Mechanical Behavior of Friction Welded Dissimilar Steels under Varying Axial Pressures

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Abstract—*Owing to the superior properties of stainless steel, it is pertinent to make use of it in various automotive, aerospace, nuclear and chemical applications. It is observed that a wide range of dissimilar materials can be easily integrated by solid phase bonding techniques. However friction welding is the best suited for joining similar and dissimilar materials due to its properties such as low heat input, ability to join dissimilar materials and environment friendliness. Friction welding can be used to join different kinds of materials which cannot be welded by conventional fusion welding processes. The present study emphasizes on joints two industrially important materials AISI 304 with AISI 1021steels, produced by friction welding have been investigated. Samples were welded under different axial pressures ranging from 75 MPa to 135 MPa, at constant speed of 1120 rpm. The tensile strength, torsional strength, impact strength and micro hardness values of the weldments were determined and evaluated. Simultaneously the fractrography of the tensile tested specimens were carried out, so as to understand the failure analysis.*

Keywords: *Friction Welding, Tensile Strength, Torsion Strength, Impact Strength, Micro Hardness, Scanning Electron Microscopy*

INTRODUCTION

Dissimilar joints between austenitic stainless steel and low alloy steel are extensively used in many high temperature applications in the energy conversion system [1]. There is an extensive need for dissimilar metal joints in power plant components, due to the severe gradients in mechanical and thermal loading. In central power stations, the parts of the boiler that are subjected to lower temperatures, are made of low alloy steel for economic reasons. The other parts, operating at higher temperatures, are constructed with austenitic stainless steel. Therefore, transition welds are needed between these two materials. The joining of dissimilar materials is generally more challenging than those of the similar materials due to difference in thermal, metallurgical and physical properties of the parent materials. The specific problems associated with welding of austenitic stainless steel are formation of delta ferrite, sigma phase, stress corrosion cracking, and sensitization at the interface. Friction welding is one such solid state welding process widely employed in such situations [2, 3]. Main advantages of friction welding are high material saving, low production cost, and ability to weld dissimilar materials [4]. Friction welding is one of the versatile and well established welding processes [2] that are capable of giving good quality welds; it gives solid state joining of the materials through the controlled rubbing of the interfaces. Due to thus produced heat softens the material and brought the localized faces into the plasticized form which results in good quality welds [5]. In this process heat energy is produced by the inter conversion of mechanical energy into thermal energy at the interfaces of the rubbing components [6].

EXPERIMENTAL DETAILS

Austenitic stainless steel AISI 304 and low alloy steel AISI 1021 specimens having diameter of 20 mm and 100 mm length were joined together. The chemical composition of austenitic stainless steel and low alloy steel is presented in Table 1. A continuous drive lathe machine was used for the experimentation. A designed load cell [7] was fitted on the machine to measure axial pressure. Test samples with 20 mm diameter and 100 mm length were prepared for friction welding experiments. Prior to friction welding the contacting surfaces was faced on the lathe machine and then cleaned using acetone [8]. The rotational speed for this study selected was 1120 rpm. The required rotational speed was set by the levers attached on this machine. Within a fraction of seconds, the constant speed was achieved; subsequently the axial alignment of the specimens was checked. Then the axial pressure was applied. The welds were prepared at different axial pressures in the steps of 15 MPa starting from 75 MPa to 135 MPa to form different welds for the study. The welding joint so formed was allowed to cool down for 4–5 minutes. In this way, necessary number of weldments were prepared and subjected to various tests for evaluation of their mechanical characterization. Fig. 1 shows the welded specimens at different axial pressures.

Table 1: Chemical Composition of the Parent Materials

Metal	Cr	Ni	C	Mn	Si	P	S	Fe
AISI 304	17-20	9-13	0.08	2	0.75	----	----	Remaining
AISI 1021	----	----	0.15-0.25	0.6-0.9	----	----	----	Remaining

A robot is a programmable machine that can perform variety of tasks depending upon the requirements and the programming. Robots normally perform pre-specified tasks in a predictable environment. Initially, the robots were extensively used for material handling in the manufacturing systems, especially in assembly operations. Due to high load carrying capacities and the wide working range, the robots are highly preferred for material handling in the industry.

