Hot tensile deformation behaviours of friction welded dissimilar joints of Inconel 600 with AISI 410 martensitic stainless steel

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Abstract

The dissimilar joints of Inconel600 with AISI 410 martensitic stainless steel were fabricated by continuous drive friction welding process. Hot tensile properties of these joints were evaluated by hot tensile test at the temperature range of 25°C– 600°C and strain rate of 0.001 s\(^{-1}\) as per ASTM E21 standard. The results showed that the highest ultimate tensile strength of 1362 MPa was achieved at the temperature of 25°C for smooth specimen whereas the lowest ultimate tensile strength of 981MPa was achieved at the temperature of 150°C. Similarly, for notched specimen, the highest and lowest UTS of 604MPa and 244MPa were obtained respectively at the temperatures of 25°C and 600°C. The percentage of elongation was found to be maximum at the temperature of 25°C for both smooth specimen and notched specimen. The Notch Strength Ratio (NSR) showed that the joints are notch brittle category. The micro structural characteristics and micro hardness variations were also carried out to understand the deformation behaviour of friction welded dissimilar joints of Inconel 600 and AISI 410 martensitic stainless steel.

Keywords: Dissimilar Joints, Friction welding, hot tensile properties, Inconel, Martensitic stainless steel.

1. Introduction

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]. Generally, material flow behaviors during the hot forming processes (such as rolling, forging, and extrusion) are often complex [2]. It is well known that the effects of processing parameters on mechanical properties of metals and alloys are significant. During the hot forming process, there are several types of metallurgical phenomena in metals and alloys with low or medium stacking fault energy, such as the dynamic recrystallization (DRX) [3-5], static recrystallization (SDRX) [6-8], and metadynamic recrystallization (MDRX) [9-12], which result in the complex microstructural evolution in alloys [13,14]. As an important grain refining and flow softening mechanism, the DRX has a great significance for the control of microstructures and the improvement of mechanical properties. Dynamic recrystallization behaviors of 42CrMo steel [15-17], 304 austenitic stainless steel [18], Cu-bearing HSLA-100 steel [19], Ti–6.5Al–3.5Mo–1.5Zr–0.3Si alloy [20], TiAl alloy [21], and some typical superalloys [22,23] were studied in detail.

In particular, there is a strong demand for dissimilar joining of nickel based super alloy to martensitic stainless steel. Inconel 600 typically finds application in furnace components, chemical processing, food processing and nuclear engineering. As Inconel 600 is relatively an expensive alloy, a cheaper material with good properties can be used in lower risk conditions to reduce material costs [24]. AISI 410 martensitic stainless steel is relatively a low cost material used in high temperature applications.

Conventional fusion welding of many such dissimilar metal combinations is not feasible owing to the formation of brittle and low melting intermetallics due to metallurgical incompatibility, wide difference in melting point, thermal mismatch, etc. Solid-state welding processes that limit extent of intermixing are generally employed in such situations. Friction welding is one such solid-state welding process widely employed in such situations [25]. 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.

Friction welding is well known amongst solid state joining methods. This method is very useful for the joining of dissimilar materials and the welding process is easily automated. 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 [26]. Also, this welding method has several advantages over fusion welding, e.g. high energy efficiency, narrower heat affected zone and low welding cost [27].

Hot deformation behaviour of S31042 austenitic heat-resistant steel was investigated over the temperature range of 900- 1200°C and strain rate range
of 0.01-10 s\(^{-1}\) [28]. 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 [29]. Hot tensile test is also employed to study the hot deformation and super plastic behaviour of intermetallic compounds such as NiAl, FeAl, TiAl, and CoTi [30]. 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 super plastic alloys [31]. 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 [32]. Hot tensile properties of as cast NiTi and NiTiCu shape memory alloys were investigated by hot tensile test at temperature range of 700–1100°C using the strain rate of 0.1 s\(^{-1}\) [33]. 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 [34]. 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 [35].

From the literature review, it is understood that the work on hot tensile properties of friction welded dissimilar joints of Inconel 600 and AISI 410 martensitic stainless steel 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 AISI 410 martensitic stainless steel.

2. Experimental work
In this investigation, 12mm diameter and 75mm length of cylindrical rods of Inconel 600 and 410 martensitic stainless steel were used. Fig.1 shows the experimental details of friction welded dissimilar joints of Inconel 600-AISI 410 MSS . Fig. 1a shows the joint dimension and configuration of the joint. The chemical composition of Inconel 600 and AISI 410 martensitic stainless steel are presented in Table 1 and Table 2. The mechanical properties of parent metal used in this experiment are listed in Table 3.

