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

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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.

Keywords: Welding, Heat treatments, Intermetallics, Fracture

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 et al. [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 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].

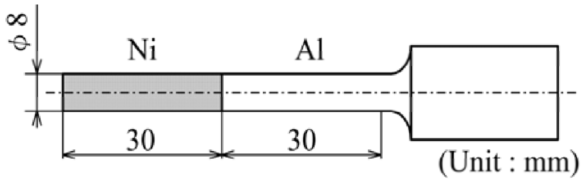


Fig. 1 Dimension of pure Ni and pure Al friction weld joint for fracture test.

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

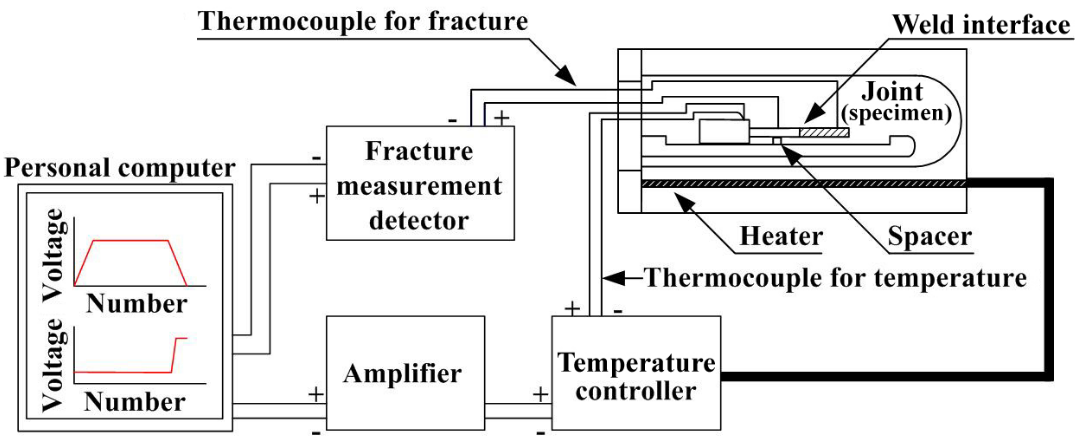


Fig. 2 Schematic illustration of joint fracture test equipment.

negligible effect for joint fracture in this study.

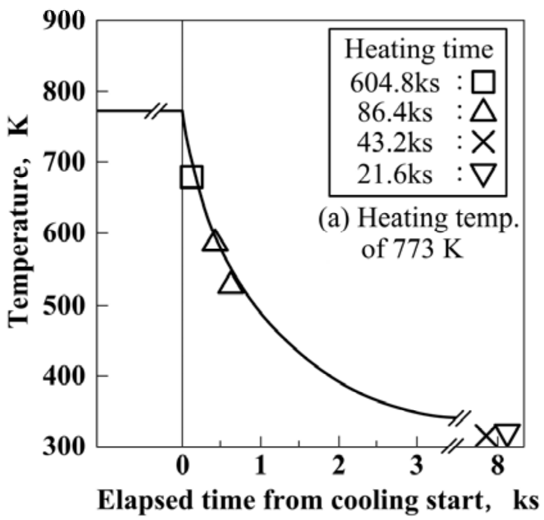
Figure 2 shows the fracture test equipment with a vacuum furnace that carried out with PWHT in order to progress with IMC interlayer growth. The joint (specimen) was set on the spacer that was put into a vacuum furnace, the Ni side of it was set to like as cantilever. Furthermore, two kinds of thermocouples 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 to 168 hours) 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.

