In-situ observation of interlayer growth during heat treatment of pure titanium and pure aluminium friction weld joint

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ABSTRACT

The growth of intermediate layer (layer) consisted with intermetallic compound phase of pure titanium (Ti) and pure aluminium (Al) friction weld joint heated at 853K for up to 173ks (580oC-48H) was clarified by in-situ (direct) and continuously observation method with a high temperature optical microscope. The followings are concluded. The layer grew from Al substrate to Ti one, and neither linear nor parabolic time-dependence could be applied to the rate of layer growth. The layer growth stopped for a while (for several hours) after heating of approximately every 36ks (10H). That is, several plateaus appeared during heat treatment. It can be though that nucleation and growth of nuclei of Al-Ti binary intermetallic phase are necessary for layer growth. The layer growing rate of the interlayer of pure Ti and highly pure Al joint was faster than that of pure Ti and commercially pure Al joint. This is due to silicone content in Al base metal. There was slight difference of the layer growing rate as for the locations along the radius of the joint and as for friction time.

INTRODUCTION

Dissimilar welding operations have several severe problems in the industrial usage. One of these occurs when dissimilar welding joints are operated at high temperature environment. That is, an intermediate layer (hereafter called as layer) consisting of brittle intermetallic compound phases grows at the interface of dissimilar joint, and it gives a detrimental damage on the mechanical and metallurgical properties of the joint. There were a lot of and wide range of studies investigated for the diffusion phenomena and the layer growth at the weld interface of dissimilar weld joints or diffusion couples up to date [1-11]. Generally speaking, the relation between the rate of layer growth and heating time is according to parabolic time-dependence, i.e. square root relation when the layer growth occurs due to mutual diffusion of each element in both substrates joined. However the parabolic theory cannot be applied to some combinations of dissimilar joints. For example, it could not be fit to the relation of the layer width versus heating time of a diffusion couple between pure titanium (Ti) and pure aluminium (Al) [1,2,8-11]. This reason is due to the experimental method; most of all researches were carried out to observe the layer growth at room temperature, i.e. specimens were cooled after heat treatment. Therefore, most of the data are intermittent (discontinuous), so that true diffusion phenomena and layer growth by long heating could not be clarified for dissimilar joints because of fracture occurring in layers.

Taking these backgrounds into considerations, the author has studied for the layer growth of dissimilar friction-welded joints by in-situ (direct) and continuously observation method with a high temperature microscope system that is a more fruitful approach. The present report will describe the phenomena on the layer growth of pure Ti and pure Al friction-welded joint.

EXPERIMENTAL PROCEDURE

The material used for the experiment was commercially pure Ti. Commercially pure Al with 0.12%Si and highly pure Al with 0.01%Si were used as foreign metals to examine the effect of silicone (Si) in Al substrates on layer growth. All materials were 30mm in diameter to clarify the effect of the location along joint radius on layer growth. A Brake type friction welding machine was carried out for joining. Polishing with a buff was carried out to finish the faying (contacting) surface of all materials. During friction welding operations, the following conditions were kept constant: rotational speed was 25revolution per second (1500revolution per minute); friction pressure was 50MPa, upsetting pressure was 50MPa; and upsetting time was 6s. To change the width of the layer generating during friction operations, friction times (hereafter called as FT) were 2s and 7s.

The specimens with 3mm in diameter and 3mm in thickness for in-situ and continuous observation were extracted perpendicular to as-welded joint interface including an interface by a Wire-Electric Discharge Machining. The locations of the specimens extracted were the centerline (joint axis) and 5mm from outer surface (periphery) of joints. Figure 1 shows the specimen preparation method. Each specimen was inserted into the sample holder of a high temperature microscope and heat treated in vacuum environment. Heating temperature was 853K (580oC), and heating time was up to approximately 172.8ks (48H). An optical microscope in the magnification of 400times was used to observe layer width, and the width was recorded with a digital VTR recorder continuously. Figure 2 schematically shows the in-situ observation system. The layer width was measured every 3.6ks (1H) by a personnel computer. SEM analysis was carried out to analyze the chemical composition at interface region. The heat cycles during friction welding were measured.

