Mechanical Properties of Friction-Stir Welded Titanium Joint

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ABSTRACT

The Commercial purity titanium (cp-Ti) plates with a 2 mm thickness, were butt-welded by friction-stir welding (FSW). Using a W alloy tool, FSW was performed at 200rpm and 50-300 mm/min. The mechanical properties of the joints were evaluated using tensile tests and Vickers micro-hardness tests. The microstructure was observed by optical microscopy (OM), field emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM). An electron back-scattering pattern (EBSP) technique was also used in the FE-SEM to clarify the crystallographic features of the microstructure. The tensile strength of joints significantly increases with the increasing welding speed because the grain size decrease and the dislocation density increases. The tensile strength of the specimen welded at 200 mm/min exceeds that of the base metal, and therefore the specimen fractured in the base metal during the tensile tests. However, the defects were formed in the specimen at 300 mm/min leading to decrease in tensile strength. The friction-stir welded cp-Ti microstructure consists of recrystallized grains with many dislocations, and the dislocation density increased with the increasing welding speed (decreasing heat input). For pure Al or IF steel, few dislocations are observed because the recovery occurs during cooling. Accordingly, the change in strength of the stir zone by varying heat inputs is greater for cp-Ti than for pure Al or IF steel.

INTRODUCTION

The friction-stir welds of low melting point materials such as Al[1-4], Mg[5-6], Cu[7] have been widely investigated since its development by The Welding Institute (TWI) in 1991. Recently, welding research activities on high melting point materials such as IF steel[8], and carbon steel[9-12], and stainless steel[13-16] have also started. However, there are few reports on welding of Ti[17-20] whose melting point is higher than that of steel. Lee[17] and Ramirez[18] succeeded in welding pure Ti plates (α-Ti) and jointed Ti-6Al-4V (α-β Ti), respectively. John[19] investigated the residual stress of FSWed Ti-6Al-4V and Reynolds[20] reported the texture of the FSWed Ti metal 21S (β Ti).

Ti is widely used in aerospace industry because it is not only a light weight and high strength material but also has superior heat resistance. Moreover, Ti is used in the sea water environment and for the petrochemistry due to its high corrosion resistance. In addition, Ti is also used for biomedical implants materials due to its good compatibility to the human body, and more applications are expected in the future. When FSW is performed for Ti alloys, a tool with a high temperature strength is necessary because of its excellent mechanical properties as in the previous study[17-18, 20]. An atmosphere control is also needed because Ti is very easily oxidized. The crystal structure of Ti is a hexagonal closed packed (hcp) structure under 880°C and a body centered cubic (bcc) structure over 880°C. A smaller number of slip systems in the hcp structure than in the bcc or fcc[20] structures may affect the deformation behavior, although friction-stir welding has been already used for Mg[5-6], a hcp metal.

In this study, the cp-Ti plates were successfully friction-stir welded. The effect of the welding conditions on the mechanical properties and microstructure of the joints is also investigates so that the best welding conditions could be determined.

EXPERIMENTAL PROCEDURE

Commercial purity Ti plates with 300 mm length, 50 mm width, and 2 mm thickness, were butt-welded by friction-stir welding. The chemical composition (wt %) of the base material was 0.007% C, 0.0013% B, 0.08% O, 0.004% N, 0.05% Fe and balance Ti. The ultimate tensile strength, 0.2% proof strength, elongation and hardness of base material were 418 MPa, 319 MPa, 39%, 146 Hv respectively. A W alloy tool with shoulder diameter of 15 mm, probe diameter of 6 mm, and probe length of 1.8 mm, was used at a rotation rate of 200 rpm. The welding speed was varied at 50-300 mm/min to control the heat input. During welding, an Ar gas was thrown around the tool for the atmosphere to prevent Ti from being oxidized.

After welding, an electrical discharge machine was used to form the tensile test specimens and cross-sections perpendicular to the welding direction for the hardness test. The configuration and size of the transverse tensile specimens were prepared according to Figure 1, where RS and AS denote the retreating side and advancing side, respectively. The type (a) in Fig.1 was used for all specimens, and type (b) was used for specimens 200 mm/min because the type (A) specimen was broken at the base metal during the tensile tests. The crosshead speed was 1 mm/min during the tensile tests. The Vickers micro hardnesses were measured under a load of 0.98 N for 15 seconds along the centerlines of the cross-section with a spacing of 0.5 mm.

The microstructure was observed by field emission scanning electron microscopy (FE-SEM), transmission electron microscopy (TEM). An electron back scattering pattern (EBSP) technipue was also used in the FE-SEM to clarify the crystallographic features of the microstructure. After cross-sections of the stir zone perpendicular to the welding direction were cut off for the EBSP, they were polished by emery papers and electrochemical polished using a twin jet electro polishing machine.