Continuous drive friction welding machine was used to fabricate the dissimilar joints, which is capable of operating with high precision and excellent repeatability. Friction welding was carried out using optimised friction welding parameters and the parameters used in this study are presented in Table 4. Fig.1b shows the photograph of the friction welded joints. The dimensions for unnotched and notched tensile test specimens according to ASTM E21 standard are given in Fig.1c and Fig. 1d. Prior to loading, the specimens were heated to the test temperature with the heating rate of 10 °C/min.

The hot tensile deformation behaviors of friction welded dissimilar joints of Inconel 600 with AISI 410 martensitic stainless steel were studied by uniaxial test. The hot tensile tests were conducted on a Instron 5803 250KN UTM fitted with split furnace operating from RT to 1200 °C and the strain rate of 0.001 s\(^{-1}\). Tensile properties of these joints were evaluated at four different temperature ranging from 25°C to 600°C.

Fig.1e and f shows the photograph of unnotched and notched specimen. In order to reveal the micro structural characteristics, the metallographic specimens were prepared by polishing and etching chemically with a solution consisting of 5g CuCl\(_2\) +100ml HCl +100ml C\(_2\) H\(_5\) OH. Micro hardness survey was carried out along the centre line of the weld.

3. Results and Discussion
3.1 Macrostructure
Fig.2 shows the macrograph of the friction welded specimen, which reveals the clear bonding of the joint without any macro level defects and the flash formation during friction welding. The weld flash predominantly formed at the 410 stainless steel side while Inconel 600 did not participate much in flash formation. The reasons can be attributed to the lower tensile strength of 410 martensitic stainless steel than that of Inconel 600.

3.2 Microstructure
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 [36]. The friction welded sample was examined in the metallurgical microscope while microstructures were analyzed in base metal, HAZ and Interface of the two dissimilar materials. Fig.3a-f shows the optical micrographs of base metals and welded joint of Inconel 600-AISI 410 martensitic stainless steel. Fig. 3a shows the microstructure of 410 martensitic stainless steel base metal, revealing a tempered martensite matrix with no evidence of δ-ferrite whereas the Fig. 3b shows the microstructure of Inconel 600base metal, revealing coarse alpha grains. 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 [37]. Similarly, Fig. 3c shows the HAZ of 410 martensitic stainless steel, in which the microstructure of the material was modified mainly by the thermal field of the welding process, although this region also underwent some degree of deformation. The HAZ of Inconel 600 reveals soft dense grain structure as shown in Fig.3d. The width of the Heat affected zone (HAZ) in Inconel 600 side is
much larger than the 410 side. The above phenomenon could be caused by the non-uniform heat generation at the welding interface. Fig. 3e and f show the optical microstructures of the interface region at different magnification. The formation of weld interface region is not so clear in these optical micrographs, due to thermo mechanical action, is observed on both the base metals nearer to the joint line.

3.3 Micro hardness
Vickers micro hardness measurements were made across the center line of the weld as shown in Fig.4. Vickers’s hardness measurements were taken down in accordance with ASTM E384-09. High hardness is observed in the Inconel 600 side adjacent to interface of joint. A maximum hardness of 210 HV has been obtained near the weld interface in Inconel 600 and 199HV in 410 martensitic stainless steel. From the weld interface, the joint shows a declining trend in hardness towards the free ends of both the materials. The increase in hardness at the weld zone (WZ) can be attributed to the micro structural 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 [38].

3.4 Hot tensile deformation behaviour of joints
Fig.5 shows the stress–strain curves of friction welded dissimilar joints of Inconel 600 with 410 martensitic stainless steel tested at different temperatures. The maximum UTS of 1362 MPa was achieved at 25°C and further the UTS reduces as the temperature increases. At elevated temperature, a maximum UTS of 1309 MPa (approximately equal to the UTS at 25°C) was achieved at 450°C. The value of UTS shows a minimum of 981MPa at 600°C which provides long time for energy accumulation, and high temperature promotes the nucleation and growth of dynamically recrystallized grains and dislocation annihilation [39] which reduces the flow stress. The percentage of elongation decreases with the increase of temperature. It is attributed to the lower deformation at elevated temperatures than at 25°C.

Table 5 shows the transverse tensile test results of the friction welded Inconel 600- AISI 410 martensitic stainless steel dissimilar joints. The ductility decreased with increase in test temperature and the tensile stress increases with deformation until the UTS is reached. Meanwhile, due to the combined effects of work hardening and thermally activated softening mechanisms, the flow stress curves show the different hot tensile behaviours under various tested conditions. 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 popularly understood that accessional substructures can be generated in the initial grains when the strain rate is high, which will produce more nuclei per unit volume of the grains. This mechanism can make the grain fine when the strain rate is high [40]. With the increase of strain, the energy rapidly accumulates, which provides the sufficient driving force for dislocation movement such as dislocation climb or cross slip. Then, the dynamic recovery occurs and the increasing rate of flow stress slows down. Under the high deformation temperatures and relatively low strain rates, the high dislocation density will promote the occurrence of dynamical recrystallization. The flow stress curve shows a typical DRX characteristics, i.e. 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 [41]. Then, the flow stress is the competition result of work hardening, dynamic recovery and the dynamic recrystallization.

