The inertia friction welding process was used to weld the nickel base superalloy Ni76Cr19AlTi to martensite steel 4Cr10Si2Mo. Ni76Cr19AlTi is a f.c.c superalloy strengthened by precipitates of $\gamma'$. 4Cr10Si2Mo is a martensite stainless steel strengthened by martensite transformation and precipitates of carbides. The microstructure evolution on the nickel base superalloy Ni76Cr19AlTi side of the weld was studied. It was found that the welds formed can be divided into three zones: thermomechanically affected zone, heat affected zone and base metal. The thermomechanically affected zone consisted of two subzones: one is the mixed chemical composition zone of about 100 $\mu$m in width formed by mechanical stirring and interdiffusion of alloying elements and the other was pure shear zone located adjacent to the mixed chemical composition zone. In the chemical composition mixture zone, a large number of carbides with sizes of less than 100 nm formed in the austenite matrix. However, no $\gamma'$ phase can be observed in this region. The dislocation density decreased gradually as the distance to the weld interface increased. The dislocation density in the pure shear zone was very high. Grain size coarsened markedly in the heat affected zone, in which the $\gamma'$ phase was precipitated. The primary mechanism of the grain growth was the bulging of grain boundary between two adjacent grains with high-angle boundary.

KEY WORDS: nickel-based alloys; inertia friction welding; compression and shear; microstructure.
2. Experimental Procedure

The nickel-base alloy and martensite stainless steel used were Ni76Cr19AlTi and 4Cr10Si2Mo, respectively. The chemical composition of the Ni76Cr19AlTi alloy is Ni–0.04C–1.49Al–2.11Ti–19.36Cr–0.64Fe–0.12Si (wt%). The chemical composition of the 4Cr10Si2Mo alloy is Fe–0.42C–0.81Mo–9.68Cr–0.3Mn–2.13Si (wt%).

The Ni76Cr19AlTi bar with a diameter of 10 mm was supplied by Shanghai materials researching institute. Spheroidizing annealed 4Cr10Si2Mo bar with a diameter of 10 mm was provided by Hunan Anfu valve factory. The bars of 4Cr10Si2Mo and Ni76Cr19AlTi were joined by friction welding. The maximum torque, upsetting force, rotating speed, welding time and force holding time used in the welding process were 60 N.M., 410 MPa, 5000 r/min, 4.5 s, 2 s, respectively.

Tensile strength of the welds was measured on an Instron testing machine. Optical microscopy study was carried out on a Germany Polymeter optical microscope. The welds were sectioned at every 0.5 mm distance in a direction parallel to the welding interface using a wire cutting machine. The sections were polished for XRD analysis, which was performed on a Rigaka X-ray diffractometer with a scanning rate of 0.1°/min; a Cu Kα source and a voltage of 2 kW were used for the analyses.

The weld samples for TEM analysis were firstly mechanically polished to 0.1 mm and then were jet-polished with a solution of 5% HClO₄ in ethanol with a voltage of 15 V. TEM analysis was made on a H800 transmission electron microscope.

3. Results and Analysis

3.1. Structure and Property of Nickel Alloy before Friction Weld

The tensile strength of the as-received nickel-based alloy at room temperature are 1 397 MPa and the elongation of the alloy is more than 10%. Microstructure of the as-received nickel alloy is given in Fig. 1. The grain size of the as-received nickel-based alloy is about 20 μ. A great number of twins can also be seen clearly in microstructures of the alloy.

3.2. Interface of the Welds

The longitudinal section of the weld is shown in Fig. 2. The flash can be clearly observed at the weld of the two dissimilar alloys. It is larger on the 4Cr10Si2Mo side than on the nickel-based alloy side. This is mainly because the strength of nickel alloy is markedly higher than that of the 4Cr10Si2Mo alloy at high temperatures to which the contact interface of the two alloys was heated by shearing of the two alloys at very high strain rate. Hardness along the longitudinal section in the weld in the Ni76Cr19AlTi alloy is shown in Fig. 3. It can be seen that the hardness at the interface of the two alloys was the highest maximum at about 52HRC, but it reached a minimum at the location of 1.4 mm from the interface and then remained almost constant with further increase in the distance from the interface.

Chemical concentrations of major alloy elements in the weld region were determined by EDS analysis. The results are given in Fig. 4. It shows that alloy elements migrated into the respective counter alloys to a depth of about 50 μ to the interface, which were a result of the mechanical stirring and the inter-diffusion of atoms during the welding process. However, the former is likely to be the primary cause for the formation of such a mixture region.
calculated using the following equation\(^{(10)}\)

\[
\varepsilon = \frac{\beta \cot \theta}{2}
\]

where \(\beta\) is the peak width, \(\varepsilon\) micro-strain, \(\theta\) the angle at the reflection peak analyzed. The spacing between the \(\langle 200 \rangle\) planes changes with variation of the different lattice distortion. The microstains estimated are presented in Fig. 6. It can be seen that the microstrain is the highest at the interface. It decreased as the distance to the interface increased. It decreased to a very low value at a distance of 1 mm to the interface. When the distance to the welding interface was greater than 1 mm, the microstrain became almost constant. It may thus be deduced that the width of the region that was deformed during the friction welding process was about 1 mm. The subgrain size changed with the distance to the welding interface in a manner opposite to that of the microstrain.