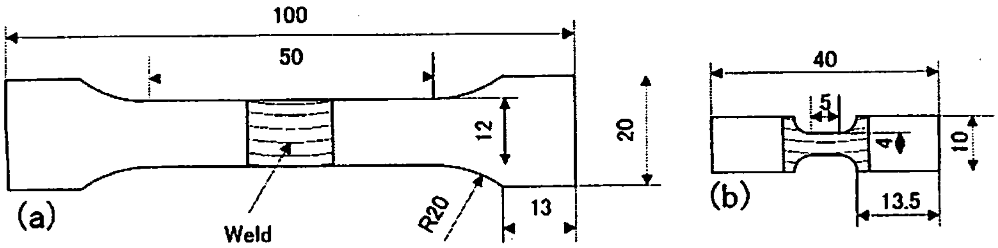

Figure 1. Configuration and size of the tensile tests used for (a) all specimens (b) only specimens welded at 200 mm/min.

RESULTS AND DISCUSSION

Tensile Strength of Joints

Figure 2 shows the tensile strength of FSWed cp-Ti at different welding speeds. Two specimens were tested under each condition. The broken line indicates the tensile strength of the base metal. The tensile strength increases with the increasing welding speed (decreasing heat input). Especially, the tensile strength of the joint exceeded that of the base metal at 200 mm/min. and therefore, the specimen was fractured in the base metal during the tensile tests. The other specimens were fractured in the stir zone during the tensile tests. However, the tensile strength of the specimens welded at 300 mm/min were decreased due to the defect formed at butt interface.

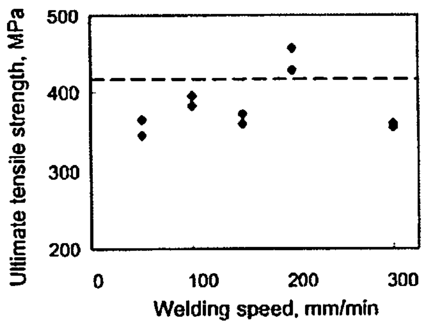

Fig. 2 Tensile strength of FSWed cp-Ti joints.

Hardness Distributions of Joints

Figure 3 shows the Vickers micro hardnesses along the centerlines on the cross-sections. The broken line indicates hardness of the base metal. In common with the tensile strength, the hardness increases with the increasing welding speed (decreasing heat input). The hardest value of about 200 Hv was obtained at 300 mm/min.

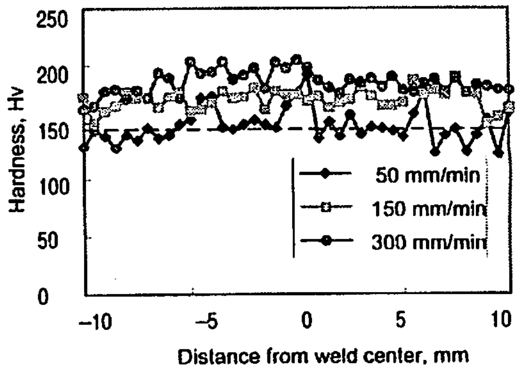

Figure 3. Hardness distribution of cp-Ti.

TEM observation

Figure 4 shows TEM bright field images at the center of stir zone. In common with the EBSP analysis, the crystal grains become finer with the increasing welding speed. Furthermore, the dislocation density increased with the increasing welding speed. It is considered that the dislocations at a high welding speed were not recognized as the low angle boundary due to the small difference in the orientation. This result clearly indicates that cp-Ti was dynamic recrestallized during welding by getting great deal of strain.

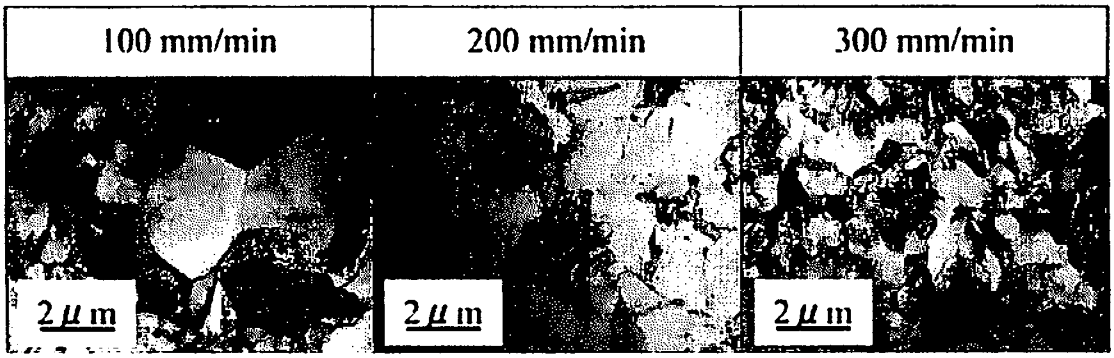

Figure 4. TEM photographs of FSWed cp-Ti

CONCLUSIONS

(1) Commercial purity Ti (cp-Ti) was successfully friction-stir welded at 50 mm/min to 300 mm/min. The mechanical properties of the FSWed cp-Ti increases with the increasing welding speed because the grain size decreases and the dislocation density increases due to the plastic deformation under the welding conditions. In this study, the highest tensile strength was obtained at 200 mm/min, because a small defect was formed at 300 mm/min.

(2) In the stir zone of FSWed, cp-Ti equiaxial grains with lots of dislocations were observed, indicating that dynamic recrestallization occurred.

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