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Joining phenomena and tensile strength of friction welded joint between pure titanium and low carbon steel

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ABSTRACT

This paper describes the effect of the friction welding condition on the joining phenomena and the tensile strength of friction welded joint between pure titanium (P-Ti) and low carbon steel (LCS). The adjacent region of the weld interface at the P-Ti side was intensely upsetting with accompanied large deformation of itself when the joint had sparkle at both applied friction pressures of 30 and 90 MPa, although that of the LCS side was hardly upset. The temperature of the whole weld interface at a friction pressure of 30 MPa reached to 1150 K or over at a friction time of 3.0 s or longer. However, the half radius and centreline portion temperatures of the weld interface at a friction pressure of 90 MPa was not reached to 1150 K, although the periphery portion of that was reached to its temperature. The central portion of the weld interface at a friction pressure of 90 MPa was deformed to a convex shape from the viewpoint of the P-Ti side, although that of 30 MPa remained almost flat after when the friction torque reached the initial peak. When the joint was made at a friction pressure of 30 MPa, a friction time of 3.0 s or longer, and a forge pressure of 270 MPa or higher, it achieved 100% joint efficiency and the P-Ti base metal fracture with no crack at the weld interface. However, many joints at friction times of 1.2 and 1.5 s fractured at the weld interface, although those achieved 100% joint efficiency, because whole weld interface temperature was below 1150 K. On the other hand, many joints at a friction pressure of 90 MPa with high forge pressure also fractured at the weld interface, although those achieved 100% joint efficiency, because the weld interface temperature at the half radius and periphery portions was below 1150 K. Those joints did not have the intermetallic compound layer at the weld interface. The difference of the fractured portion of the joint in both applied friction pressures was due to the difference between the maximum temperature at the weld interface during the friction process and the deformation amount of the LCS side caused by applied forge pressure. To obtain 100% joint efficiency with the P-Ti base metal fracture with no crack at the weld interface, the joint should be made with high forge pressure, low friction pressure, and with opportune friction time at which the temperature at whole weld interface reached around 1150 K.

1. Introduction

Titanium (Ti) and its alloys (referred to as Ti-system material) are well-known materials with highly attractive characteristics in terms of mechanical and metallurgical properties, e.g., high specific strength and excellent corrosion resistance. They are very widely used for the important structural components in aerospace vehicles, architecture, automobiles, and so on. Moreover, they are also useful as biomedical materials due to their low allergenic effect on the human body. On the other hand, fusion welding between Ti-system material and such other materials as steel, stainless steel, aluminium (Al), and copper (Cu) have poor mechanical properties due to the brittle intermetallic compound (IMC) layer produced at the joint interface [1,2]. Therefore, a welding process for between Ti-system material and other material joints which will result in less degradation of the mechanical and metallurgical properties of the joint is urgently required.

The solid state joining methods such as diffusion welding, friction welding, and friction stir welding, can be applied to join between Ti-system material and other materials. Some researchers have reported that the mechanical and metallurgical properties of the friction welded joints of Ti-system materials and various steels [3–5] or stainless steels [6–12] show desirable characteristics. For example, the friction welding condition for the joint which had the good tensile strength of pure Ti and stainless steel joint was individually demonstrated as following combinations: pure

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Ti and American Iron and Steel Institute (AISI) standard type 321 stainless steel of Lee et al. [6], pure Ti and AISI 304L stainless steel of Dey et al. [7], and pure Ti and AISI 316 stainless steel of Akbarimousavi et al. [8]. In addition, Fuji et al. [9–11] showed the results of the good tensile strength and bend ductility and improving point of those mechanical properties for pure Ti and AISI 304L stainless steel joint. Ochi et al. [12] also showed the results of X-ray diffraction analysis at the fractured surface of pure Ti and AISI 304 stainless steel joint. In those ways, some researchers have reported that the joining of Ti-system materials and stainless steels could be successfully achieved and a relatively good joint was obtained. On the other hand, research on the friction welding of the combination between Ti-system materials and various steels has been slight in comparison with that of Ti-system materials and stainless steels, because the friction weldability of the former combination differed with the latter combination [13]. In this case, the friction welding condition for the joint which had the good tensile strength of pure Ti and steel joint was individually showed: the combination between pure Ti and plain carbon steel of Hasui et al. [3] and pure Ti and the combination between medium carbon steel of Shinoda et al. [4]. Also, Meshram et al. [5] showed the results of SEM–EPMA analysis at the adjacent region of the weld interface for the joint of combination between Ti and Fe. However, the joining mechanism of dissimilar materials friction welding between Ti-system materials and various steels has not been fully clarified, so that the friction welding conditions for material combinations are determined by trial and error. That is, the joining mechanism of friction welding for dissimilar materials was not clarified, and the condition that the joint does not fracture at the weld interface when it will be satisfied with some state was not theoretically displayed. Furthermore, the joining mechanism of friction welding of dissimilar materials differs from that of similar materials, because mechanical properties such as the tensile strength and thermal properties such as the thermal conductivity are different in their combinations. To determine the friction welding conditions theoretically, it is very essential to clarify the joining phenomena and the joint mechanical properties. In particular, clarifications of the joining mechanism are strongly required concerning the weldability between the Ti-system materials and other material such as steel, because an expansion in the use of Ti-system material and steel is expected and widely used in various component parts.

