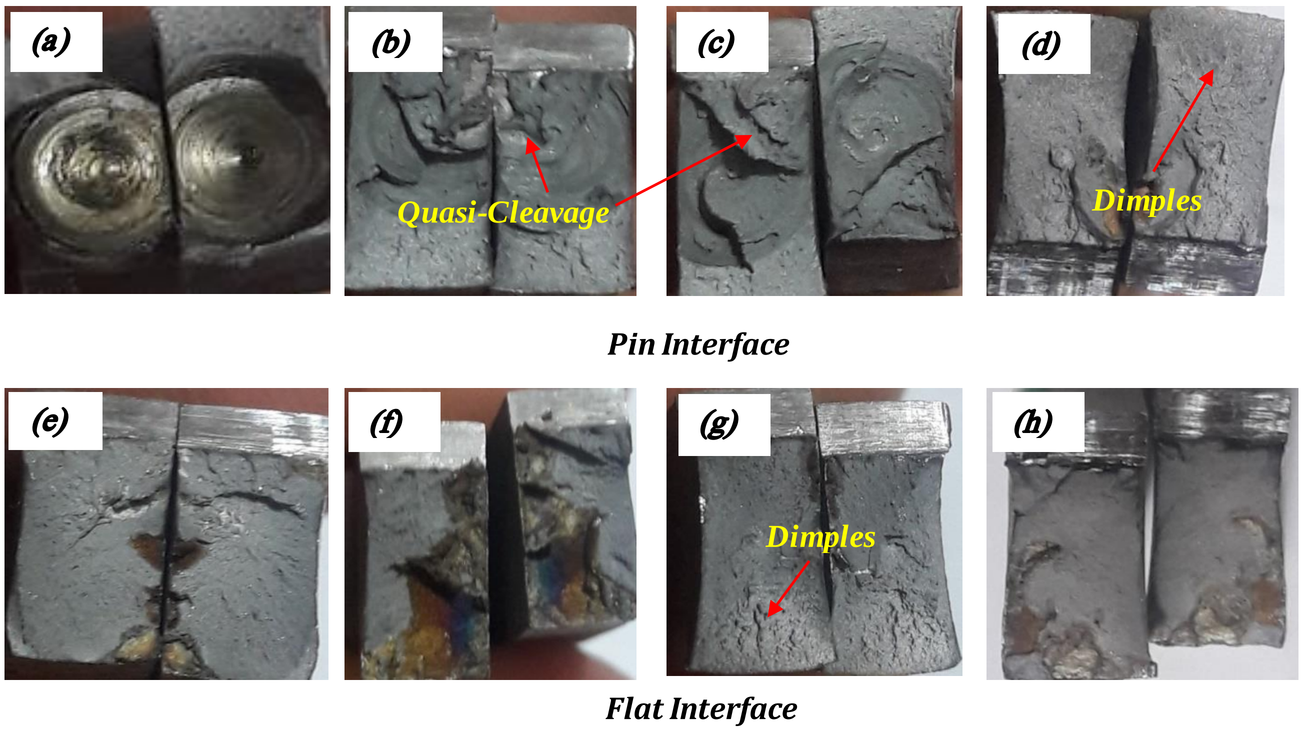

Figure 9 Impact fracture (pin and flat interface) specimens at different forging pressures (*a, e*) 192.4 MPa, (*b, f*) 240.5 MPa, (*c, g*) 288.6 *MPa* and (*d, h*) 384.8 *MPa*.

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