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Technical Paper

Joining phenomena and tensile strength of friction welded joint between Ti–6Al–4V titanium alloy and low carbon steel

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ABSTRACT

Dissimilar metal joints (dissimilar joints) have such several advantages as high functionalities for the industrial usage. However, the dissimilar joints have severe problems such as generating the intermediate layer consisting of a brittle intermetallic compound (IMC interlayer) during welding process. Friction welding is very useful for making of dissimilar joint. This paper described the joining phenomena and the tensile strength of friction welded joint between titanium alloy (Ti–6Al–4V) and low carbon steel (LCS). The joining phenomena during the friction process such as joining behavior, friction torque, and temperature changes at the weld interface were measured. The effects of friction pressure, friction time and forge pressure on the joint strength were also investigated, and the metallurgical characteristics of joints were observed and analyzed. Then, the joint, which had 100% joint efficiency, the fracture on the LCS base metal with no crack at the weld interface, and no IMC interlayer on the weld interface, could be successfully achieved. It was suggested that the joint should be made with high friction pressure, opportune friction time to prevent generating of the IMC interlayer, and with high forge pressure in order to achieve completely joining of the weld interface.

1. Introduction

Titanium (Ti) and its alloys (referred to as Ti-system material) are well-known materials, and those materials are provided with highly attractive characteristics in terms of the mechanical and metallurgical properties, e.g., high specific strength and excellent corrosion resistance. To use Ti-system materials for various structures, it is necessary to join. However, a welding of Ti-system materials is not easy since the weld zone of the joint will have such defect as a blowhole or crack on account of Ti-system materials intensely react with O_2 or N_2 under high temperature condition [1]. Specifically, a fusion welding between Ti-system materials and such other materials as carbon steel, stainless steel, aluminum (Al), and copper (Cu) has poor mechanical properties owing to a brittle intermediate layer consisting of intermetallic compound (IMC interlayer) produced on the joint interface. Therefore, a welding process is urgently required, so that will reduce the degradation of the mechanical and metallurgical properties of the joints.

Solid state joining methods such as diffusion welding, friction welding, and friction stir welding can be applied to join between Ti-system materials and other materials. In particular, friction welding is very useful for joining of a combination with dissimilar materials, and this welding method is easily automated for the welding process. This welding method has also several advantages over fusion welding specifically high energy efficiency, narrower heat affected zone (HAZ), and low welding cost [2–4]. It was reported that the mechanical and metallurgical properties of joints between pure Ti and stainless steels by friction welding showed desirable characteristics. For example, Ochi et al. [5] studied the mechanical properties of joints between pure Ti and American Iron and Steel Institute (AISI) standard type 304 stainless steel, and Fuji et al. [6] described those characteristics between pure Ti and AISI 304L stainless steel. Dey et al. [7] explained the properties of joints between pure Ti and AISI 304L stainless steel in boiling nitric acid condition. Akbari-mousavi et al. [8] investigated the characteristics of joints between pure Ti and AISI 316 stainless steel, and Lee et al. [9] investigated the microstructures and mechanical properties between pure Ti and AISI 321 stainless steel, respectively. In those ways, several researchers have reported that the joining of pure Ti and various stainless steels could be successfully achieved and a relatively good joint was obtained. In contrast, a carbon steel and stainless steel

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has different weldability [10]. Few research on friction welding of a combination between pure Ti and various carbon steels have been performed in comparison with the joint between pure Ti and various stainless steels, although steel is generally being known as an inexpensive material than stainless steel. The friction welding condition for joints which had the good tensile strength and some metallurgical properties were showed of following combinations: pure Ti and plain carbon steel by Hasui et al. [11], pure Ti and medium carbon steel by Shinoda et al. [12], and pure Ti and pure Fe by Meshram et al. [13]. Furthermore, few research on friction welding between Ti alloy and various steels, which included stainless steel, have been also studied in comparison with the joint between pure Ti and various steels. Specifically, Li et al. [14] described the characteristics of joint between Ti alloy of Ti–6Al–4V and AISI 321 stainless steel. Also, Kumar et al. [15] demonstrated the characteristics of joints between Ti–6Al–4V Ti-alloy and AISI 304 stainless steel with Cu insert metal, and Dong et al. [16] investigated the properties of joints between TC4 Ti-alloy and 40Cr steel with post-weld heat treatment condition. Nevertheless, the joining mechanism of friction welding between Ti alloy and various steels has not been fully clarified, so that the friction welding conditions for material combinations are determined by trial and error. In particular, the joining mechanism for Ti alloy and various steels differs from the mechanism of pure Ti and various steels, since the mechanical properties such as the tensile strength and the thermal properties such as the thermal conductivity are different in their combinations. To determine the friction welding conditions theoretically, the weld between Ti alloy and various steels by experiment is very essential to clarify the joining phenomena and the mechanical properties of joints. It is particularly suited to use for the joint of this combination as some structural applications in various engineering fields of automotive and aerospace industries, because the use of steel can be reduced [17]. Thus, to clarify the joining mechanism are strongly required concerning the weldability between the Ti alloy and carbon steel for the reason that an expansion in the use of Ti alloy is expected and widely used in various component parts.