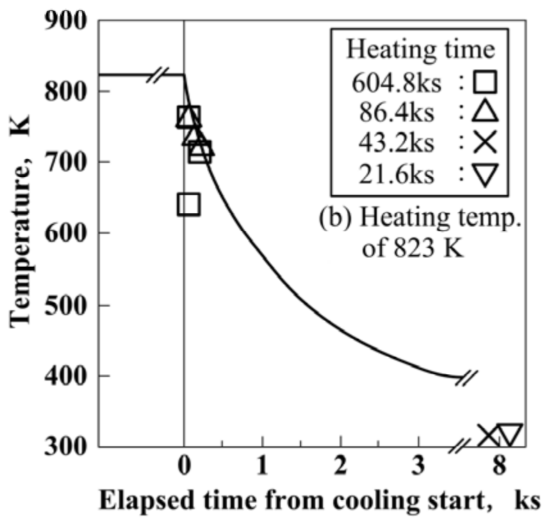
3. Results

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

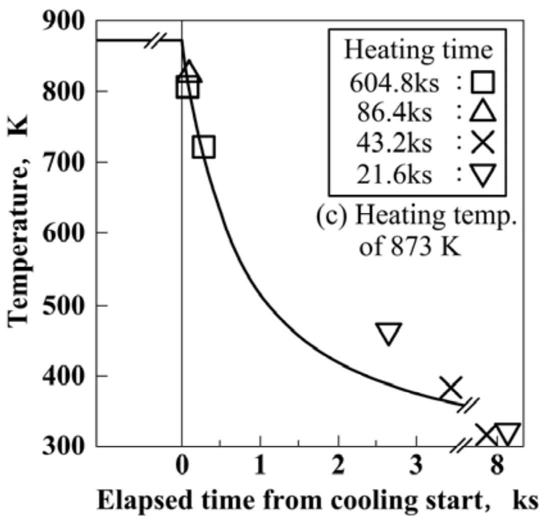
Figure 3 shows the relationship between the



(a) Heating temperature of 773 K



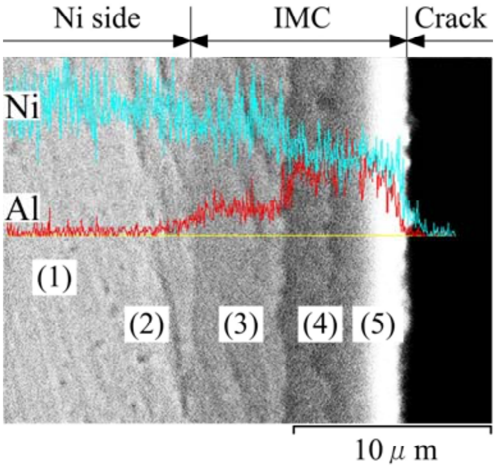
(b) Heating temperature of 823 K



(c) Heating temperature of 873 K

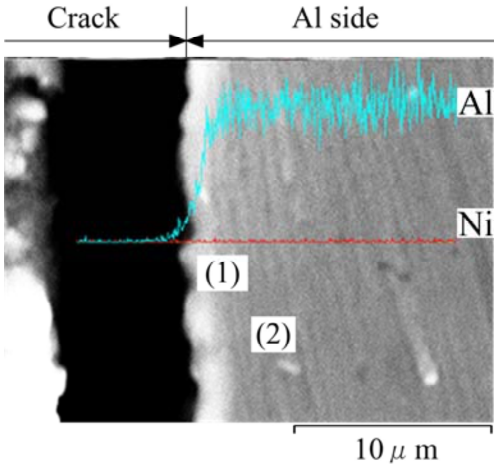
Fig. 3 Relationship between temperature and elapsed time from cooling start during cooling process (cooling temperature curve): heating temperature of (a) 773 K, (b) 823 K, and (c) 873 K.

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



Location	Chemical composition, mol.%	
	Ni	Al
(1)	100.0	0.0
(2)	100.0	0.0
(3)	81.1	18.9
(4)	59.2	40.8
(5)	52.0	48.0

