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EVALUATION OF MECHANICAL AND METALLURGICAL PROPERTIES OF FRICTION WELDED INCONEL 600 AND AISI 304L AUSTENITIC STAINLESS STEEL DISSIMILAR JOINTS

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ABSTRACT

The effect of mechanical properties of Inconel 600 and 304L austenitic stainless steel was evaluated by RT tensile, hot tensile, Charpy impact and hardness tests and the metallurgical properties of optical and scanning electron microscopy were used to analyse the microstructure of the welded joint. The bonded Inconel 600 and 304L austenitic stainless steel samples were produced by keeping the friction pressure, friction time and the rotational speed constant. The ultimate tensile strength, Percentage elongation, yield stress and maximum tensile load of the parent metal and welded joints were determined by RT tensile test and hot tensile tests. The welded specimen is evaluated by hardness test measurement. The highest ultimate tensile strength of 500 MPa was obtained in the joint. The highest ultimate hot tensile strength of 487MPa was obtained at the temperature of 300°C. A maximum hardness of 216 HV has been obtained near the weld interface in Inconel 600 and 199HV in 304L austenitic stainless steel.

Key words: *Friction welding, Dissimilar joints, Inconel 600, 304L, Mechanical properties, Metallurgical properties.*

1. Introduction

Friction welding process is a solid state joining process that produces a weld under the compressive force contact of one rotating and one stationary work piece. The coalescence is caused by the heat generated through friction at the rubbing surfaces, which raises the temperature at the interface high enough to cause the two surfaces to be forged together under high pressure [1]. Friction welding has gained importance in the fabrication industry. The advantages of this process include high reproducibility, short production time and low energy input [2]. Friction welded joints have very reliable integrity and becomes stronger than that of the individual base materials.

Inconel 600 is a nickel base super alloy which is extensively used in many reducing and oxidizing environments due to its excellent hot corrosion. Since Inconel 600 is relatively an expensive alloy, a cheaper material with good properties can be used in lower risk conditions to reduce material costs [3]. The dissimilar joints of Inconel 600 with 304L are used especially in the automotive industry due to the potential weight reduction of both vehicle components and structures[4]. Due to the excellent mechanical properties, good corrosion resistance and breaking tenacity under elevated temperatures, the super alloys are widely used in the high-temperature parts of aviation and aerospace engines [5,6].Conventional fusion welding of many such dissimilar metal combinations is not feasible owing to the formation of brittle and low melting intermetallic due to metallurgical incompatibility, wide difference in melting point, thermal mismatch, etc [7].

The friction welding of mild steel and stainless steel are studied and the strength of the joints obtained were good and reasonable [8]. Ozdemir has joined AISI 304L austenitic stainless steel and AISI 4340 steel by friction welding using different rotational speeds in their studies [2]. He found that the tensile strength of joints was markedly affected by rotational speed selected. Sarecelik et al carried out the dissimilar material of AISI 4140 steel and AISI 1050 steel and mechanical properties are investigated. The highest tensile strength developed in the welded specimens is 6% higher than parent AISI 1050 steel and the lowest tensile strength obtained was 1.9% lower than the parent AISI 1050 steel [9]. A statistical approach has been conducted for optimum parameters in the dissimilar materials of joining the copper and aluminium materials by friction welding and grey layer was observed at the fracture

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surfaces of welded parts and thus decreased the strength of the joint [10].

The joining of stainless steel with dissimilar materials are studied extensively based on strength and metallurgical aspects and good amount of literature are available in friction welding process. However, the joining of austenitic stainless steel and Nickel base super alloy are limited. Thus, the aim of this experiment is to evaluate the mechanical and metallurgical properties of friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel.

2. Experimental Procedure

Base materials Inconel 600 and AISI 304L austenitic stainless steels used in this investigation were cylindrical rods of 12mm diameter and 75mm length. Friction welding machine used is capable of operating with high precision and excellent repeatability of weld parameters. Hydraulic controlled, continuous drive friction welding machine (20 KN capacity) was used to fabricate the joints. Fig.1shows the dimensions of the specimens. The mechanical properties of materials used in this experiment are listed in Table 1 and chemical composition of the materials; Inconel 600 and 304L stainless steel are listed in Table 2 and 3, respectively. Fig.1 (a) shows the dimensions of the base materials in as-received condition. Fig.1(b, c) show the dimensions of the unnotched and notched hot tensile specimens, respectively, according to ASTM E-21 standard. Fig.1(d, e) show the dimensions of the unnotched and notched tensile specimens, respectively, according to ASTM E-8 standard. Prior to friction welding, the surfaces were polished using emery papers and cleaned using acetone. In this experiment, the friction welding was carried out under optimised process parameters. The friction welding parameters used in this study are listed in Table 4.