RESULTS AND DISCUSSION

Figure 3 shows an example of the optical microstructure at the interface of A-joint heated at 853K (580oC) for 720ks (200H). The joint was welded with FT of 2s. The layer almost grew from Al substrate to Ti one. The interface between the layer and Ti substrate was smooth whilst it was irregular between the layer and Al one. It was assumed that the microstructure of the layer heated after 720ks was composed with Al3Ti phase by SEM-EDS analysis.

Figure 4 shows the relation between the heating time and the layer width at the interface of centerline portion of A- and B-joints welded with a friction time of 2s. In this case, Fig.4 (a) shows the result by using linear scale for heating time (horizontal axis). On the other hand, Fig.4 (b) shows that by square root scale. The layer growing rates were depended on neither parabolic nor linear relation for heating time. The layer almost saturated up to approximately 80microns in width for both joints. It is most important to note that the layer growth stopped for a while (several hours) on approximately every 36ks (10H). That is, several plateaus showing as "P" in Figures 3 (a) and (b) appeared. The layer growing rate of B-joint was faster than that of A-joint.

Figure 5 shows the relation between heating time and layer growth at periphery portion of both joints with FT of 2s by using linear scale for heating time. The layer growth was also depended on neither parabolic nor linear relation for heating time. The layer almost saturated up to approximately 70microns in width for A-joint, and 85microns for B-joint, respectively. The layer growth stopped (plateau region) for several hours on approximately every 36ks (10H). The layer growing rate of B-joint was also faster than that of A-joint. These results were same as centerline portion (Fig3 (a)). While the layer saturated time at periphery portion is approximately 20hours, which is about 40hours at centerline of the joint. That is, the layer growing rates at periphery is little faster than those at center portion.

Figure 6 shows the relation between heating time and layer growth at periphery portion of both joints with FT of 7s by using linear scale for heating time. The layer growth was also depended on neither parabolic nor linear relation for heating time. The layer almost saturated up to approximately 75microns in width for A-joint, and 100microns for B-joint, respectively. The plateau regions are also observed. The layer growing rate of B-joint was also faster than that of A-joint. These results were similar to the centerline portion of the joint with FT of 2s (Fig.4 (a)).

Figure 7 shows the relation between the layer width by every 3.6ks (1H) and heating time at centerline of the joint welded with FT of 2s. It can be seen that the rate of layer growth for 1 hour decreased when heating time increased. This result indicates that it takes longer time for element to diffuse through interface as increasing layer width. Furthermore, the layer growing rate dropped to zero at approximately every 36ks (10H). This is corresponded to the plateau region.

Throughout this experiment, the layer growing rate was depended on neither parabolic nor linear time-dependence relation, and several plateaus occurred during layer growing. The author has clarified that the plateau occurred in the layer growth of Al/Cu and Al/Fe dissimilar friction weld joints. These reasons might be thought as follows. The growth of intermetallic compound phase (IMC) is not simply depended on the mutual diffusion of both elements (Ti and Al) through interface or layer. The author had already reported that, in case of pure Ti and pure Al friction weld joint, the layer of IMC grew according to two steps [11]. That is, nucleation of IMC occurred at the first step, and nuclei of IMC coarsened at the second step. Some content of each element is essential to make nuclei of IMC. The interface between IMC and Ti substrate is irregular as it can be pointed out in Fig.3. The crystals are smaller than those between IMC and Al substrate. Most of researchers calculated and reported for the activation energy for the layer growth at the interface of dissimilar weld joints or diffusion couples in convenience. However, the conventional activation energy cannot express the phenomena of layer growth consisted with IMC precisely. This is a very important and worthful conclusion.

The layer growing rate of B-joint was faster than that of A-joint. This is due to Si in commercially pure Al substrate, i.e. the Si accumulated between the layer and Ti substrate, and Si layer avoided the diffusion of Al element from Al substrate to Ti one as a barrier [10,11].

It can be estimated that microstructure and strain, generated by the heat cycle during friction welding operation, affect the layer growth. However, there was slight difference of the layer growing rate as locations along radius direction i.e. centerline and periphery (Fig.4 (a) and Fig.5) and as friction times of 2s and 7s (Fig.4(a) and Fig.6). The author had been clarified that several 10nm wide IMC layer occurs at the interface of pure Ti and pure Al friction weld joint in as-welded condition by TEM observation [11], and its width increased from several 10nm to more than 100nm with increasing of FT. However, the initial width of IMC cannot affect the layer growing rate during post-weld heat treatment.