RESULTS AND DISCUSSION

Friction welded parts were subjected to variety of mechanical tests to determine their suitability for the anticipated service applications. They were necessary to carry out so as to ensure the quality, reliability and strength of the welded joints. In our investigation mechanical properties like tensile strength, impact strength and micro hardness were evaluated combined with the visual examination.

Visual Examination

The friction welded specimens of five different welding combinations were prepared by varying the axial pressures at constant speed of 1120 rpm; it was observed that the flash has been produced during friction welding process and the amount of flash increases with the increase in axial pressure. The formation of flash has been reported in Fig. 1. The experimental observations made during friction welded shows that the formation of flash is higher towards the low alloy steel than that of austenitic stainless steel for all the cases. This might be attributed to the presence of Cr in austenitic stainless steel, also austenitic stainless steel having greater hardness at higher temperatures as compared to low alloy steels. For this reason austenitic stainless steel does not undergo extensive deformation while the low alloy steel undergoes extensive deformation. This phenomenon may be attributed to the low strength of AISI 1021 steel [9].

Tensile Testing

Tensile test was performed on the Universal Testing Machine of make HIECO, having the capacity 600 KN. The standard specimens using ASTM standards were followed for preparing the samples. The gauge lengths of the specimens were maintained according to the ASTM A370-12 standards keeping the weld interface at the center of the gauge length. This test was carried out on the samples to know their strength in tension, the specimens were subjected to axial tensile stress, and load was applied gradually till the fracture occurs. In all the cases, the strain increases with the rise in stress, subsequently, the stress starts declining after achieving a maximum value, however, the strain continuously increases till the fracture occurs; similar results have been reported by Ozdemir [7]. Fig. 2 shows the variation of stress Vs strain at different axial pressures, it depicts that with the increase in stress the strain increases, During tensile testing, brittle fracture appeared to occur at 75 MPa and 90 MPa axial pressures and the joint fails from the weld interface without showing any necking; whereas at an axial pressure of 105 MPa the joint too failed from the weld interface but small amount of necking appears at the weld interfaces; whereas cup and cone fractures observed at pressures of 120 and 135 MPa. The tensile strength of these two specimens was found to be much more than the other samples. This might be attributed to the increase in the axial pressures, more mass is thought to be transferred out of the interface due to more friction, thus increasing the tensile strength. Tensile strength obtained from the specimens varied from 320.57 MPa to 432.20 MPa. Table 2 shows the maximum values of stress and strain; similar results have been reported by Arivazhagan *et al.,* [11]. The value of strain varied from 0.1562 to 0.3178, depending upon the axial pressure used. It also depicts that the specimen welded at 120 MPa shows the maximum ductile behavior while the maximum strength was achieved at an axial pressure of 135 MPa.

SEM Analysis

For supporting the visual inspection of failure, the fracture analysis was done. For that scanning electron microscope (SEM) of make JEOL model no. JSM-6610LV was used. The SEM analysis was carried out to show the fracture behavior of tensile test which justifies the visual inspection results of brittle and ductile failures. The magnified images were captured at the fractured locations taken at 1,500 X magnification. The effect of tensile strength has been observed on the fractured surface appearance. In the Fig. 3 (A), the fractograph indicates the pure brittle failure. This may be due to the formation of martensite at the interface of the joints [12], also has been observed from the tensile test that minimum time has been taken by the specimen before getting failed.

Figure 3 (B) indicates the sign of river like pattern, which depicts the brittleness of the joint. Fig. 3 (C) reveals

Fig. 1: Represents the Friction Welded Specimen at Different Axial Pressures Welded at 1120 rpm

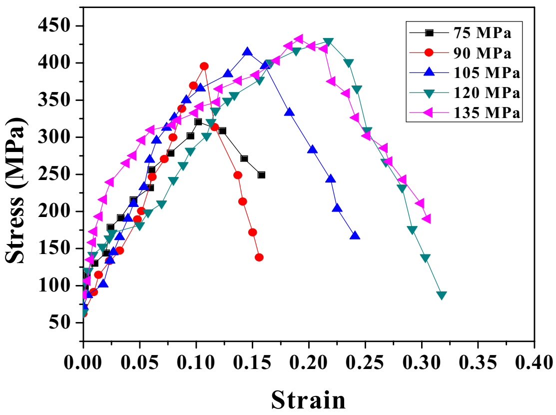


Fig. 2: Variation of Stress *vs.* Strain at Different Axial Pressures Friction Welded at 1120 rpm