Table 1. Mechanical properties of materials used in the experiment

Mechanical properties	Inconel 600	304L stainless steel
Ultimate Tensile strength (Mpa)	714	583
Yield strength (MPa)	725	235
Elongation (%)	45	65

Table 2. Chemical composition (wt %) of Inconel 600

Element	Ni	Cr	Mn	C	Fe
Inconel 600	72.28	16.75	0.51	0.04	7.55

Table 3. Chemical composition (wt%) of 304L stainless steel

Element	C	Cr	Mn	Ni	P	S	Si	Fe
304L	0.09	14.08	1.42	8.41	0.04	0.03	0.29	74.53

Table 4. Friction welding parameters used to fabricate the joint

Friction Pressure (MPa)	Friction Time (s)	Forge Pressure (MPa)	Forge Time (s)	Rotational Speed (RPM)
35	3	35	3	1000

After welding, the micro structural analysis of friction welded interfaces were obtained by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). For SEM observations, cross section interface of Inconel 600 / 304L austenitic stainless steel friction welded joints were grounded by using a SiC paper, and were micro polished using 0.3µm Al_2O_3 powder. The micro hardness values were measured on both sides of welded specimens using a 500g indentation load. Mechanical properties of friction-welded joints were evaluated by tensile and hot tensile tests. Tensile tests were performed at room temperature using a Servo controlled universal testing machine (UNITEK-94100) with the maximum load of 10KN and the strain rate of $3X10^{-3}$ S^{-1} and 5mm/min cross head speed. Similarly, the hot tensile tests were conducted in order to determine the mechanical properties of the bonded specimens at different temperatures and the strain rate of $0.001s^{-1}$. Tensile test was conducted at various temperatures of RT, 300°C,450°C and 600°C.

Fig.2 shows the photographs of friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel. Samples for optical metallography were prepared by sectioning the welded joint at right angles to the bond-line. The sectioned samples were subjected to the standard metallographic procedure such as grinding and polishing techniques before applying the etchant. The Kroll's reagent was used to etch on Inconel 600 side, whereas the stainless steel side was etched using an aqua regia solution. Subsequent to etching, the micro structural studies of samples were examined by using optical microscope and Scanning Electron Microscope (SEM).

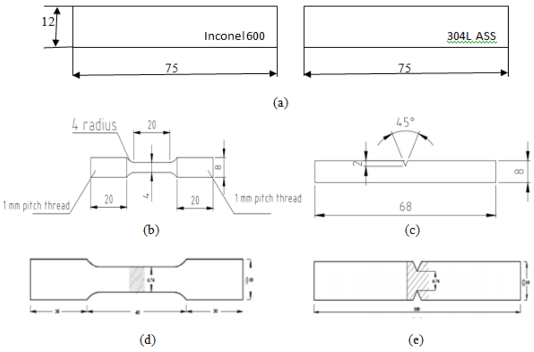


Fig.1 Dimensions of the specimens. (a) Dimensions of the base materials before welding.(b) Dimensions of the Unnotched hot tensile specimen. (c) Dimensions of Notched hot tensile specimen. (d) Dimensions of unnotched tensile specimen. (e) Dimensions of notched tensile specimen.

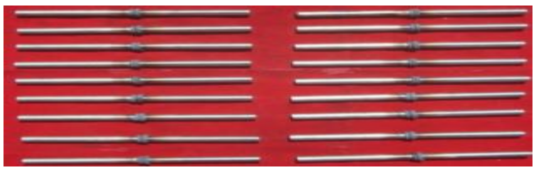


Fig.2 Photographs of friction welded joints

Impact test was carried out for the samples prepared from the welded joints with adoption of the ASTM E2248-12 standard test method. Specimens were sectioned from the weldment with specimen axis transverse to the weld joint and with notch location at the weld centre, as shown in Fig.3(a). The location and orientation of the test sample in the bond zone is shown in Fig. 3(b). The notch was cut from the top surface. The tests were carried out in a Tinius Olson (TO) machine at room temperature.

