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INVESTIGATION ON HOT TENSILE DEFORMATION BEHAVIOUR OF FRICTION WELDED DISSIMILAR JOINTS OF INCONEL 600 WITH AISI 304L AUSTENITIC STAINLESS STEEL

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ABSTRACT

With the help of continuous drive friction welding process, the dissimilar joints of Inconel 600 with 304L austenitic stainless steel were fabricated. Hot tensile properties of these joints were evaluated by hot tensile test at the temperature range of 25ºC– 600ºC and strain rate of 0.001× s^{-1} as per ASTM E21 standard. The results showed that the highest ultimate tensile strength of 487MPa was achieved at the temperature of 300º C for smooth specimen whereas the lowest ultimate tensile strength of 437MPa was achieved at the temperature of 600ºC. The micro structural characteristics, micro hardness variations and fracture surface anlaysis were carried out to understand the deformation behaviour of friction welded dissimilar joints of Inconel 600 and AISI 304L stainless steel.

***Keywords**: Friction welding, Inconel 600, 304L austenitic stainless steel, Dissimilar Joints, hot tensile properties.*

1. Introduction

AISI 304L austenitic stainless steel is relatively a low cost material used in high temperature applications. Bimetallic combinations have gained considerable attention due to the rapid development of new materials for structural applications in various engineering fields, such as power plants, aerospace, chemical and nuclear industries [1]. 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 a relatively expensive alloy, a cheaper material with good properties can be used in lower risk conditions to reduce material costs [2]. In particular, there is a strong demand for dissimilar joining of nickel based super alloy to austenitic stainless steel. Solid state welding techniques, such as diffusion bonding, explosion welding and friction welding can be more suitable than those related to fusion ones since many problems associated with melting are eliminated or reduced [3].

Friction welding is a solid state joining process, where the joint is made well below the melting temperature of the metal. The inherent property of lower temperature and shorter welding time in friction welding is beneficial for suppressing the metallurgical reaction. In friction welding, the heat is generated through mechanical friction between a moving work piece and a stationary work piece, with the addition of a lateral force called “upset’’ to plastically displace and fuse the materials. When a certain amount of upsetting has occurred, the rotation stopped and the compressive force is maintained or slightly increases to consolidate the weld [4].

Hot ductility is a reliable and accurate measure of the intrinsic hot workability and is affected by dynamic structural changes and by the occurrence of cavitation and wedge cracking phenomena [5].Hot tensile test is also employed to study the hot deformation and superplastic behaviour of intermetallic compounds such as NiAl,FeAl, TiAl, and CoTi [6]. Some interesting results disclosed by these studies show that the mechanism leading to super plastic behaviour in these intermetallic is completely different from that of conventional fine grained superplastic alloys [7] .Hot deformation behaviour of S31042 austenitic heat-resistant steel was investigated over the temperature range of 900- 1200ºC and strain rate range of 0.01-10 s^{-1} [8].Hot deformation behaviour of S30432 which also belongs to austenitic heat-resistant steel, but the difference in chemical composition between 304L steel and S30432 steel is obvious, leading to the hot deformation results of S30432 steel not to be applied in 304L steel [9]. Hot tensile properties of as cast NiTi and

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NiTiCu shape memory alloys were investigated by hot tensile test at temperature range of 700–1100ºC using the strain rate of $0.1s^{-1}$ [10]. Lin et al proposed a revised Arrhenius type model to describe the flow behaviour of 42CrMo steel over wide ranges of strain rate and deformation temperature [11]. Wu et al. investigated the hot deformation characteristics of Inconel (IN) 600 super alloy, and found that DRX plays a dominant role in the microstructural evolution under low temperatures or high strain rates [12]. From the literature review, it is understood that the work on hot tensile properties of friction welded dissimilar joints of Inconel 600 and 304L is very scant. Hence, this investigation was carried out to evaluate the high temperature tensile properties of the friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel.