CONCLUSIONS

The growth of intermediate layer (layer) consisted with intermetallic compound phase of pure Ti and pure Al friction weld joint heated at 853K for up to 173ks (580oC-48H) was clarified by in-situ (direct) and continuously observation method with a high temperature optical microscope. The followings are concluded.

(1) The layer grew from Al substrate to Ti one.

(2) Neither linear nor parabolic time-dependence relation could be applied to the layer growing rate, and the layer growth stopped for several hours on heating of approximately every 36ks (10H). These are due to nucleation and growth of nuclei of Al-Ti binary intermetallic phases at the interface.

(3) The layer growing rate of pure Ti and highly pure Al joint was faster than that of pure Ti and commercially pure Al joint. This was due to silicone in Al substrate.

(4) There was slight difference of the layer growing rate between at the centerline and at the periphery portions of the joint and friction time of 2s and 7s.

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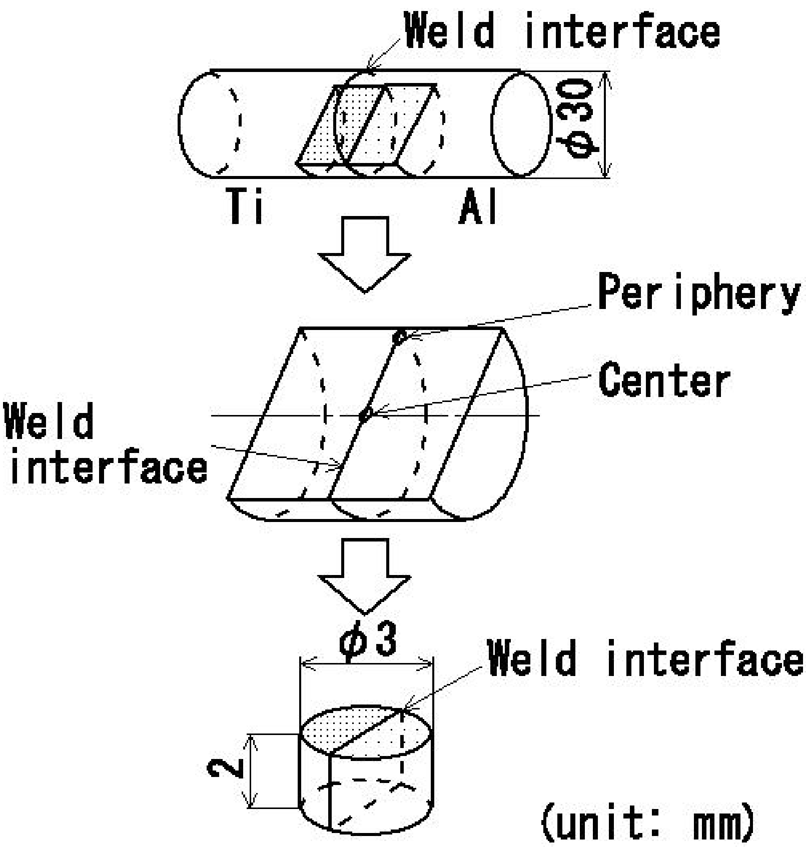

Fig.1 Specimen preparation method for in situ observation.

