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LETTER

Friction stir welding of Inconel alloy 600

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Nickel-based superalloys have been developed to increase the energy efficiency, performance and to reduce the cost of industrial turbine engines and the other high temperature components. To manufacture a modern, flexible and high performance turbine system, joining or welding processes including gas tungsten arc welding (GTAW), electron beam welding (EBW), laser welding or friction stir welding (FSW) are generally required [1]. FSW, which was invented in 1991 by The Welding Institute (TWI), Cambridge, England [2], is a solid-state joining process. Since FSW involves no melting, this process eliminates the problems associated with fusion welding such as fumes, arc glare, spatter, solidification cracking, shrinkage, severe distortion and solidification stress. It also provides a significant economic advantage in terms of savings in the weld preparation time, welding time, consumable costs and labor rate for veteran technicians [3–5]. Over the past 15 years, it has been proven to be a promising joining process for low melting point materials including aluminum and magnesium alloys. However, these materials represent less than 10% of the welded products in the world. On the other hand, high melting point materials, such as steel and nickel-based superalloys, represent more than 80% of the welded materials [6]. Therefore, it is very promising to apply FSW to high melting point materials. In this study, a new approach was made to join the Inconel alloy 600 by FSW, and the joint properties and microstructures were examined.

One of the major obstacles for the commercialization of FSW applying in high melting point temperature materials is the relatively short tool life due to wear [7], therefore, good wear resistant tungsten carbide-based alloy tools and polycrystalline cubic boron nitride (PCBN) tools are commonly applied. A tungsten carbide-based alloy tool developed by our group [8] was used in this study and its appearance is given in Fig. 1. The diameter of the probe was 6 mm and its length was 1.8 mm. The base material was a 2-mm-thick nickel-based superalloy (commercially called Inconel 600) with a melting point of 1630 K, and its nominal composition (wt.%) was 76.0 Ni, 15.5 Cr, 8.0 Fe, 0.25 Si, 0.50 Mn, 0.08 C and 0.008 S. A butt friction stir welded (FSWed) joint was produced at a welding speed of 1.67 mm/s and a tool rotation speed of 400 rpm. The tool was tilted at 3° from the vertical and argon shielding gas was utilized to prevent oxidation of the joint surface.

Fig. 2 is a photograph of the FSW process applying in Inconel 600. The tool shoulder reached a bright orange color. Also, as the tool travels along the seam, the weld track behind the trailing edge of the rotating tool appeared orange/bright red. Smooth and glossy surface appeared on the surface of the joint with a uniform surface semicircular ripple, which was caused by the final sweep of the trailing edge of the rotating tool. The temperature of the plate's backside was measured and the results are summarized in Fig. 3. The temperature at the point of 2 mm away from the weld center dropped significantly about at 80 K/s (Fig. 3 (a)) and the maximum temperature at the weld line of the plates' backside approximated to 1073 K. The temperature was also dependent on the rotation speed, increasing with higher speed and decreasing with lower speed. Fig. 4 shows the macro- and microstructures of the stir zone of the transverse cross section of the joint and the microstructure of the Inconel 600 base metal (BM) (Etched by $HNO_3 + HCl + H_2O$). No volumetric defect and kissing bond were observed within the joint. The stir zone was

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Fig. 1 Details of tungsten carbide based alloys tool used in FSW