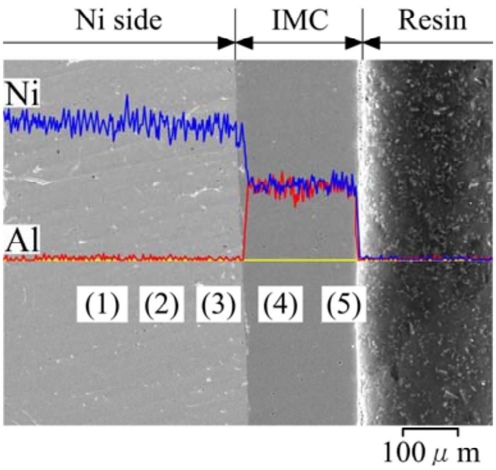
(a) Ni side



Location	Chemical composition, mol.%	
	Ni	Al
(1)	0.0	100.0
(2)	0.0	100.0

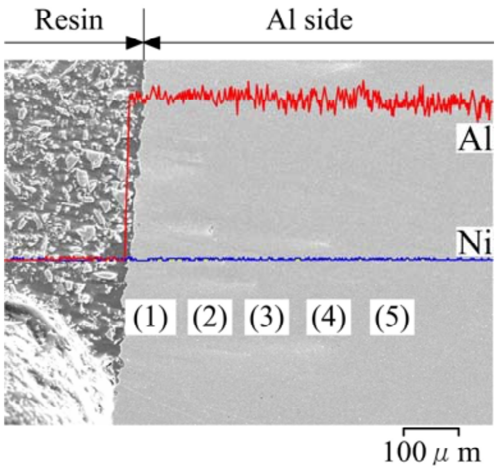
(b) Al side

Fig. 4 SEM photographs and analysis results of chemical compositions at half-radius portion in axial direction of cross-section for 773 K-604.8 ks joint after fracture testing:(a) Ni and (b) Al sides.



Location	Chemical composition, mol.%	
	Ni	Al
(1)	100.0	0.0
(2)	99.9	0.1
(3)	100.0	0.0
(4)	48.7	51.3
(5)	49.3	50.7

(a) Ni side



Location	Chemical composition, mol.%	
	Ni	Al
(1)	0.0	100.0
(2)	0.1	99.9
(3)	0.0	100.0
(4)	0.0	100.0
(5)	0.1	99.9

(b) Al side

Fig. 5 SEM photographs and analysis results of chemical compositions at half-radius portion in axial direction of cross-section for 873 K-604.8 ks joint after fracture testing:(a) Ni and (b) Al sides.

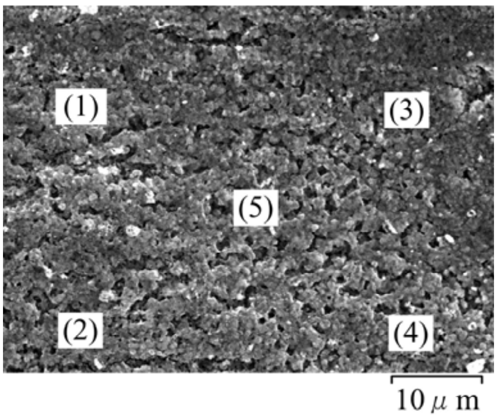
although that fractured when it was taken out from the furnace. On the other hand, the joint with 86.4 ks fractured at 769, 739, and 724 K when that was cooled from a heating temperature of 823 K, as shown in Fig. 3b. The joints with 604.8 ks also fractured at 765, 714, and 640 K, respectively. In addition, the joint with under 43.2 ks did not fracture when that was taken out from the furnace in the same as 773 K joint. Furthermore, the joint with 604.8 ks fractured at 807 and 722 K when that was cooled from a heating temperature of 873 K, as shown in Fig. 3c. The joint with 86.4 ks also fractured at 823 K and that with 43.2 ks fractured at 380 K, respectively. Then, the joint with 21.6 ks fractured at 460 K. Moreover, some of the joints with 43.2 and 21.6 ks fractured when they were taken out from the furnace although it did not fracture during the furnace cooling process. Based on the described above, the joints that were heated at more high heating temperature and for long heating time that grew IMC interlayer at the weld interface between Ni and Al almost fractured at high heating temperature during the furnace cooling process. The details of this fact will be described later.