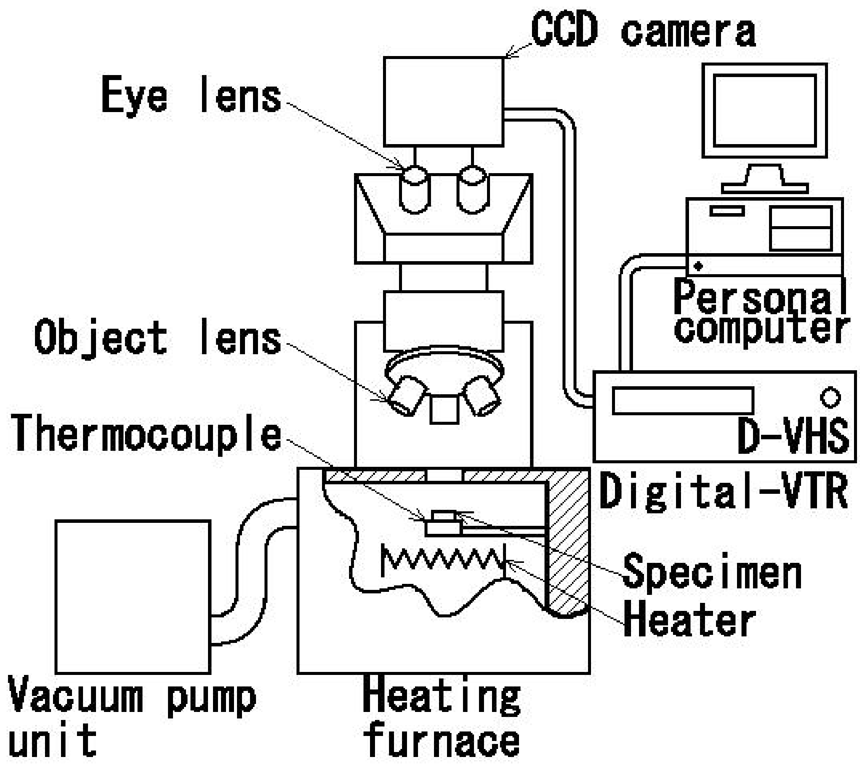

Fig.2 Schematic illustration of in situ observation system
(CCD charge coupled device; VTR video tape recorder.

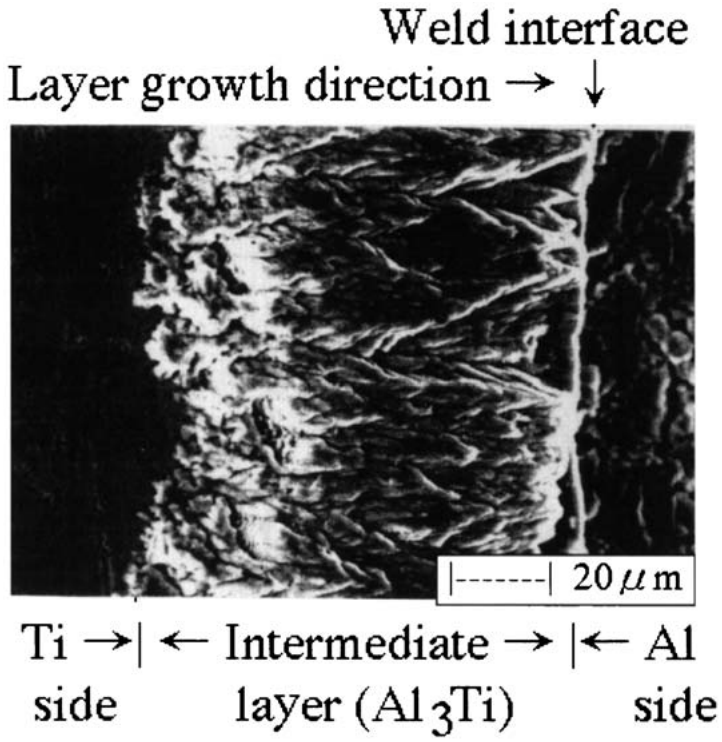

Fig.3 Example of microstructure of interlayer at interface of pure Ti – commercially pure Al friction weld heated at 580uC for 200 h (optical).