In the previous work, the joining mechanism during the friction welding process of commercially pure Ti (CP-Ti) and low carbon steel (LCS) were clarified so that were described by the authors [18]. The authors also demonstrated the friction welding condition for the joint fractured in the CP-Ti base metal with no crack at the weld interface. Nevertheless, it is difficult to estimate the friction welding condition for obtaining good joint between Ti alloy and LCS by using the results of CP-Ti and LCS, because the mechanical properties of CP-Ti differ with the properties of Ti alloys and that will be described later. Hence, to weld Ti alloy and LCS by experiment should be necessary for clarification of the joining mechanism. Moreover, it is conceivable that the results of the joint between Ti alloy and LCS becomes the selection guidelines of the friction welding conditions for making good joint between Ti alloy and various carbon steels with clarifying of the effect of the carbon contents in carbon steels on the mechanical properties for joints. If the joining mechanism for combinations between Ti alloy and steel can be joined using the same experimental method as shown in the preceding report [18], it will be clarified. Then, the establishing of the friction welding condition to the joint of material combination in this study, which will be not fractured from the weld interface with no crack, will be theoretically possible.

Based on the above background, the authors have been carrying out research to clarify the joining mechanism of friction welds for the combination of dissimilar materials. In this report, the authors investigate the joining phenomena during the friction process of friction welds between Ti–6Al–4V of a typical Ti alloy and LCS in the present work, since Ti–6Al–4V has highest tensile strength. The authors also demonstrate the results of the mechanical and metallurgical properties of the joint. In addition, the authors show the friction welding conditions for joints which had the same tensile strength as that of the LCS base metal as well as the fracture from its metal side with no crack at the weld interface. The authors also show the difference points of the joint between Ti–6Al–4V and LCS (referred to as Ti–6Al–4V/LCS joint) in comparison with the joint between CP-Ti and LCS (referred to as CP-Ti/LCS joint) for obtaining good joint.

2. Experimental procedure

The materials used were Ti–6Al–4V and LCS rods of the diameter of 16 mm. Two kinds of Ti–6Al–4V and LCS having slightly different tensile properties were used for this experiment because those materials were purchased at different times. Chemical compositions, the ultimate tensile strength (UTS), the yield strength (YS) including 0.2% YS, and the elongation (El.) for used materials are shown in Table 1. In this connection, UTS and 0.2% YS of the Ti–6Al–4V base metal were higher than those of CP-Ti base metal. Both rods were used for this experiment as received condition. Those rods were machined to 12 mm in diameter of the weld faying (contacting) surface. In addition, the temperature changes during the friction process at the centerline, half radius, and periphery portions of 1.0 mm in the longitudinal direction from the weld faying surface were measured by using the LCS side specimen, since the deformation of the LCS side was smaller than that of the Ti–6Al–4V side (this result will be demonstrated later). The details of the specimen shape for measuring the temperature changes have been explained in the preceding report [18]. All weld faying surfaces of friction welding specimens were polished with a surface grinding machine before joining to reduce the effect of surface roughness on the joint mechanical properties [19]. Incidentally, it has been confirmed that the experimental results by using two kinds of materials did not have difference for the joining phenomena and the mechanical properties of joints.

A continuous (direct) drive friction welding machine was used for the joining. During the friction welding operations, the friction welding condition was set to the following combinations: a friction speed of 27.5 s^{-1} (1650 rpm), a range of friction pressures from 30 to 150 MPa, a range of friction times from 0.4 to 30.0 s, a range of forge pressures from 30 to 330 MPa, and a forge time of 6.0 s. The detailed combination of each friction welding parameters is shown in Table 2. In this study, the authors carried out two experimental methods.

(1) The friction torque was measured with a load-cell. Also, the temperatures were measured with a mineral insulated thermocouple composed with a chromel–alumel, and those thermocouples were inserted to all holes of the LCS specimen. The friction torque and the temperature were recorded with a personal computer through an A/D converter with a sampling time of 0.001 s.
(2) The welding method, of which the relative speed at the weld interface between both specimens simultaneously is decreased to zero when the friction time expired to prevent braking deformation during rotation stop, was performed. In particular, this experimental method was used to obtain the joint with no braking deformation.

All joint tensile test specimens were machined to 12 mm in diameter and 84 mm in parallel length. That is, all flash (burr or collar), which was exhausted from the weld interface during the friction welding process, were removed from the joint to make tensile test specimens. Then, the joint tensile test was performed with as-welded condition at room temperature. Incidentally, the shapes and dimensions of the joint tensile test specimen were in