3.2 Observation and chemical compositions analysis of cross-section for joint

Figures 4 and 5 show the SEM photographs and analysis results of chemical compositions of the cross-section for 773 K-604.8 ks and 873 K-604.8 ks joints, respectively, after fracture testing. Those were observed at a half-radius portion in the axial (longitudinal) direction of the cross-section for Ni and Al sides. In case of 773 K-604.8 ks joint as shown in Fig. 4, three interlayers were observed on the Ni side although no IMC interlayer was observed on the Al side. That is, the chemical compositions of the locations (1) and (2) were 100%Ni (in mol.%), and that at (3) was 81.1%Ni-18.9%Al, of which was shown in Fig. 4a. Those of locations (4) and (5) were 59.2%Ni-40.8%Al and 52.0%Ni-48.0%Al, respectively. However, only Al was detected on the Al side (see Fig. 4b). On the other hand, in case of 873 K-604.8 ks joint as shown in Fig. 5, while the chemical compositions of IMC interlayer were approximately 49%Ni-51%Al for the locations (4) and (5), almost only Al was detected on the Al side. In addition, the width of IMC interlayer at the axial direction of the joint increased with increasing heating time, and that of this joint had approximately 150 μm. In this connection, the right side dark region of the photo in Fig. 5a and the left side one in Fig. 5b were resin, and that was used to mount the joint for SEM observation.

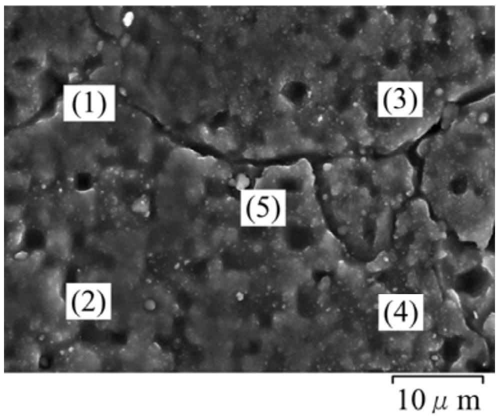
3.3 Observation and chemical compositions analysis of fractured surface for joint

Figures 6 and 7 show the SEM photographs and analysis results of chemical compositions for fractured surfaces on Ni and Al sides of 773 K-604.8 ks and 873 K-604.8 ks joints, respectively. In case of 773 K-604.8 ks joint as shown in Fig. 6, the facet of the fractured surface of the Ni side was smaller than that of the Al side one. The Ni side was observed a void-like pattern, and the Al side was observed little void. The chemical composition of the Ni side was mainly (48.0-50.7)%Ni-(52.0-49.3)%Al (see Fig. 6a). By adding another data that were not attached here due to space limitations, as a conclusion, the fractured surface was covered with mainly NiAl and some $NiAl_3$ (and Ni_2Al_3 that will be described later). However, only Al was detected on the Al side fractured surface (see Fig. 6b). On the other hand, when the joint was



Location	Chemical composition, mol.%	
	Ni	Al
(1)	49.6	50.4
(2)	48.0	52.0
(3)	50.2	49.8
(4)	48.8	51.2
(5)	50.7	49.3