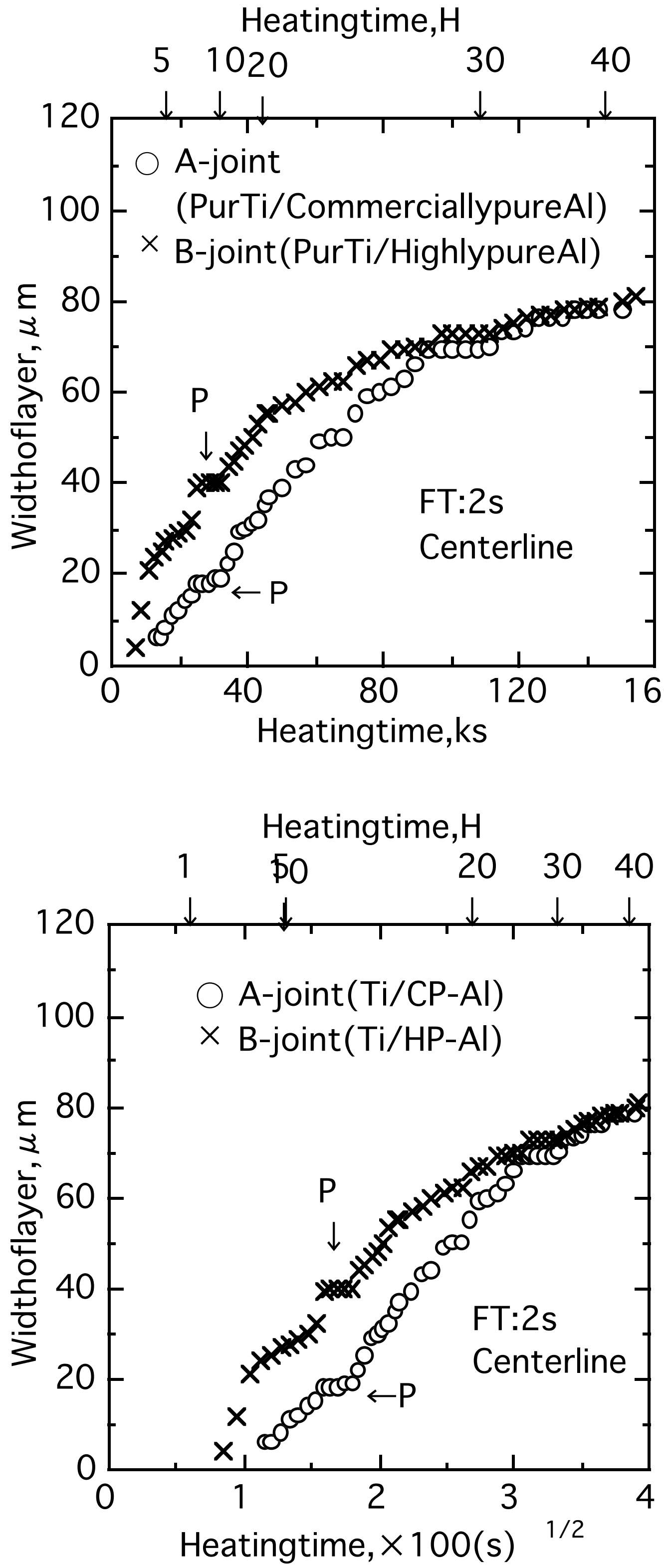

Fig.4 Relationship between heating time and layer width at interface of centreline region of pure Ti – commercially pure Al joint (A joint) and pure Ti – highly pure Al joint (B joint) welded with friction time (FT) of 2 s: results are shown using a linear scale and b square root scale for heating time (horizontal axis).

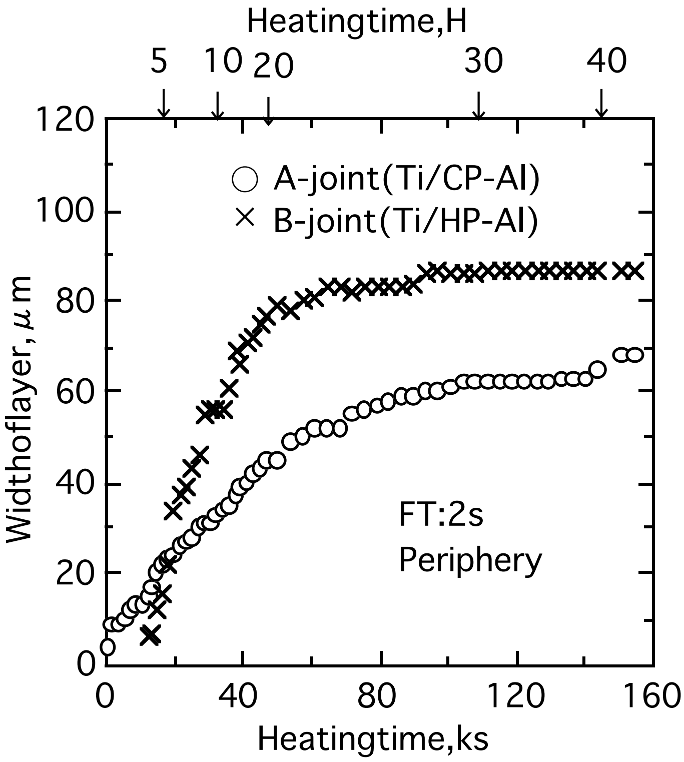

Fig.5 Relationship between heating time and layer growth at periphery of A and B joints welded with FT of 2 s, using linear scale for heating time.