2. EXPERIMENTAL WORK

In this investigation, 12mm diameter and 75mm length of cylindrical rods of Inconel 600 and 304L stainless steel were used. Fig.1shows the photograph of unnotched and notched specimens of friction welded dissimilar joints of Inconel 600-304L.The chemical composition of Inconel 600 and stainless steel 304L are presented in Table 1and Table 2. Friction welding was carried out using optimised friction welding parameters and the parameters used in this study are presented in Table 3. The tensile tests were conducted under a constant strain rate of 10^{-3} s^{-1} till failure. The hot tensile tests were conducted on a Instron 5083 250KN UTM fitted with split furnace operating from 300 to 1200 ºC. Tensile properties of these joints were evaluated at five different temperatures ranging from RT to 600º C. After welding, the micro structural analysis of friction welded interfaces was obtained by optical microscopy. The micro hardness values were measured on both sides of welded specimens using a 50g indentation load.

Table 1. 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 2. Chemical composition (wt%) of 304L ASS

Element	C	Cr	Mn	Ni	P	S	Si	Fe
304L	0.09	14.1	1.42	8.4	0.04	0.03	0.29	74.53

Table 3. Optimised Friction welding parameters

Friction Pressure MPa	Friction Time Sec	Forge Pressure Mpa	Forge Time Sec	Rotational Speed
35	3	35	3	1000

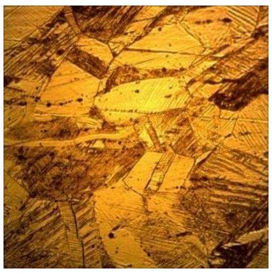
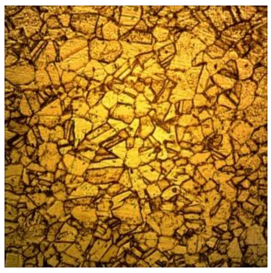
Fig.1.Photographs of notched and unnotched specimens

3. RESULTS AND DISCUSSION

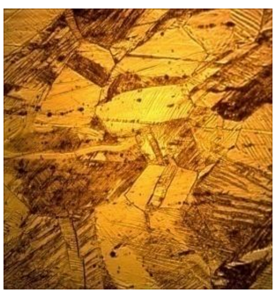
3.1 Characteristics of Joints

3.1.1 Microstructure

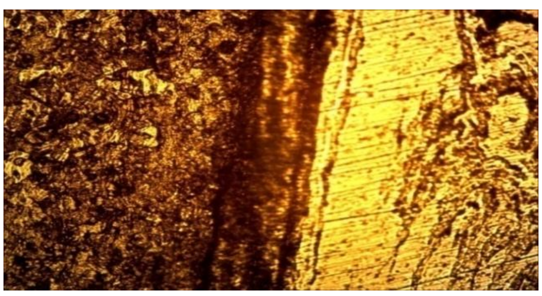
With the help of optical microscope, the friction welded samples were examined. The microstructure analysis was carried out on three zones of the friction welded joints. Fig.2 displays the optical micrographs of base metals and welded joints of Inconel 600-304L. The heat developed on the parent metal during friction welding process causes the temperature gradient resulting different microstructures on various zones of the material [13]. An equiaxed annealed austenitic grains observed in 304L base metal as shown in Fig.2 a, while the coarse alpha grains observed in Inconel 600 base metal as shown in Fig. 2 b. 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 [14].Similarly, Fig. 2c shows dispersed recrystallized alpha grains whereas the HAZ of Inconel 600 revealed soft dense grain structure in Fig.2d. The width of the Heat affected zone (HAZ) in Inconel 600 side is much larger than the 304L side. This is caused because of non-uniform heat generation at the welding interface. Fig.2e shows the optical microstructure of the interface region. Due to thermo mechanical action, the formation of weld interface region is not so clear.

a) 304L ASS b) Inconel 600




c) HAZ of 304L ASS d) HAZ of Inconel 600



e) Weld centre / Interface region

Fig.2 Micrographs of base metals and welded joint.