Table 2: Maximum Values of Stress and Strain at Different Axial Pressures

Sample No.	Axial Pressure (MPa)	Max. Stress (MPa)	Max. Strain	Fracture Location
S. 1	75	320.57	0.1577	At Weld Interface
S. 2	90	395.32	0.1562	At Weld Interface
S. 3	105	414.33	0.2408	At Weld Interface
S. 4	120	429.67	0.3178	Away from Weld Interface
S. 5	135	432.20	0.3052	Away from Weld Interface

Table 3: Torsional Values at Different Axial Pressures

Sample No.	Axial Pressure (MPa)	Max. Torque (Nm)	Max. Angle of Twist	Fracture Location
S. 1	75	12.72	8	At Weld Interface
S. 2	90	14.53	10	At Weld Interface
S. 3	105	18.41	14	At Weld Interface
S. 4	120	21.35	16	At Weld Interface
S. 5	135	19.3	15	At Weld Interface

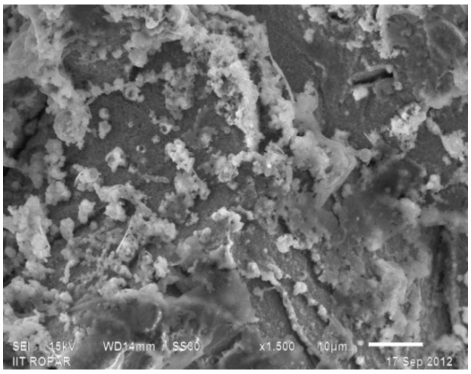
cleavage pattern as well as dimples at various locations; this indicates the fracture may have occurred by the mixed phenomenon i.e. quasi cleavage fracture mechanism [13]. Fig. 3 (D) and (E) represents dimpled pattern showing ductile fracture. Fig 3 (D) and (E) also depicts that the dimples are deep as compared to Fig. 3 (C) indicating more ductility. In the Fig. (D) and (E) the failure was located in AISI 1021 side therefore ductile fracture similar to that of pure Fe was observed [2].

Torsion Test Analysis

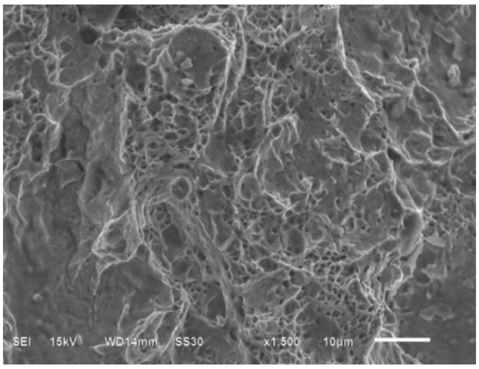
Torsion test was performed on the torsion testing machine of make scientific instruments limited. In this test torque was applied on the specimens till its fracture occurs. The specimen was fitted in the jaws of machine with one jaw is kept fixed and other rotates when the torque is applied. During the application of twisting moment the specimen a start twisting at an angle called angle of twist and this angle was measured during the application of torque. The maximum torsion strength obtained from the tests varied from 12.72 Nm to 21.35 Nm and the angle of twist in terms of degrees varied from 8° to 16°, Similar results have been reported by Shribman at el [14, 15]. It has also been observed during testing that the entire specimen fails at the weld interfaces. Fig. 4 shows the variation of the torque with respect to angle of twist. With the increase in torque the angle of twist increases; it has also been noticed from the experiment that with the increase in axial pressure the torque as well as the angle of twist increases. This might be the effect of the diffusion of alloying elements from austenitic stainless steel to low alloy steel at the joint interface [16]. When the axial pressure increases beyond 120 MPa there is little bit decline in the torque but this difference is very marginal. The maximum torque available was 21.35 Nm and the maximum angle of twist was 16°and these results were obtained at 120 MPa axial pressure. The torsion test values have been reported in Table 3.

