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Investigation of Microstructure and Mechanical Properties of Friction Stir Lap Jointed Ni Base Superalloy

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Abstract. This study evaluated the microstructure and mechanical properties of friction stir welded lap joints. Inconel 600 and SS 400 as experimental materials were selected, and friction stir welding was carried out at tool rotation speed of 200 rpm and welding speed of 100 mm/min. Applying the friction stir welding was notably effective to reduce the grain size of the stir zone, as a result, the average grain size of Inconel 600 was reduced from 20 μm in the base material to 8.5 μm in the stir zone. Joint interface between Inconel 600 and SS 400 showed a sound weld without voids and cracks. Also, the hook, along the Inconel 600 alloy from SS 400, was formed at advancing side, which directly affected an increase in peel strength. In this study, we systematically discussed the evolution on microstructure and mechanical properties of friction stir lap jointed Inconel 600 and SS 400.

1. Introduction

Friction stir welding (FSW), applicable welding process at solid state, has several advantages in defect suppression such as blow hole, segregation and cracking which mainly occurs in fusion welding [1]. Notable grain refinement in the stir zone due to FSW can expect the outstanding increase in mechanical properties of the welds. In constructing the chemical and power plants, Ni base superalloys have been used in many parts, moreover, fusion welding as construct method, such as gas tungsten arc welding, electron beam welding and laser welding, has been mainly used [2-4]. However, fusion welding has a limit in an increase in chemical and mechanical properties in the welds. Lately, Ni base superalloys to which FSW applied have been reported with notable enhancement in mechanical properties, resulted in refined grains in the welds [5]. These researches showed the possibility in applying the FSW, directly. On the other hands, welding between the dissimilar materials can be used in many ways. FSW as a welding method between dissimilar materials is promising to be a new welding process, and many researches on dissimilar materials (Al/Mg, Al/Steel and Al/Cu) has been reported [6-8]. However, the research on Ni base superalloy and Steel has not been reported thus far. Therefore, this study was carried out to evaluate the microstructures and mechanical properties of lap jointed Inconel 600 and SS 400.

2. Experimental procedures

The materials used in this study were Inconel 600 and SS 400. To carry out the FSW, samples were prepared by 200 mm × 70 mm × 1 mm (Inconel 600, the upper side) and 200 mm × 75 mm × 10 mm (SS 400, the lower side) sheets in size. FSW was conducted using WC-Co tool with 15 mm shoulder in diameter, and 6 mm probe in diameter and 1 mm in length. To obtain a sound welds, the tool was tilted at 3° forward from the vertical, and argon gas was utilized to prevent the surface oxidation during the welding. FSW was performed at a tool rotation speed of 200 rpm, a tool down-force of 22.5 kN and a traveling speed of 100 mm/min. In addition, the two types of welds, in which Inconel 600 alloy is located at advancing side and retreating side, were fabricated by FSW, respectively.

In order to observe the macro and microstructure of the welds, 10 ml $HClO_4$ and 90 ml CH_3OH solution was prepared, and samples were electro etched on surface after polished with abrasive paper. Also, to evaluate the microstructure of the welds, scanning electron microscope (SEM) was employed. Evaluation on grain shape, size and grain misorientation of the welds was carried out through electron backscattering diffraction (EBSD) technique. For the evaluation of mechanical properties, tensile and peel tests were employed. In case of tensile test, two types of tensile test specimens, in which Inconel 600 is located at advancing side and retreating side, were used to evaluate the transverse tensile strength of friction stir lap joints, respectively. Two types of peel strength also carried out by similar methods, applied at tensile tests.

3. Results and discussion

Macrostructure and microstructure of friction stir welded zone are shown in Fig. 1. Cross sectioned macrostructure showed a good weld without defects such as void and cracks well formed at lap joint interface, as shown in Fig. 1(a). Microstructures on lap jointed interface (lowercase letters from b to d in Fig. 1(a)) were observed by SEM. At b and c, jointed interfaces exhibited a good weld interfaces without any weld defect, as shown in Figs. 1(b) and (c), however, a hook was formed at advancing side, along the interface of Inconel 600 alloy from SS 400, as shown in Fig. 1(d).

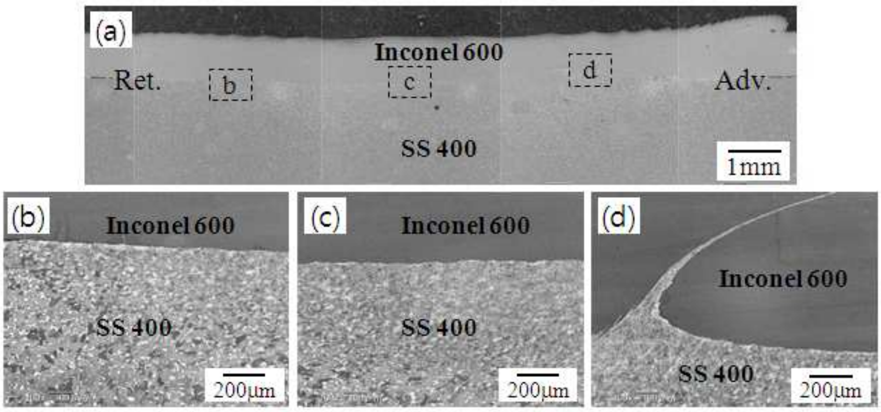

Figure 1. (a) Macro and (b-d) microstructures of jointed materials acquired by SEM. Ret. A and Adv. in figure (a) indicate retreating side and advancing side, respectively. Lowercase letters of b, c and d indicate the lap joint interfaces, and it was magnified at figures (b), (c) and (d), respectively.