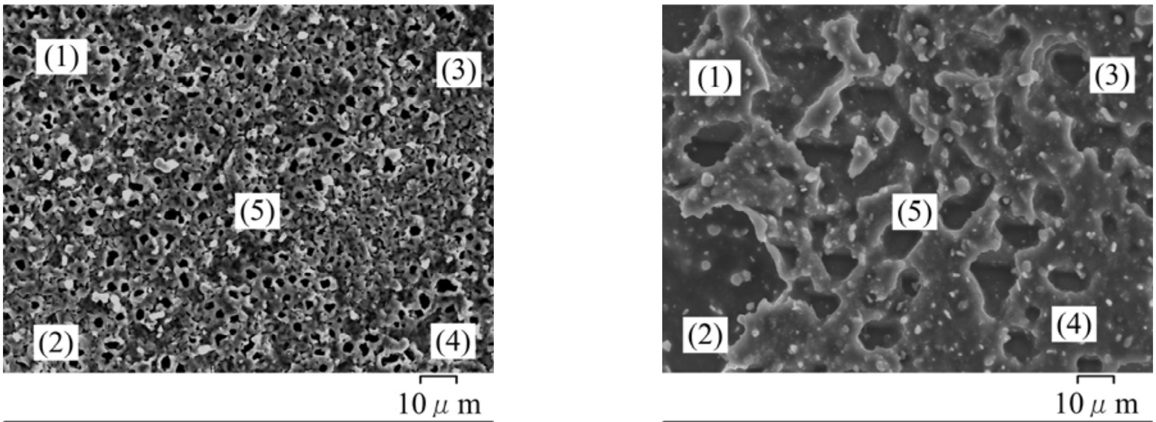
(a) Ni side



Location	Chemical composition, mol.%	
	Ni	Al
(1)	0.0	100.0
(2)	0.1	99.9
(3)	0.2	99.8
(4)	0.0	100.0
(5)	0.0	100.0

(b) Al side

Fig. 6 SEM photographs and analysis results of chemical compositions for fractured surfaces of 773 K-604.8 ks joint: (a) Ni and (b) Al sides.



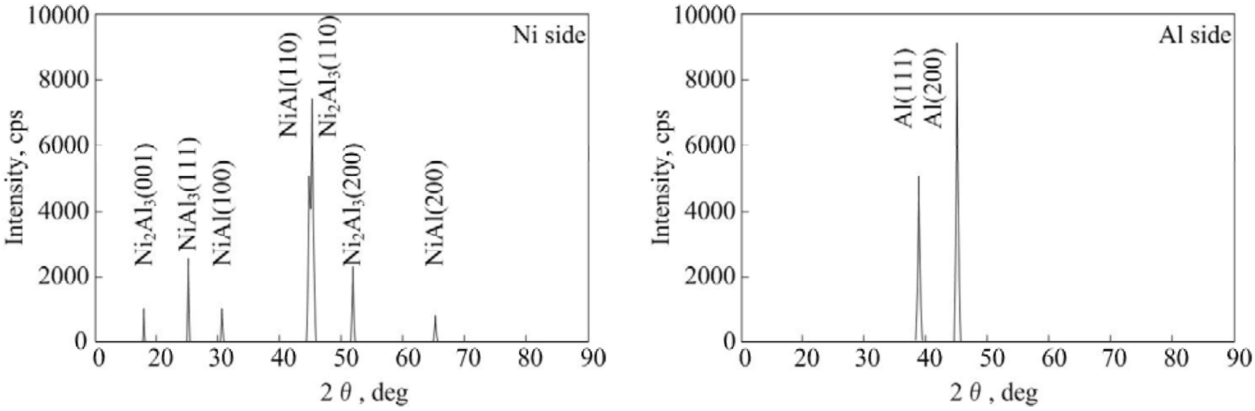
Location	Chemical composition, mol.%	
	Ni	Al
(1)	55.4	44.6
(2)	26.0	74.0
(3)	48.8	51.2
(4)	55.3	44.7
(5)	48.7	51.3

(a) Ni side

Location	Chemical composition, mol.%	
	Ni	Al
(1)	0.0	100.0
(2)	0.0	100.0
(3)	0.0	100.0
(4)	0.0	100.0
(5)	0.1	99.9

(b) Al side

Fig. 7 SEM photographs and analysis results of chemical compositions for fractured surfaces of 873 K-604.8 ks joint: (a) Ni and (b) Al sides.



(a) Ni side (b) Al side

Fig. 8 X-ray diffraction analysis results of fractured surfaces for 773 K-604.8 ks joint: (a) Ni and (b) Al sides.

