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Investigation of fracture for friction welded joint between pure nickel and pure aluminium with post-weld heat treatment

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ABSTRACT

The present paper described the investigation of the fracture of friction welded joint between pure nickel (Ni) and pure aluminium (Al) with post-weld heat treatment (PWHT). Most of joints autogenously fractured from the adjacent portion of the intermediate layer (interlayer) consisting of intermetallic compound (IMC) on the weld interface due to growing of that after long heating time during the cooling process after PWHT. The IMC interlayer was composed with mainly NiAl, and that grew at the weld interface with PWHT. The joint fracture temperature increased with increasing width of the IMC interlayer in the axial direction of the joint. That is, the fracture of the joint occurred at the interface between NiAl layer and Al base metal. The fractured surface was covered with a little Ni_2Al_3 and/or $NiAl_3$, and that was like as disbonding. Furthermore, when the width of the IMC interlayer was smaller than approximately 40 μm, the joint fracture temperature of the joint was under about 470 K. However, when the width of the IMC interlayer exceeded 50 μm, the joint fracture temperature drastically increased up to about 800 K. Hence, it was able to be estimate that the joint fracture temperature increased with increasing width of the IMC interlayer. Therefore, one of the main reasons for the fracture of the joint could be concluded as remarkable decreasing of the bonding strength between NiAl layer and Al base metal, which was produced with PWHT.

1. Introduction

Dissimilar welding operations have several severe problems in industrial usage. First of all, one problem will occur when the dissimilar metal joints (referred to as dissimilar joints) are welded by using fusion welding process which conventionally produce intermediate layer (interlayer) consisting of brittle intermetallic compound (IMC) at the weld interface of both base metals to be joined. IMC interlayers usually give detrimental damages on mechanical and metallurgical properties of dissimilar joints [1]. Generally speaking, solid state joining process, e.g. diffusion joining or friction welding can minimize IMC generation. Many researchers have reported that the dissimilar joints were able to easily weld by solid state joining process [2–6]. However, another problem will occur when joints are operated at elevated temperature environment or after post-weld heat treatment (referred to as PWHT) condition, although it differed with similar friction welded joint [7,8]. That is, IMC interlayers at the weld interface of the dissimilar joint will grow during operation, so that will be giving fatal damage to equipments. For example, not so much research has been reported for PWHT conditions on the mechanical and metallurgical properties of the joint as following combinations: low alloy steel and austenitic stainless steel by Murti and Sundaresan [9], aluminium (Al) alloy and austenitic stainless steel by Ochi et al. [10], and nickel (Ni) based superalloys dissimilar combinations joints by Li et al. [11]. Furthermore, a few researches were reported for the fracture behaviour of dissimilar joints welded by solid state joining process [12–14]. However, PWHT condition for dissimilar friction welding has not been fully clarified. To utilize of dissimilar friction welded joint for industrial usage, it is very essential to clarify the joint strength and fractured portion of that under various PWHT conditions.

In previous works, some of the authors were investigated as basic research that the effect of friction welding conditions on the mechanical (mainly tensile strength) and metallurgical properties of the joint with various PWHT conditions in addition to as-welded condition up to now for dissimilar friction welded joints as following combinations: pure titanium (Ti) and austenitic stainless steel [15,16], pure Ti and pure Al [17–20], pure Ti and Al alloys [21–24], pure Ti and pure Ni [25], Al alloys and low alloy steel (LCS) [26], pure Al and LCS [27], and brass and LCS [28]. In particular, IMC

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interlayer of friction welded joint between pure Ti and austenitic stainless steel with as-welded condition was composed of sub-micron order, of which was clarified [15]. Hence, even though the friction welding process can minimize the generation of IMC interlayers between dissimilar metals, it was able to estimate that IMC interlayer will be affected by PWHT condition for the joint fracture. Furthermore, some of the authors also clarified the effect of friction welding conditions and PWHT on the joint mechanical and metallurgical properties of friction welded joint between pure Ni and pure Al [29]. From many combinations of the dissimilar joints, the reasons why the combination of pure Ni and pure Al was selected in that report [29] are as follows: both metals have a lot of superior mechanical and metallurgical properties with them, and several IMC interlayers will occur at the weld interface during PWHT. Therefore, metallurgical analysis is relatively easier than another combination of dissimilar metals. However, the detail fracture mechanism of the joint was not clarified in the previous report [29]. That is, the precise fractured portion and the timing of the fracture for friction welded joint between pure Ni and pure Al with PWHT must be investigated, because IMC interlayers at the weld interface of the dissimilar joint will grow. In particular, it is very useful to clarify the fractured portion of the joint to design of dissimilar friction welded joint.

According to the back ground described above, the authors have been carrying out research to clarify the fracture mechanism of dissimilar friction welded joint with PWHT. The authors investigate in the present work into the fracture of friction welded joints between pure Ni and pure Al under various PWHT conditions. The authors also will clarify the composition of IMC interlayer and its growing mechanism during PWHT. Then, the authors will present about how the fracture will occur at the adjacent region of the weld interface of friction welded joint between pure Ni and pure Al during the cooling process after PWHT.