Impact Test Analysis

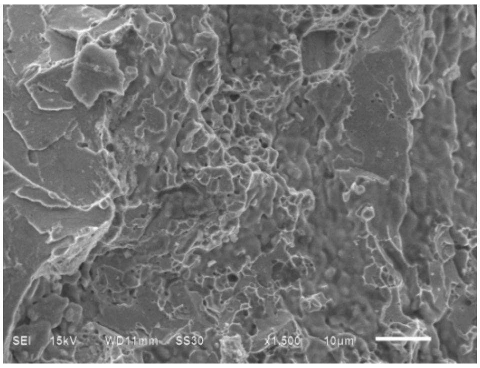
This test was carried out on the pendulum type single blow impact testing machine so as to measure their notch impact toughness. Again the samples were prepared according to the ASTM standards maintaining the notch at the center of the weld interface. For Charpy impact test the specimens were supported at both ends as a simple supported beam and was broken by a falling pendulum on the face opposite to the notch and the energy absorbed by the specimen was noted down. Side by side Izod test was also performed in this test the specimens were vertically placed and the notch was facing towards the falling pendulum. The notch impact toughness tests were carried out to find amount of energy absorbed during fracture. For this Charpy and Izod Impact tests were carried out so as to find out the amount of energy absorbed by the specimens before failure. The results of both Charpy and Izod impact test results in terms of energies absorbed before fracture have been reported in the Table 4. As it can be seen from the table that the Charpy toughness of the welded parts is slightly larger than the Izod impact toughness [17], this may be the reason of the placement of the impact samples towards the impact load.



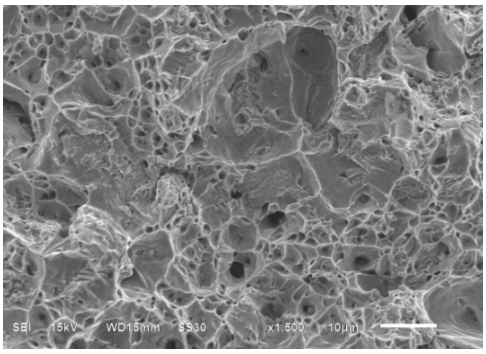
(A) SEM Image at 75MPa Axial Pressure



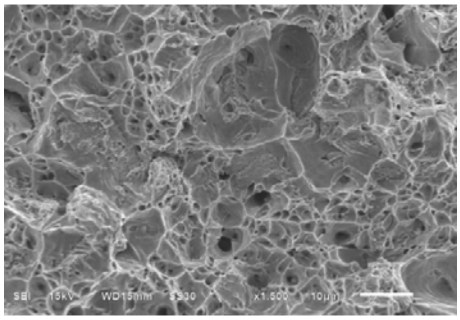
(B) SEM Image at 90 MPa Axial Pressure



(C) SEM Image at 105 MPa Axial Pressure



(D) SEM Image at 120 MPa Axial Pressure



(E) SEM Image at 135 MPa Axial Pressure

Fig. 3: SEM Images at 1500x Magnification during Tensile Testing at Different Axial Pressures

In case of Charpy Impact test, the specimens are placed as a simply supported and the blow of the hammer was done on the opposite side of the notch, while, in case of Izod Impact test, the specimens are placed as a cantilever and the notch of the specimen is facing towards the blow of impact. Fig. 5 reveals that the Charpy impact strength decreases with the increase in axial pressure. Almost similar trends have been recorded during Izod impact testing, Fig. shows that impact strength decreases a little bit at 105 MPa and then it remains constant up to 135 MPa. The similar results have been reported in the literature [18]. It has also been observed that with the increase in the axial pressure the flash increases, and experimentally it has been found that with the increase in the flash the impact strength decreases [11, 19].

Micro Hardness Testing

For micro hardness testing Vickers hardness testing machine was used. In this test a square based pyramid type diamond indenter was used and the hardness variation on the weld interface as well as along the axis of shaft at the intervals of 1 mm on both the parent materials was obtained by applying a constant load of 500 gf. The indentations were made at the weld interface and on both the so as to find out the effect of heat on the hardness values. Fig. 6 shows the hardness variations on both the sides of the friction welded joint. Fig. 6 depicts that AISI 1021 shows less hardness as compared to the AISI 304. This decrease in hardness may be attributed to recrystallization process taking place at the heat affected zone towards the low alloy steel [20, 21]. It has also been observed that the maximum hardness was obtained at the weld interface for all the joints [22, 12]. The peak hardness of friction welded joints increases with the increase in burn-off length [11], similarly our plot follows the similar trends. It was observed that with the increase in burn-off length a soft region appears on the austenitic stainless steel adjacent to the weld interface. The formation of soft region can be attributed to decarburization. This may be occurred by the presence of heat as the thermal conductivity of the material is relatively low [9]. In addition to that the higher values of hardness at the weld interface were probably due to the oxidation process which takes place during friction welding [11].