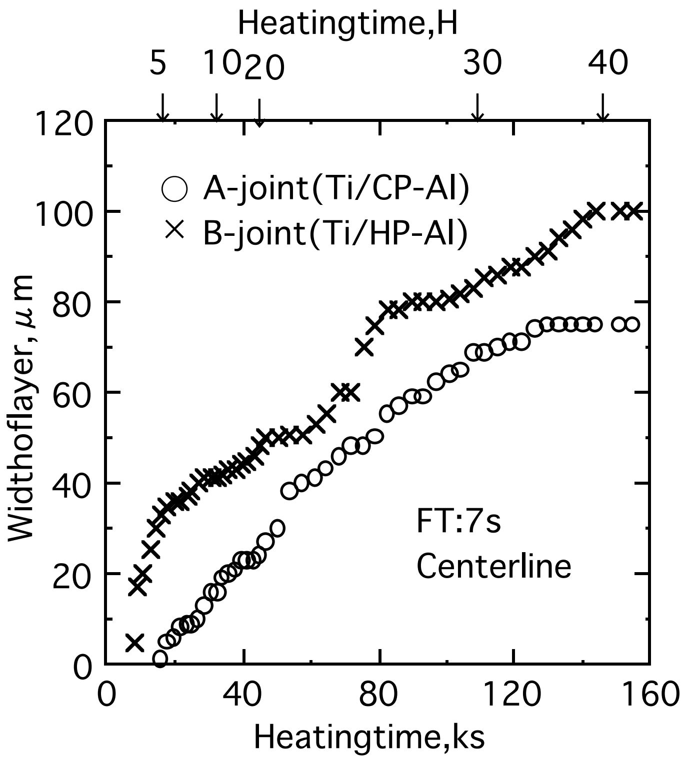

Fig.6 Relationship between heating time and layer growth at centreline of A and B joints welded with FT of 7 s, using linear scale for heating time.

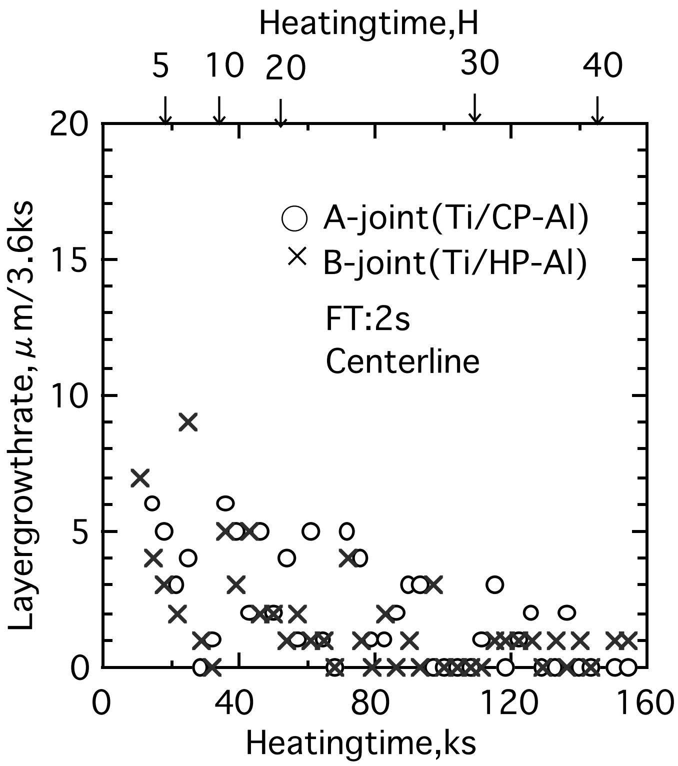

Fig.7 Relationship between increase in layer thickness per 3.6 ks (1 h) and heating time at centreline of A joint welded with FT of 2 s.