2. Experimental procedure

2.1. Materials used and friction welding condition

Commercially pure Ni and pure Al base metals of 16 mm diameter round bars were used throughout in this experiment. Ni bar had the chemical compositions of 0.02%Fe–0.01%Al–Ni in balance (mass%), and that was supplied with an ultimate tensile strength of 515 MPa, a yield strength of 476 MPa, and an elongation of 14.5%, respectively. Al bar had the chemical compositions of 0.12%Si–0.54%Fe–Al in balance (mass%), and that was supplied with an ultimate tensile strength of 91 MPa, a 0.2% yield strength of 46 MPa, and an elongation of 47.0%, respectively. Both round bars were used for this experiment as received condition. Ni bar was machined to 12 mm in diameter of the weld faying (contacting) surface, and Al bar was used with received diameter. All weld faying surfaces were polished with a buff before joining in order to minimize the effect of its surface roughness on the joint properties [17,30,31].

A continuous (direct) drive friction welding machine was employed for joining. According to our previous research [29], the friction welding conditions that can achieve the joint efficiency was more than 100%, i.e. the joint fractured in Al base metal by tensile test of the joint with as-welded condition. They were as follows: a friction speed was 25 s^{-1} (1500 rpm), a friction pressure was 20 MPa, a friction time was 0.5 s, a forge pressure was 50 MPa, and a forge time was more than 6.0 s.

2.2. Fracture test of joint and PWHT condition

The specimen of the joint was machined to 8 mm in diameter in the parallel length portion for fracture test equipment as shown in Fig. 1. In this case, the moment that applied to the outer surface (outer surface moment with self weight of Ni part) at the weld interface of the joint was 2 Nmm. In this connection, the joint fractured in the furnace during PWHT with large outer surface moment at the weld interface when the effect of the outer surface moment was investigated in the pre-experiment (data not shown due to space limitations). Hence, the outer surface moment was determined to 2 Nmm, because that value had a negligible effect for joint fracture in this study.

Fig. 2 shows the fracture test equipment with a vacuum furnace that carried out with PWHT in order to progress with IMC interlayer growth. The joint (specimen) was set on the spacer that was put into a vacuum furnace, the Ni side of it was set to like as cantilever. Furthermore, two kinds of thermocouples were attached to Ni and Al base metals, respectively, for fracture test. One thermocouple was used for measuring temperature of the joint, and another was for measuring occurrence of fracture. The former thermocouple was connected to the large diameter part of the joint, and the latter one was connected to the 8 mm diameter part of that. When the joint autogenously fractured from the adjacent portion of the weld interface, the latter thermocouple indicated its temperature and timing with a breaking of measuring current. The heating temperatures were at 773, 823, and 873 K, and the heating times were from 21.6 to 604.8 ks (6–168 h) under the vacuum environment of approximately 0.1 Pa (7.5×10^{-4} torr). After PWHT, the joint was cooled by furnace cooling, i.e. the heating was stopped. The joint fracture temperature was measured with the thermocouple as described above. Thereafter, the joint was taken out from the furnace. Hereafter calls as "773 K–21.6 ks joint", for example, to the joint heated at 773 K for 21.6 ks.

After fracture testing, the metallurgical test was carried out at the cross-section of autogenously fractured joint and its fractured surfaces by a SEM attached with an EDS. In this case, some samples for SEM observation of the cross-sections of the joints were mounted into resin for ease of handling, and those were analysed. Furthermore, the fractured surfaces of the joints were analysed using X-ray diffraction analysis.

3. Results

3.1. Relationship between temperature and elapsed time from cooling start during cooling process

Fig. 3 shows the relationship between the temperature of the joint and the elapsed time from cooling start during the cooling process after PWHT at various heating temperatures. That is, this result showed the cooling temperature curve of the joint at various heating temperatures. In case of the cooling process start from a heating temperature of 773 K as shown in Fig. 3a, the joint with 604.6 ks fractured at 679 K, and that with 86.4 ks fractured at 593 and 533 K, respectively. However, the joint with under 43.2 ks did not fracture during the furnace cooling process although that fractured when it was taken out from the furnace. On the other hand, the joint with 86.4 ks fractured at 769, 739, and 724 K when that was cooled from a heating temperature of 823 K, as shown in Fig. 3b. The joints with 604.8 ks also fractured at 765, 714, and 640 K, respectively. In addition, the joint with

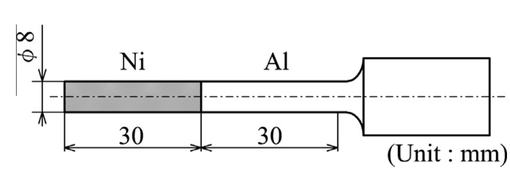

Fig. 1. Dimension of pure Ni and pure Al friction weld joint for fracture test.