Grain boundary maps of Inconel 600 part are shown in Fig. 2. At base material, the grain size in average was approximately 20 µm, and the low angle boundaries in the grain interiors was not observed, as shown in Fig. 2(a). Stir zone consists of significantly refined grains than those of base material, showing the average grain size of 8.5 µm. There is not also observed the low angle boundaries in the grain interiors, as shown in Fig. 2(b). Grain misorientation angle distributions observed in Fig. 2 are shown in Fig. 3. At all materials, the high angle boundaries occupied over 92% in fraction. Particularly, the 60° distribution of the whole misorientation angle in both materials showed the best fraction, as shown in Figs. 3(a) and (b), which were identified by annealing twin boundaries.

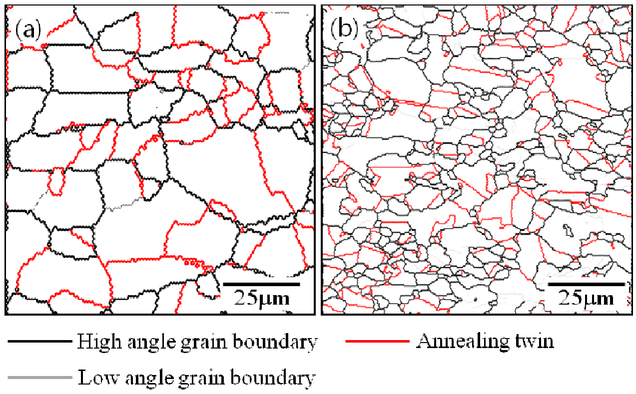

Figure 2. Grain boundary maps of friction stir welded Inconel 600 acquired by EBSD. (a) base material and (b) stir zone.

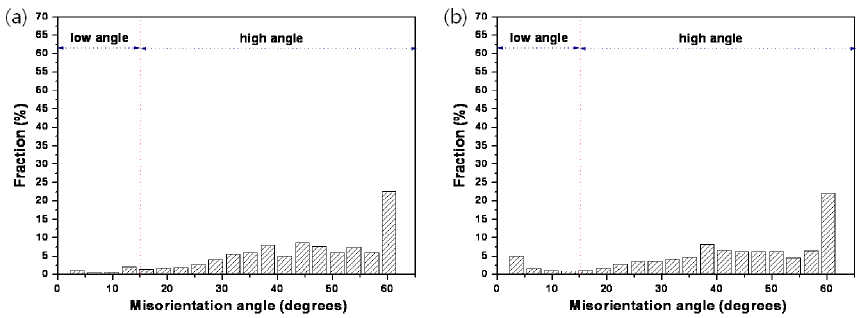

Figure 3. Misorientation angle distributions of (a) base material and (b) stir zone in Inconel 600.

Tensile properties of base material and joint material are shown in Fig. 4. At base material, yield and tensile strengths were 319 and 656 MPa, with elongation of 51%. Friction stir welded joints showed slightly higher values, as a result, yield and tensile strengths of specimen, in which Inconel 600 alloy is located at advancing side, exhibited 328 and 663 MPa with elongation of 50%. Specimen welded at retreating side (Inconel 600) showed 346 and 685 MPa in yield and tensile strength, respectively, while elongation was 49%. Results of peel test on friction stir lap joints are shown in Fig. 5. Peel tested specimen on Inconel 600 which located at advancing side in the welds was fractured at the hook area, as shown in Fig. 5(a). However, the joint located at retreating side was fractured at joint interface, and the jointed Inconel 600 alloy was wholly divided from SS 400, as shown in Fig. 5(b). Peel strength of the joints exhibited 0.128 and 0.44 kN/mm in adv. and ret. specimens, respectively, significantly higher strength at ret. specimen.

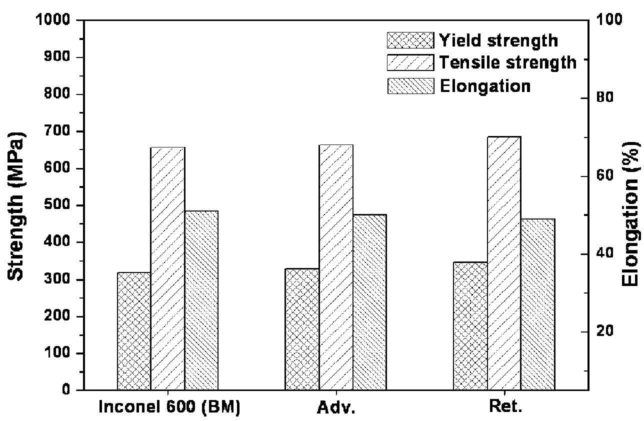

Figure 4. Tensile properties of base material (Inconel 600) and friction stir welded materials.