3.1.2 Micro hardness

Vickers micro hardness measurements were made across the weld as shown in Fig.3. Vickers's hardness measurements were taken down in accordance with ASTM E384-09 and ASTM E407-99 standards respectively. The hardness was measured across the centre line of the weld. Maximum hardness is observed near the interface of Inconel 600. A maximum hardness of 293 HV has been obtained near the weld interface in Inconel 600 and 138HV in austenitic stainless steel (304L). The joint shows a declining trend in hardness towards the free ends from the weld interface of both the materials. The increase in hardness at the weld zone (WZ) occurred due to the micro structural transformation that occurs during the friction welding process. The hardness variations are caused due to the different thermal diffusivity of materials and intermetallic layer existing at the interface [15].

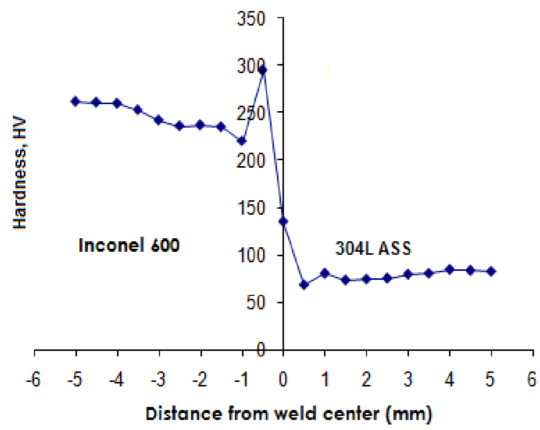


Fig.3 Micro hardness profile on friction welded joint

3.2 Hot tensile behaviour of joints

Fig.4 shows the stress– strain curves of friction welded dissimilar joints of Inconel 600 with 304L austenitic stainless steel tested at different temperatures. The maximum value of UTS of 487 MPa was registered at 300ºC. This value approximately equals to the UTS of the specimen at RT. The UTS value showed a minimum of 437 MPa at 600ºC. This is attributed to the reason of low strain rate. The low strain rate provides long time for energy accumulation while the high temperature promotes the nucleation and growth of dynamically recrystallized grains [16]. The percentage of elongation seems to be lower at RT and maximum elongation of 6.14% was attained at 300°C. The higher deformation was observed at elevated temperatures than RT. Table 4 shows the transverse tensile test results of the friction welded dissimilar joints.

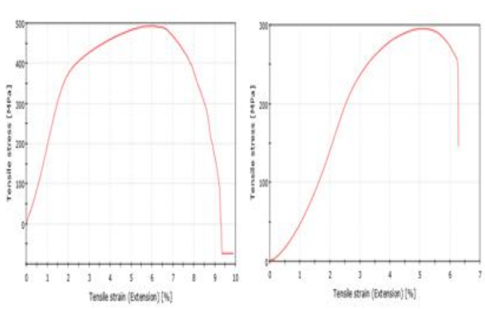
The UTS and ductility decreased with increase in test temperature and the tensile stress increases with deformation until the UTS is reached, and then decreases slightly with increasing strain (softens at high temperatures) followed by a rapid decrease. The flow stress curves show the different hot tensile behaviours under various tested conditions. This is because of the combined effects of work hardening and thermally activated softening mechanisms. At low deformation temperatures, the flow stress firstly increases to a peak value and then decreases monotonously till fracture with the increase of deformation degree. The dislocation density increases drastically in the initial deformation stage, the stress strain curves show obvious work hardening. It is known that when the strain rate is high, the accessional substructures can be generated in the initial grains which will produce more nuclei per unit volume of the grains. When the strain rate is high, this mechanism makes the grain fine [17].

The sufficient driving force for dislocation movement such as dislocation climb or cross slip was obtained from the accumulated energy with the increase of strain. The high dislocation density will promote the occurrence of dynamic recrystallization under the high deformation temperatures and relatively low strain rates. From the flow stress DRX characteristics, it is observed that the flow stress firstly increases to a peak value and then follows by flow softening up to the quasi-stable deformation stage, in which the material becomes more sensitive to the strain rate [18]. The flow stress is the combined result of work hardening, dynamic recovery and the dynamic recrystallization.