3.3. Microstructure of Friction Weld Joint

Microstructures at the different areas of the weld are illustrated in Fig. 7. The microstructure of the Ni76Cr19AlTi alloy at the weld consisted of three different zones: thermomechanical affected zone, heat affected zone and base metal. A large number of dropwells can be observed on surface of the polished and etched sample in the thermomechanical affected zone, which may result from the overetching of microstructure affected by the severe deformation in the region and the mixture of chemical composition of 4Cr10Si2Mo and Ni76Cr19AlTi. Grains became obviously coarser in the heat affected zone as compared with those in the base metal.

3.4. TEM Analysis on the Nickel Alloy Side of the Weld after Friction Welding

TEM analysis of thermomechanical affected zone is shown in Fig. 8. It consisted of two sub-zones. One was the mixed chemical composition mixture zone (see Fig. 8(a)), which was formed by mechanical friction and atom interdiffusion at the interface. The carbon in the 4Cr10Si2Mo alloy diffused into the Ni76Cr19AlTi alloy and the chromium in the Ni76Cr19AlTi alloy diffused into the 4Cr10Si2Mo alloy at high temperatures. The mixed chemical composition mixture zone was very narrow. Thus, carbides with a size in the range of less than 100 nm formed. The other subzone is pure shearing zone (see Figs. 8(b)–8(d)), in which a dislocation density of more than \(3 \times 10^{10}/\text{cm}^2\) can be observed with dislocations interacting with each other. In some locations, dislocations had rearranged and cell structures formed, suggesting that the temperature had been higher than the recovery or recrystallization tempera-
ture of the Ni76Cr19AlTi alloy. Dislocation density decreased gradually from the weld to the base metal of the Ni76Cr19AlTi alloy. No obvious γ' phase was observed in the mixed chemical composition zone and in pure shearing zone, indicating that the original γ' phase was dissolved at high temperatures generated by plastic deformation process.

TEM image of the heat affected zone and base material is shown in Fig. 9. The as-received nickel alloy was hot-rolled. Thus dislocations of very high density can be observed in the Ni76Cr19AlTi alloy near the weld interface. Additionally, γ' Phase can be seen in the heat affected zone, which was probably formed as a result of a slower cooling rate after hot rolling.

Fatigue 9 also reveals that dislocation density was much lower in heat affected zone than in thermomechanical affected zone. High-angle boundary can be clearly observed in this region, suggesting that the temperature in the heat affected zone had increased to levels above the recrystal-lization temperature of the Ni76Cr19AlTi alloy. A large number of coarsened γ' phases were detected in this region. Grain boundaries of one grain bulging to another between adjacent large orientation grains can also be seen in this region. The γ' phase in heat affected zone became coarser.

Fig. 7. Microstructure of Ni76Cr19AlTi in the weld of Ni76Cr19AlTi/4Cr10Si2Mo. a) Thermomechanical affected zone. b) Chemical composition mixture zone. c) Pure shearing zone. d) Heat affect zone.

Fig. 8. TEM structure of thermomechanical affected zone, a) interface, b) 0.5 mm to interface, c) 1 mm to interface, d) 1.5 mm to interface.
as compared with that in base metal. Moreover $\gamma'$ phases semi-coherent with the matrix were also detected in this region. These semi-coherent $\gamma'$ phases may be newly precipitated from the matrix during welding process.

4. Conclusions

The microstructure and physical characteristics on the Ni76Cr19AlTi side of inertia friction weld joint of the Ni76Cr19AlTi alloy to the 4Cr10Si2Mo alloy was studied. It was observed that the weld region consisted of three zones: thermomechanical affected zone, heat affected zone and base material zone. Thermomechanical affected zone consist of two sub-zones: one was the mixed chemical composition mixture zone with total width of about 100 $\mu$m in width and another was the pure shear zone. The matrix of the mixed chemical composition zone was austenite with large numbers of dispersed fine carbides with a grain size of less than 100 nm, but with no precipitates of the $\gamma'$ phase. Dislocation density in pure shear zone was extremely high. The grain size coarsened markedly in the heat affected zone, which was facilitated by grain boundary bulging. The precipitates of the $\gamma'$ phase were semi-coherent with the matrix present in the next affected zone.

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