Fig. 2 Photograph of the FSW process applying in Inconel 600

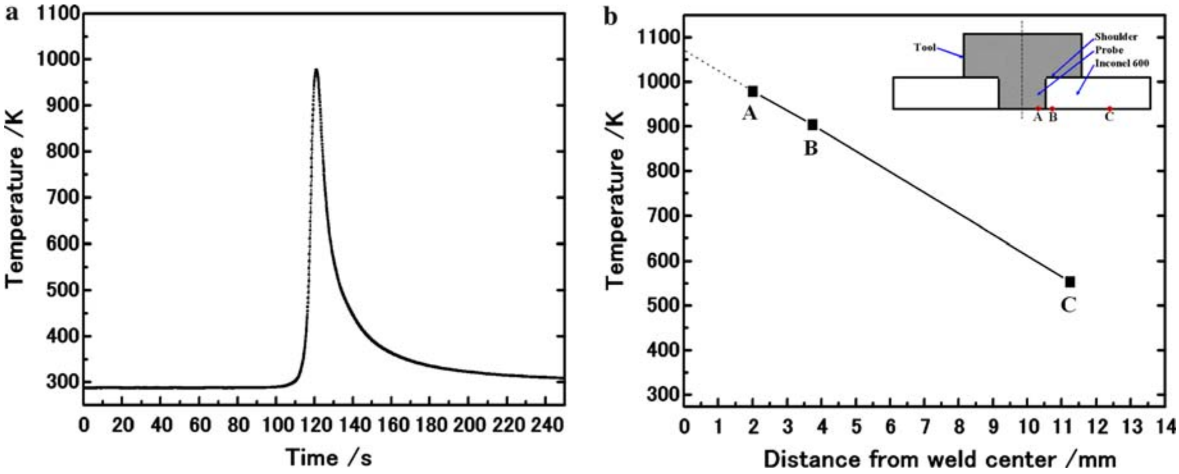

Fig. 3 The temperature hysteresis (**a**) and maximum temperature (**b**) of the Inconel 600 in the FSW process

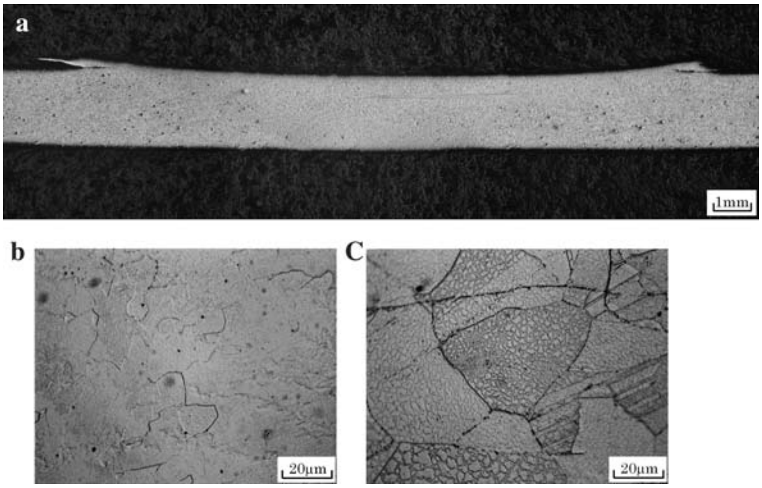

Fig. 4 The macro (**a**) and microstructure (**b**) of stir zone of the transverse cross section of the joint and the microstructure of Inconel 600 BM (**c**) (Etched by $HNO_3 + HCl + H_2O$)

recrystallized and intergranular boundaries were not deeply etched compared with that of the BM. The Vickers hardness profile is shown in Fig. 5. The measurement position was 1 mm from the surface of the test piece with an applied load of 200 gf at 0.25 mm intervals. Although the Vickers hardness of the joint was relatively homogeneous, it slightly increased compared with that of the BM. No heat-affected zone (HAZ) softening was detected in the joint. Fig. 6 illustrates the transverse tensile properties of the FSWed joint, BM and longitudinal tensile properties of the FSWed stir zone. The ultimate tensile strength of the FSWed stir zone was higher than that of the FSWed joint, which was almost the same as that of BM. The elongation of the joint was over 35%. Fig. 7 shows the fractured transverse tensile specimens, typical SEM images of the fractured joint surface and FSWed stir zone. The transverse failure of the joint occurred through necking outside the weld region, which also means that the tensile strength of the stir zone was greater than that of the BM. The fractured joint surface exhibited intergranular dimples and the fracture initiated mainly from the grain boundaries and the precipitation sites. The fractured FSWed stir zone showed smaller dimples, which resulted partly from the smaller grain size in the stir zone.

The yield strength of the high melting point materials is an indicator as friction stir weldability. Generally, it is easier to weld low yield strength materials by FSW. The yield strength at 0.2% offset of Inconel 600, Inconel 625, Inconel 718 and steel SUS304L at 1143 K is 40, 275, 330, and 340 MPa, respectively [9, 10]. Fujii and co-workers [9] have successfully welded SUS304L sheets using the tool used in this study. Based on these investigations and analysis, a promising approach to join nickel-based superalloys by FSW was suggested. It is feasible to apply FSW to join the other conventional superalloys, steels [6, 9, 11–13], and to extend it to commercial application in the future.