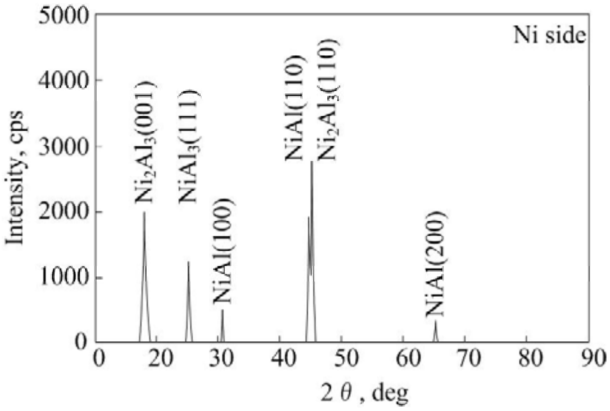
treated with 873 K-604.8 ks as shown in Fig. 7, the facet of the Ni side was smaller than that of the Al side. The Ni side was observed a void-like pattern, but the Al side was not observed. These results were almost same as 773 K-604.8 ks joint. The chemical compositions of the Ni side fractured surface were mainly (48.7-55.4)%Ni-(51.3-44.6)%Al, although the location (2) was 26.0%Ni-74.0%Al (Fig. 7a). However, almost only Al was detected on the Al side (Fig. 7b).

3.4 X-ray diffraction analysis of fractured surface for joint

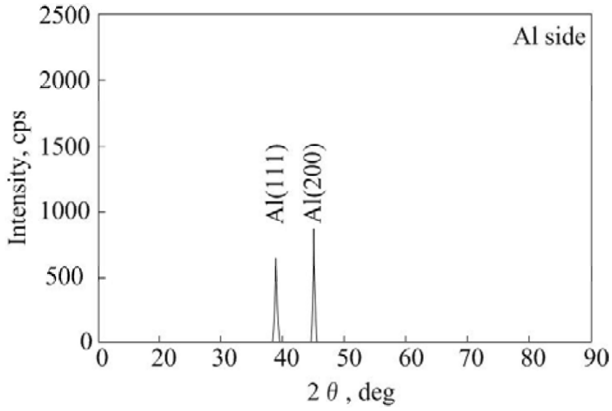
Figures 8 and 9 show the X-ray diffraction analysis results of the fractured surfaces on Ni and Al sides of 773 K-604.8 ks and 873 K-604.8 ks joints, respectively. Mainly NiAl and Ni_2Al_3 diffraction patterns including some $NiAl_3$ were detected on the Ni side fractured surface of 773 K-604.8 ks joint (Fig. 8a), although only Al was detected on the Al side (Fig. 8b). The result of 873 K-604.8 ks joint was similar result of 773 K-604.8 ks joint, mainly NiAl and Ni_2Al_3 diffraction patterns including a little $NiAl_3$ were detected on the Ni side fractured surface (Fig. 9a). However, only Al was detected on the Al side (Fig. 9b). That is, the Ni side fractured surface had NiAl, Ni_2Al_3 and $NiAl_3$, and the Al side one had only Al. Therefore, it was clarified that the joint was fractured between NiAl layer on the Ni base metal and Al base metal.

4. Discussion

It was considered to Figs. 3 through 9 and by adding another data (was not shown due to space



(a) Ni side



(b) Al side

Fig. 9 X-ray diffraction analysis results of fractured surfaces for 873 K-604.8 ks joint: (a) Ni and (b) Al sides.

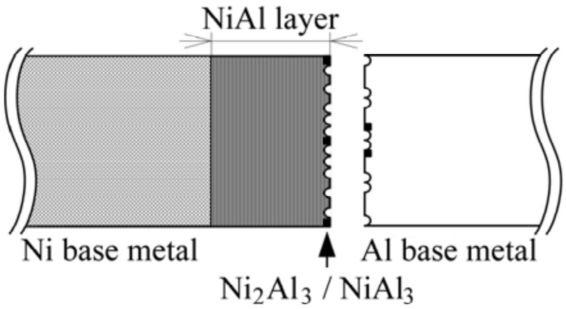


Fig. 10 Schematic illustration of relation between IMC interlayers and fractured portion of joint.