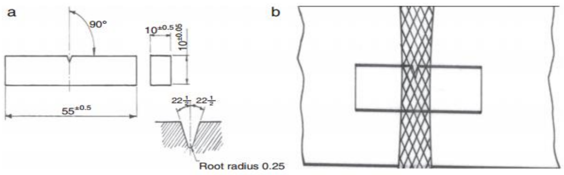


Fig.3 (a) Charpy ‘V’ notch impact specimen and (b) location and orientation of Charpy ‘V’ notch in the weld (bond) zone

3. Results

3.1 Appearance of welds

Fig. 4 shows the appearance of Inconel 600-304L austenitic stainless steel friction welded joint. Appearance of welds illustrate presence of flash due to plastic deformation. The weld flash was predominant at 304L side, the Inconel 600 did not participate much in flash formation.

Fig.4 Friction Welded Joint

3.2 Macro examination

Fig.5 shows the macrograph of the friction welded dissimilar joint of Inconel 600 and 304L austenitic stainless steel. The macro examination revealed defect free weld joint. The various zones like Heat affected zone (HAZ), Partially deformed zone (PDZ) and Fully deformed zone (FDZ) are depicted as c, b and a respectively on the macrograph.

Fig. 5 Cross sectional view of a friction welded sample

3.3 Tensile test results

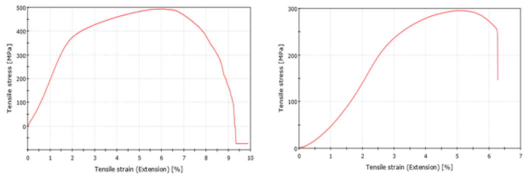
The tensile properties of the friction welded dissimilar joints were presented in Table 5. For unnotched specimen, the UTS of the joint was obtained as 500 MPa while the UTS of 826 MPa was obtained for notched specimen. It is inferred from the result that the UTS of the joints is higher than the base metals. The Notch Strength Ratio (NSR) of Inconel 600 was found to be appreciable when compared to 304L base metal and the joint.

Table 5. Tensile properties of friction welded joint

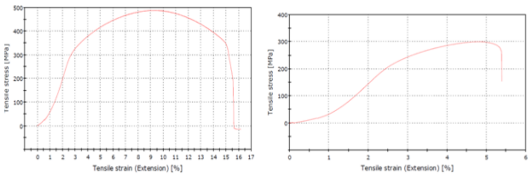
Material	Max. Tensile load, KN	UTS MPa	Yield Strength	Notch Strength Ratio (NSR)
	28.25	**500**	315	1000
	47.58	826	-	1.65

3.4 Hot tensile test results

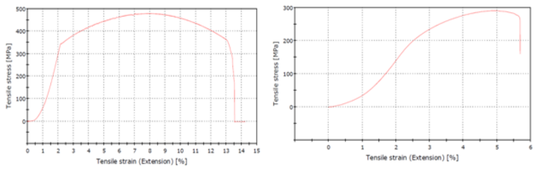
The maximum UTS of 487MPa was achieved at 300ºC, which is almost equal to the UTS of the specimen at RT. The value of UTS showed a minimum of 437MPa at 600ºC. The percentage of elongation seems to be lower at RT and higher (6.14%) at 300°C. It is attributed to the higher deformation at elevated temperatures than RT. The UTS and ductility decreased with increase in test temperature and the tensile stress increases with deformation until the UTS is reached, and then decreases slightly with increasing strain (softens at high temperatures) followed by a rapid decrease. On contrary, with the increase of strain rate, the dynamic recovery rate decreases, and thus the work hardening and dynamic recovery stage is prolonged, the peak strain is increased correspondingly [11]. Notch Strength Ratio (NSR) showed that the fracture obtained is brittle in nature which indicates that the notched specimen holds appreciable properties at high temperature.



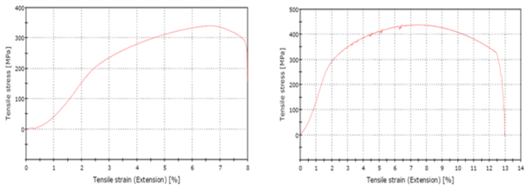
a) Unnotched specimen at RT b) Notched specimen at RT



c) Unnotched specimen at 300°C d) Notched specimen at 300°C



e) Unnotched specimen at 450°C f) Notched specimen at 450°C



g) Unnotched specimen at 600°C h) Notched specimen at 600°C

Fig.6 Stress - Strain curves for Unnotched and Notched specimen

3.4.1 Impact toughness

Charpy impact energy data for the base material as well as for friction welds at room temperature are shown in Table 6. An examination of the results indicates that the charpy energy decreases with increasing forge force values. This may be proved by a close observation of the crack path experienced by the specimens during impact loading, and supported well by report by Rajashekar et al. [12]. Among all materials, the toughness of the Inconel 600 is the highest. one can observe very clear evidence of the reduced toughness in case of welded samples; though, the base material fractures in fairly ductile mode.