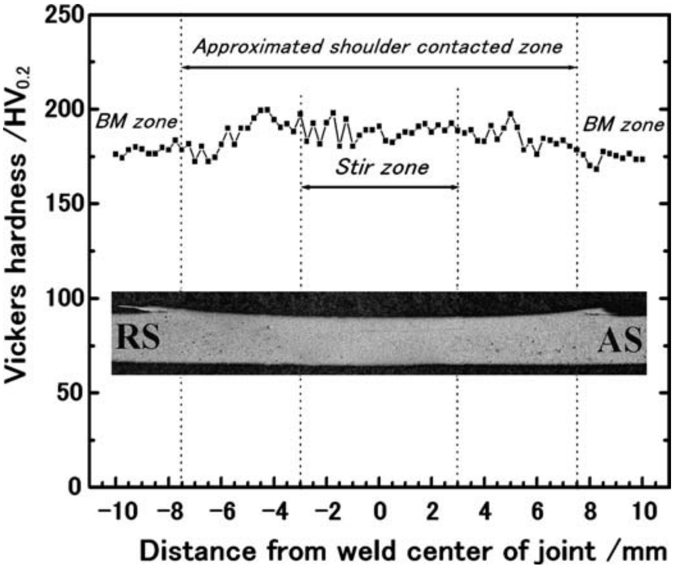

Fig. 5 The Vickers hardness of the joint as a function of distance from the centerline

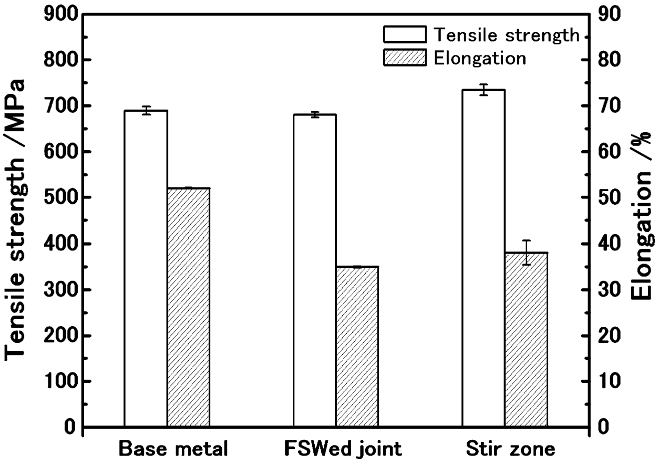

Fig. 6 Transverse tensile properties of FSWed joint, BM and longitudinal tensile properties of the FSWed stir zone

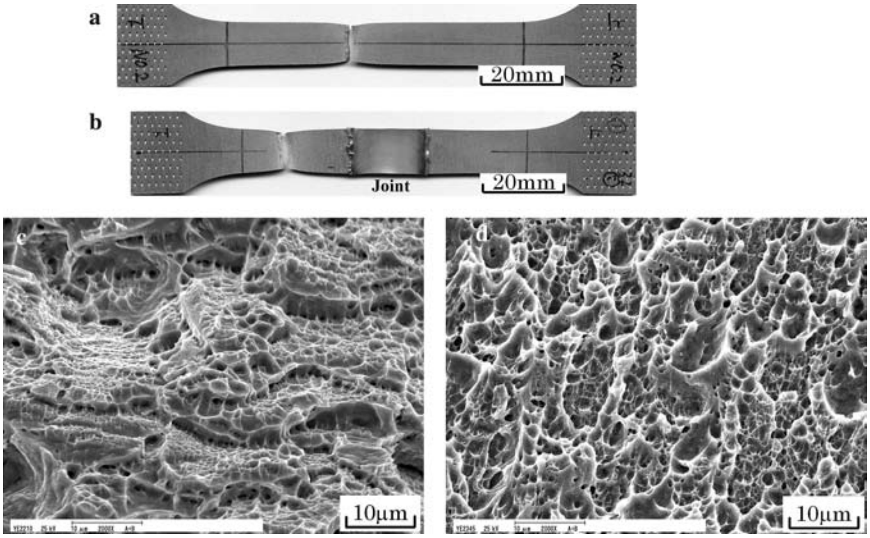

Fig. 7 Typical photographs of fractured tensile test specimens ((**a**) BM, (**b**) FSWed joint), and SEM images of fractured joint surface (**c**) and FSWed stir zone (**d**)

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