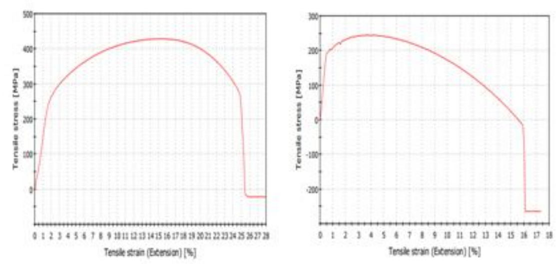
Table 4. Transverse Tensile test results

Temp °C	Notch Tensile Strength, MPa	Ultimate Tensile Strength, Mpa	Elongation %	0.2% yield strain	Notch Strength Ratio (NSR)
RT	295	486	9.87	0.0252	0.607
150	253	442	15.24	0.0243	0.572
300	300	487	16.14	0.0238	0.616
450	290	478	14.22	0.0216	0.608
600	280	437	13.01	0.0152	0.641

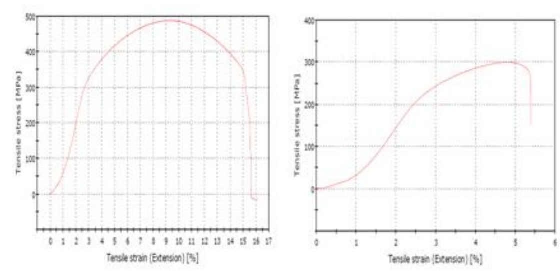
It is evident from Notch Strength Ratio (NSR) that the fracture obtained is brittle in nature. This indicates the notched specimen holds appreciable properties at high temperature. It is because of the decrease in dislocation generation rate, the dislocation density and nucleation sites with the increase of deformation temperature [19], and which weakens the effect of work hardening. With the increase of strain rate, the dynamic recovery rate decreases, and thereby the work hardening and dynamic recovery stage is prolonged, as a result of which the peak strain is increased correspondingly.



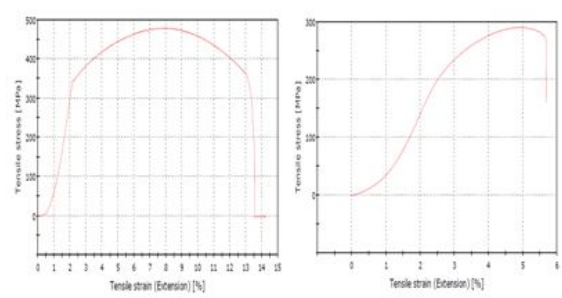
a) Unnotched specimen at RT b) Notched specimen at RT



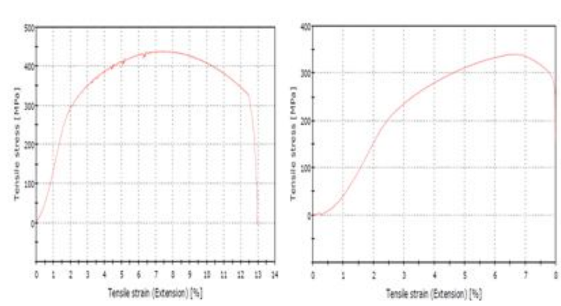
c) Unnotched specimen at 150°C d) Notched specimen at 150°C



e) Unnotched specimen at 300°C f) Notched specimen at 300°C



g) Unnotched specimen at 450°C h) Notched specimen at 450°C



i) Unnotched specimen at 600°C j) Notched specimen at 600°C

Fig.4 Stress - Strain curves for Unnotched and Notched specimens

4. CONCLUSION

1. 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. Due to lowest tensile strength of 304L austenitic stainless steel, the plastic deformation and flash was predominant on 304L side.
2. The tensile strength of the friction welded dissimilar joints 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.
3. The notch tensile strength of the friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel is not influenced by test temperature. This indicates these joints are notch brittle category.
4. Though the ductility (elongation) of the dissimilar joints are higher compared to room temperature (RT) ductility, the ductility decreases beyond 300°C.
5. The yield strain of the friction welded dissimilar joints of Inconel 600 and 304L austenitic stainless steel is highly influenced by test temperature. The yield strain decreases gradually when the temperature increases from RT to 600°C.
6. The formation of intermetallics at the weld interface are responsible for higher hardness at and adjacent to the interface for the friction welded Inconel 600-304L dissimilar joints.

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