Table 4: Impact Strength at Different Axial Pressures

Sample No.	Axial Pressure (MPa)	Charpy Impact (J)	Izod Impact (J)
S. 1	75	25	20
S. 2	90	25	20
S. 3	105	24	19
S. 4	120	23	19
S. 5	135	21	19

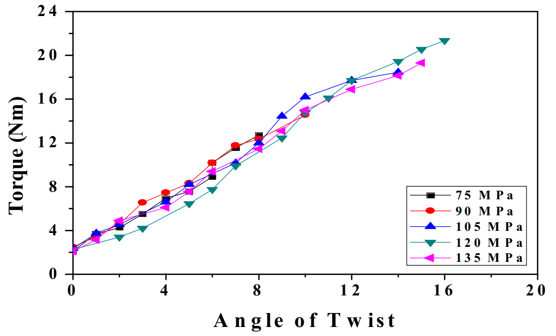


Fig. 4: Relationship between Torque and Angle of Twist Friction Welded at 1120 rpm, at Different Axial Pressures

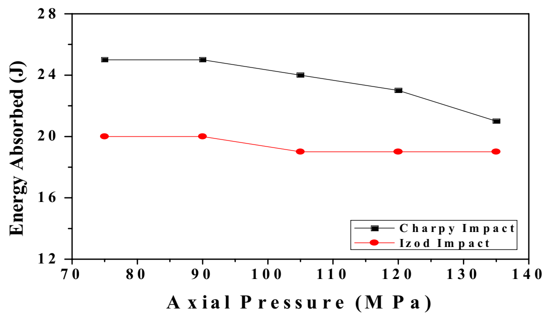


Fig. 5: Represents Impact Toughness at Different Axial Pressures Welded at 1120 rpm

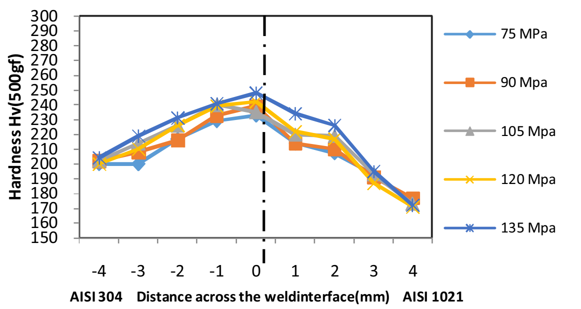


Fig. 6: Hardness Variations Across the Weld Interface

CONCLUSION

During friction welding it was found that the generated flash is confined towards ferritic steel, this was because of the austenitic stainless steel has much lower thermal conductivity and greater hardness at higher temperatures compared to low alloy steel. Tensile strength increases with the increase in frictional pressure, this was due to the transfusion of alloying elements from the AISI 304 towards low alloy steel side. This might be attributed that at higher temperatures, more elemental diffusion takes place from the austenitic stainless steel towards the low alloy steel, thus increasing the bond strength. The increased friction pressure contributes to an increased friction time, which aids in raising the temperature in the vicinity of the interface and resulting in the increase of elemental migration. The ductility slightly decreases at 135 MPa axial pressure. This reduction is probably due to flashing of the heated soft material from the interface on upset pressure. The torsional strength also increases with the rise in axial pressure. This was due to more transfer of the mass at higher axial pressures.

Investigation on the effect of burn-off length on mechanical properties of AISI 304 with AISI 1021 dissimilar welds revealed that with the rise in burn-off length the hardness increases, whereas the impact toughness follows the reverse trend. This might be related to the increase in carbon migration from the low alloy steel side towards the austenitic stainless steel due to higher temperatures that prevail around the interface region with an increase in burn-off length.

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