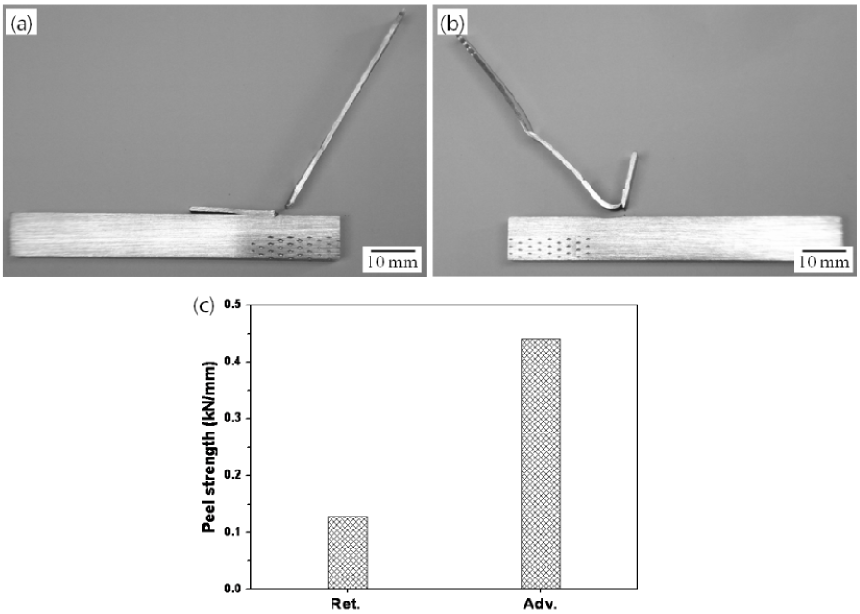

Figure 5. Results of peel tested lap joints. (a) top view of lap joint in which Inconel 600 is welded at advancing side, (b) top view of lap joint in which Inconel 600 is welded at retreating side and (c) peel strengths.

The application of FSW on the Inconel 600 alloy led to the outstanding grain refinement in the welds. As a result, the grains in the stir zone were significantly refined than those of the base material, from 20 μm (base material) to 8.5 μm (stir zone) in average, as shown in Fig. 2. The grain refinement could be explained in terms of the dynamic recrystallization by severe deformation and heat input during FSW. In other words, the material during FSW can be accompanied with the high strain (stored energy) and friction heat between material and tool [1]. Furthermore, it has been reported that the peak temperature of Inconel 600 during FSW is enough to be recrystallized [5]. Moreover, the cooling time from the peak temperature to low temperature was approximately 30 seconds, which is enough to protect against the grain growth after the recrystallization. In this study, the low angle boundaries in the grains were not observed (Fig. 2), and the high angle boundaries occupied over 92% (Fig. 3), which shows fully recrystallize state. Therefore, accompanying the high strain rate, enough heat input and fast cooling time during FSW can be led to the grain refinement, effectively.

The tool probe used in this study was a length of 1 mm, resulted in no penetration in the stir zone of SS 400 side, and joint interfaces between Inconel 600 and SS 400 showed the sound interface without any voids and cracks. Generally, FSW is accompanied with a high tool down force and heat in material, therefore, the interface of materials can be imposed the high pressure and heat, which results in mechanical bonding between the materials [9]. At lap joining, the formation of intermetallic compounds layer in the joint interface led to the deterioration in mechanical properties due to its brittleness [6, 7]. However, in this study, the intermetallic compounds layer in the joint interface was not formed. Therefore, the absent of intermetallic compounds layer and the strong mechanical bonding due to FSW in this study could lead to an increase in tensile properties, as shown in Fig. 4.

The hook formed at advancing side, along the Inconel 600 alloy at joint interface, was effective to enhance the peel strength. Especially, the specimen, in which Inconel 600 alloy is located at advancing side, showed the higher peel strength than that of the specimen located at retreating side, as shown in Fig. 5. The hook formed in this study has the shape which tilted to advancing side, along the Inconel 600 alloy from SS 400, which results in more high strength of advancing sided specimen due to the higher peel resistance in advancing side. Therefore, the peel strength of adv. specimen in this study could be shown higher value than that of ret. specimen.

4. Conclusions

Friction stir lap joints on Inconel 600 and SS 400 can be successfully obtained without weld defects such as voids and cracks. Application of FSW led to the notable grain refinement in the stir zone of Inconel 600, accompanying with dynamic recrystallization, which resulted in an increase in mechanical properties of Inconel 600. Lap joints showed a mechanically jointed sound weld interface, and intermetallic compounds layer in the welds was not formed. Also, the formation of hook in advancing side, along the Inconel 600 alloy from SS 400, was effective to develop the mechanical properties. Particularly, Lap joint, in which Inconel 600 is located at advancing side, showed notably higher peel strength. Therefore, the application of FSW in lap joint between Inconel 600 and SS 400 can develop the mechanical properties, effectively.

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