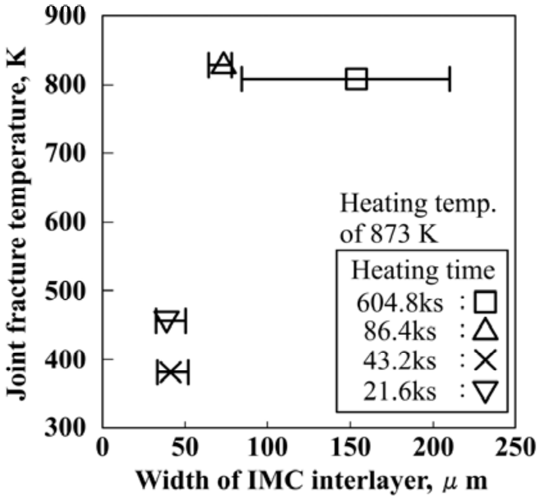


Fig. 11 Relationship between width of IMC interlayer and fracture temperature of joint with heating temperature of 873 K.

limitations) that the IMC was estimated as mainly NiAl covered with a little Ni_2Al_3 and/or $NiAl_3$ on the Ni side fractured surface although almost no IMC was produced on the Al side one. As a conclusion, the fracture mainly occurred at the interface between NiAl layer and Al base metal, of which had a little Ni_2Al_3 and/or $NiAl_3$. The schematic illustration of the relation between IMC interlayer and fractured portion of joint was shown in Fig. 10. When the joint was treated with short heating time, the width of the IMC interlayer was thin and that was composed with mainly NiAl which surface was covered with some Ni_2Al_3 and/or $NiAl_3$. Moreover, when the joint was treated with long heating time, the width of the IMC interlayer was thick and that was also composed with mainly NiAl with a little Ni_2Al_3 and/or $NiAl_3$. In this connection, other intermetallics were not observed at the weld interface of the joint which was based on the SEM observation and X-ray diffraction analysis level although the possibility of the generation of those were able to be estimate, because the heating temperature of PWHT in this study was 873 K or lower [32]. Therefore, the fracture of the joint occurred at the interface between NiAl layer and Al base metal of which surface was covered with some Ni_2Al_3 and/or $NiAl_3$, regardless of the width of NiAl layer.

Figure 11 shows the relationship between the width of IMC interlayer and joint fracture temperature during the cooling process of joints, of which was treated with a heating temperature of 873 K. The joint fracture temperature was under about 470 K when the width of the IMC interlayer was smaller than approximately 40 μm. However, the joint fracture temperature drastically increased up to about 800 K when the width of the IMC interlayer exceeded 50 μm. It was able to be estimate worth while to notice that as increasing width of the IMC interlayer, the joint fracture temperature was increased. Hence, it was considered that the bonding strength between NiAl layer and Al base metal decreased with increasing its width, because IMC interlayer was composed with mainly NiAl layer which was covered with Ni_2Al_3 and/or $NiAl_3$. The random site lattice, generally speaking, decreases the bonding strength for the grain boundary than coincidence site lattice [33,34], so that the generating of Ni_2Al_3 and/or $NiAl_3$ might decrease the bonding strength of the interface due to the crystal mismatch between NiAl layer and Al base metal. Furthermore, the bonding strength at the grain boundary was affected to the direction of that to the coincident site lattice [35]. 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, although the further investigation must elucidate the detailed characteristics of this IMC interlayer.

5. Conclusions

This report described the investigation of the fracture of friction welded joint between pure nickel (Ni) and pure aluminium (Al) with post-weld heat treatment (PWHT). It was investigated in details how fracture occurs at the weld interface of the joint at the cooling process after PWHT. The followings are concluded.

1) Joints autogenously fractured from the adjacent portion of the intermediate layer (interlayer) consisting of intermetallic compound (IMC) on the weld interface at high temperature during the cooling process after PWHT, when they were heated at heating temperature and for long heating time as IMC interlayer grew between Ni and Al base metals. The IMC was composed with mainly NiAl, which surface was covered with a little Ni_2Al_3 and/or $NiAl_3$.
2) The fracture of the joint occurred at the weld interface between NiAl layer and Al base metal. Those fractured surfaces were covered with a little Ni_2Al_3 and/or $NiAl_3$, and that was like as disbonding.
3) The joint fracture temperature was under about 470 K when the width of the IMC interlayer in the axial direction of the joint was smaller than approximately 40 μm. However, the joint fracture temperature drastically increased up to about 800 K when the width of the IMC interlayer exceeded 50 μm.

In conclusion, 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.

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