Table 6. The Charpy V notch impact energy at room temperature

Base metal and welded joint	Impact energy (J)
Inconel 600 base metal	229 ± 6
410 stainless steel base metal	222 ± 3
Inconel 600- 410 stainless steel welded joint	218 ± 2

3.5 Micro hardness

The micro Vickers hardness distribution profile on the transverse cross-section of the friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel is shown in Fig.5. The measurements were carried out both in the central axis and along the line located 2.5 mm from the periphery (surface) for Inconel 600 and 304L austenitic stainless steel [13]. High hardness is observed in the Inconel 600 side adjacent to interface of joint. A maximum hardness of 216 HV has been obtained near the weld interface in Inconel 600 and 199HV in 304L austenitic stainless steel . From the weld interface, the joint shows a declining trend in hardness towards the free ends of both the materials.

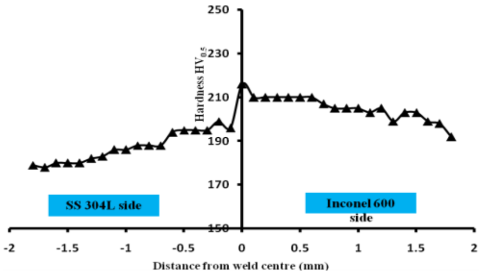
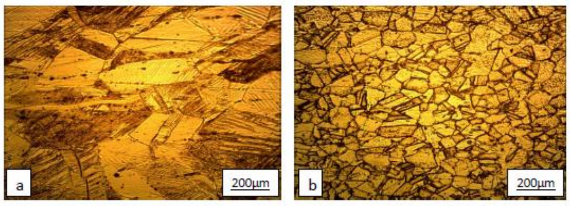


Fig.5 Micro hardness profile across the interface on friction welded joint

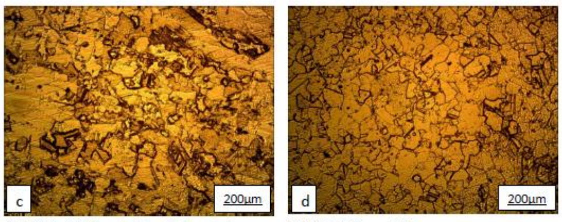
3.6 Microstructure properties

3.6.1 Optical Microscopy

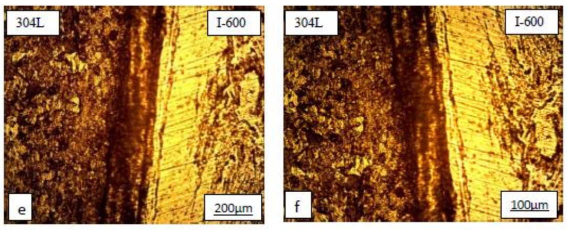
The friction welded sample was examined in the metallurgical microscope while microstructures were analyzed in base metal, HAZ and Interface of the joint. Fig.6 displays the optical micrographs of base metals and welded joint of Inconel 600-304L. Fig.6(a) shows the microstructure of austenitic stainless steel base metal. In austenitic stainless steel, the base metal revealed equiaxed annealed austenitic grains whereas in Inconel 600, the base metal shows coarse grains as shown in Fig.6(b). Similarly, Fig.6(c) shows the HAZ of austenitic stainless steel, which shows dispersed recrystallized alpha grains whereas in Inconel 600, the HAZ revealed soft dense grain structure as shown in Fig.6(d). The width of the Heat affected zone (HAZ) in Inconel 600 side is much larger than the 304L side. Fig.6(e and f) show the optical microstructure of the interface region at different magnification. The formation of weld interface region is not so clear in these optical micrographs. It is observed on both the base metals nearer to the joint line and they are displayed in Fig.6(c and d).



(a) Base metal of 304L austenitic stainless steel (b) Base metal of Inconel600



(c) HAZ of 304L austenitic stainless steel (d) HAZ of Inconel 600

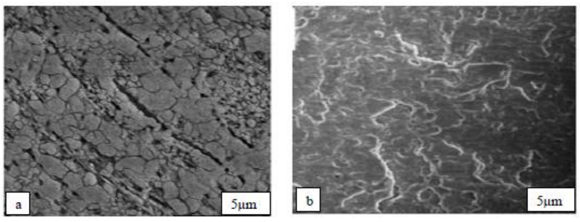


(e) weld centre / interface region (f) weld centre / interface region

Fig.6. Optical microstructure of base metals, HAZ and weld interface of friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel

3.6.2 SEM analysis

The SEM images of 304L and Inconel 600 base metals are shown in Fig.7. Fig.7 (a) shows the microstructure of 304L austenitic stainless steel which consists of a bimodal grain size distribution with an average grain size of 650 nm. The dark precipitates that can be clearly seen in the microstructure are delta ferrite. Fig.8 shows the SEM image of the interfacial microstructure of the welded joint in order to understand the bonding conditions between the two specimens. The interface line shown in Fig.8 depicts that the bonding condition between the two specimens was completely metallurgically bonded in the weld zone. It can be clearly seen that the whole joint interface is typically concurve shaped, particularly, on the 304L side it is convex shaped,while on the Inconel 600 side it is cuppy shaped. The above phenomenon could be caused by the non-uniform heat generation at the welding interface.



(a) (b)

Fig.7. Scanning Electron Micrographs of base metal of a) 304L austenitic stainless steel b) Inconel 600

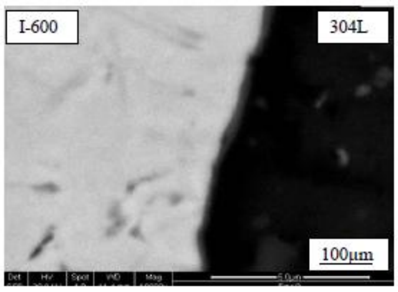


Fig.8. SEM image of the Interface

4. Discussion

Visual examination of the welded specimens showed uniform welded joints. The flash obtained was symmetric, which indicates plastic deformation on both the rotating and upsetting (reciprocating) side. The formation of plastic deformation and weld flash is predominant on 304L side,because it can be attributed to the magnitude of tensile strength of 304L which is lower than that of Inconel 600. As stainless steel is more ductile than Inconel 600, the percentage of elongation for 304L seems to be higher than Inconel 600. Notch Strength Ratio (NSR) indicates these joints are notch ductile category at room temperature. The percentage of elongation showed higher value at elevated temperature than RT. It is because of the decrease in dislocation generation rate, the dislocation density and nucleation sites with the increase of deformation temperature [15], and which weakens the effect of work hardening. Notch Strength Ratio (NSR) indicates that the fracture obtained is brittle in nature at elevated temperature. This is because the low strain rate provides long time for energy accumulation, and high temperature promotes the nucleation and growth of dynamically recrystallized grains and dislocation annihilation [16] and thus the flow stress is reduced.

The increase in hardness at the weld zone (WZ) can be attributed to the microstructural transformation that occurs during the friction welding process. This is due to the different thermal diffusivity of materials and intermetallic layer existing at the interface cause hardness variations (17]. The strengthening effect observed in this region is mostly a direct result of the rapid cooling from the welding temperature.

The frictional heat at the interface when dissipated through the parent material would result in a temperature gradient causing zones of material with different microstructure [18]. In the optical microscope observation of all welded specimens, due to the effect of rotational speeds, the grain size reduction has been observed at the deformation zone of the metal side [19]. The width of the Heat affected zone (HAZ) in Inconel 600 side is larger and the above phenomenon could be caused by the non-uniform heat generation at the welding interface. Due to thermo mechanical action, the formation of interface layers is not clear.

5. Conclusion

In this study, 12mm diameter and 75mm length of austenitic stainless steel (304L)-Inconel 600 joints were welded successfully by friction welding. The joints were evaluated through the mechanical and metallurgical characteristics and important results are deduced.

- A defect free weld joint of dissimilar materials of Inconel 600 with 304L austenitic stainless steel was obtained successfully by the continuous drive friction welded process. The more plastic deformation and flash was obtained on 304L side because of the lowest tensile strength of 304L austenitic stainless steel.
- The UTS and yield strength of the friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel are higher than base metals. This recommends the friction welding process for joining of dissimilar materials of Inconel 600 with 304L austenitic stainless steel.
- The tensile strength of the friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel is not affected much upto 450°C and the strength decreases drastically beyond 450°C. Hence, these types of joints are best suited for operating temperature below 450°C.
- A maximum hardness of 216 HV has been obtained near the weld interface in Inconel 600 and 199HV in austenitic stainless steel (304L). The micro hardness values from the weld zone toward the base metal in decreasing trend. This is due to the different thermal diffusivity of materials and intermetallic layer existing at the interface cause hardness variations.
- The Charpy impact toughness test indicates the reduced toughness of the welded joint than base materials.
- The friction welded joint of Inconel 600 with 304L exhibited good metallurgical properties. The effects of metallurgical characterization are discussed based on the micro structural studies.

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