In previous works [14–20], the authors clarified the joining mechanism during the friction welding process of similar material combinations which were various carbon steels or Al-system materials. Furthermore, the authors also clarified the joining mechanism during the friction welding process of some dissimilar material joints as following combinations: Al-system materials and pure Cu [21], Al-system materials and low carbon steel [22,23], Cu-system materials and low carbon steel [24,25], and pure Cu and pure Ti [21,26]. If combinations of dissimilar materials such as Ti-system materials and steel can be joined using the same method as that shown in previous reports [14–26], the joining mechanism will be clarified. In particular, to clarify the effect of the friction pressure on joining phenomena of the Ti-system materials and steel joint is strongly important, because the joining phenomena between pure Ti and pure Cu were affected by the friction pressure, and the difference of that was the yield stress for each material depended on the temperature in the friction process [26].

Based on the above background, the authors have been carrying out research to clarify the joining mechanism between dissimilar materials in the friction process. The authors investigate the joining phenomena during the friction process of friction welds between pure Ti and low carbon steel in the present work. The authors also demonstrate the results of the joining phenomena at various friction pressures. In addition, the authors show the joint tensile properties under various friction welding conditions, i.e. the effect of friction pressure, friction time, and forge pressure on the joint tensile strengths is clarified. Furthermore, the authors show the friction welding conditions for a joint that had the same tensile strength as the pure Ti base metal and fractured on the pure Ti side with no crack at the weld interface.

2. Experimental procedure

The materials used were commercially pure Ti (referred to as P-Ti) and low carbon steel (referred to as LCS) in 16 mm diameter rods. Although the chemical composition of the P-Ti was 0.001H–0.089O–0.006N–0.005C–0.038Fe in mass%, two kinds of P-Ti having slightly different tensile properties were used for this experiment because they had different production lots. The ultimate tensile strengths of the P-Ti were 401 and 379 MPa, the 0.2% yield strengths were 304 and 301 MPa, and the elongations were 35% and 39%, respectively. On the other hand, the chemical composition of LCS was 0.16C–0.45Mn–0.20Si–0.12P–0.18S in mass%, its ultimate tensile strength was 448 MPa, its yield strength was 291 MPa, and its elongation was 35%. Those materials were machined to 12 mm in diameter of the weld faying (contacting) surface. In addition, the temperature changes during the friction process at the centreline, half radius, and periphery portions of the 1.0 mm longitudinal direction from the weld faying surface were measured using the LCS specimen. In this connection, the sufficient data could be obtained in order to understand the temperature distribution of the radius direction at the weld interface, although the weld interface temperature was able to estimate as this temperature or higher. The details of the specimen shape for measuring temperature changes have been described in previous reports [22–27]. All weld faying surfaces of the specimens were polished with a surface grinding machine before joining to eliminate the effect of surface roughness on the joining behaviour. In this case, the centreline average height of the roughness of the P-Ti side specimen was about 0.34 μm, and the LCS side specimen was about 0.10 μm.

A continuous (direct) drive friction welding machine was used for the joining. This friction welding machine had three kind of welding method as follows.

(1) The conventional friction welding method that have the braking system when the friction time expired, for measuring the friction torque and the temperature change at the weld interface.
(2) The welding method that the fixed side specimen is simultaneously and forcibly separated from the rotating side specimen when the friction time expired, for observation of the transitional changes at the weld interface.
(3) The welding method that the relative speeds at the weld interface between both specimens simultaneously is decreased to zero when the friction time expired to prevent braking deformation during rotation stop, for observation of the cross-section at the weld interface region.

To clarify the joining phenomena during the friction process, the authors carried out three above welding methods. In particular, the experimental methods of (2) and (3) were used to obtain the joint without braking deformation. The details of these methods have been described in previous reports [14–26,28]. During friction welding operations, the friction speed and pressure were set to the following combinations: 27.5 s^{-1} (1650 rpm) for 30 MPa and 27.5 s^{-1} for 90 MPa. The forge pressure was applied at an identical friction pressure. The joining behaviour was recorded by a digital video camera. The friction torque was measured with a load-cell, and the temperatures were measured with a mineral insulated