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. It is because of the decrease in dislocation generation rate, the dislocation density and nucleation sites with the increase of deformation temperature [42], and which weakens the effect of work hardening. On the 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.

4. Conclusion
1. The tensile strength of the friction welded dissimilar joints of Inconel 600 and 410 martensitic stainless steel is influenced by test temperature. Initially, the tensile strength decreases upto 150°C and then gradually increases upto 450°C and drastically reduced thereafter. Hence, these type of joints are best suited for operating temperature below 450°C.

2. The notch tensile strength of the friction welded dissimilar joints of Inconel 600 and 410 martensitic stainless steel decreases gradually with the increase of temperature. However, notch tensile strength of these joints are higher than unnotched specimens. This indicates these joints are notch brittle category.

3. The percentage of elongation of the dissimilar joints is influenced by test temperature. The elongation decreases with the increase in temperature.
4. The yield strain (0.2%) of the friction welded dissimilar joints of Inconel 600 and 410 martensitic stainless steel is influenced by test temperature. The yield strain decreases gradually when the temperature increases from 25°C to 600°C.

5. The formation of intermetallics at the weld interface are responsible for higher hardness at and adjacent to the interface for the friction welded Inconel 600–410 martensitic stainless steel dissimilar joints.

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References


Table 1 Chemical composition (wt %) of Inconel 600

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<tr>
<th>Element</th>
<th>Ni</th>
<th>Cr</th>
<th>Mn</th>
<th>C</th>
<th>Fe</th>
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<td>Inconel 600</td>
<td>72.28</td>
<td>16.75</td>
<td>0.51</td>
<td>0.04</td>
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Table 2 Chemical composition (wt %) of 410 martensitic stainless steel

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
<th>Si</th>
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<td>410</td>
<td>Max 0.15</td>
<td>11.5-13.5</td>
<td>Max 1</td>
<td>0.75</td>
<td>Max 0.04</td>
<td>Max 0.03</td>
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Table 3 Mechanical properties of base metals

<table>
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<th>Mechanical properties</th>
<th>Inconel 600</th>
<th>410 stainless steel</th>
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<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>856</td>
<td>713</td>
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<tr>
<td>Yield strength (MPa)</td>
<td>784</td>
<td>670</td>
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<tr>
<td>Elongation (%)</td>
<td>51</td>
<td>60</td>
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<tr>
<td>Hardness (Hv)</td>
<td>206</td>
<td>199</td>
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<tr>
<td>Impact toughness (J)</td>
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Table 4 Optimised Friction welding parameters

<table>
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<tr>
<th>Friction Pressure (MPa)</th>
<th>Friction Time (s)</th>
<th>Forge Pressure (MPa)</th>
<th>Forge Time (s)</th>
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Table 5 Transverse Tensile test results

<table>
<thead>
<tr>
<th>Temperature ºC</th>
<th>Notch Tensile Strength, MPa</th>
<th>Ultimate Tensile Strength, MPa</th>
<th>Elongation (%)</th>
<th>0.2% yield Strain, mm/mm</th>
<th>Notch Strength Ratio (NSR)</th>
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<td>25</td>
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<td>1362</td>
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<td>532</td>
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<td>1275</td>
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<td>435</td>
<td>1309</td>
<td>11</td>
<td>24</td>
<td>0.33</td>
</tr>
<tr>
<td>600</td>
<td>244</td>
<td>1131</td>
<td>8</td>
<td>16</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Fig. 1. Experimental Details of friction welded dissimilar joints

a) Joint dimensions and configurations

b) Photograph of Inconel 600-410 SS friction welded dissimilar joint

c) Unnotched tensile specimen Dimension

d) Notched tensile specimen Dimension

e) Photograph of unnotched specimen

f) Photograph of notched specimen

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Fig. 2. Macrograph of the friction welded specimen

Fig. 3. Optical micrographs of base metals and welded joint.

a) Base metal of 410 Stainless Steel  
b) Base metal of Inconel 600

c) HAZ of 410 Stainless Steel  
d) HAZ of Inconel 600

e) weld centre / Interface region  
f) weld centre / Interface region

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Fig. 4. Micro hardness profile across the interface on friction welded joint.

- **a)** Notched specimen at RT
- **b)** Unnotched specimen at RT
- **c)** Notched specimen at 150°C
- **d)** Unnotched specimen at 150°C
Fig. 5. Stress - Strain curves for Notched and Unnotched specimen