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TECHNICAL PAPER

The Microstructure and Mechanical Properties of Friction Welded Cast Ni_3Al Intermetallic Alloy

Ibrahim Celikyürek[1] · Bedri Baksan[1] · Osman Torun[2] · Gökhan Arıcı[3] · Akın Özcan[1]

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Abstract Ni_3Al alloy was bonded with itself by friction welding. Various friction speeds, friction durations and friction pressures were tested to find optimum friction welding parameters, and the effects of the welding parameters on the welding interface, microstructure and mechanical properties were investigated. SEM and optical microscopy were carried out to examine the microstructural variations of the welding interfaces. Also, the microhardness distribution across the interface was evaluated considering the microstructural variations. In addition, the shear strengths of welded parts were measured. It was observed that the shear strengths of welds were dependent on welding time, friction pressure and friction speed. The maximum shear strength was found as 354 MPa.

Keywords Electron microscopy · X-ray diffraction · Intermetallic · Friction welding · Interfaces

✉ Osman Torun
otorun@aku.edu.tr

Ibrahim Celikyürek
cibrahim@ogu.edu.tr

1 Metallurgical and Materials Engineering Department, Faculty of Engineering and Architecture, Eskişehir Osmangazi University, Eskisehir, Turkey

2 Bolvadin Vocational School, Afyon Kocatepe University, Bolvadin, Afyonkarahisar, Turkey

3 Materials Engineering Department, Faculty of Engineering, Selcuk University, Konya, Turkey

1 Introduction

Nickel aluminides based on Ni_3Al have low density, high fatigue resistance and high temperature oxidation resistance and strength [1, 2]. However these alloys have low fracture strength and formability at room temperatures [3, 4]. Although significant progress has been made in an effort to commercialize Ni_3Al, important technological issues related to its processing, fabrication, mechanical behavior, and environmental resistance have not been completely resolved yet. Weld-ability is a specific issue related to fabrication technologies that is a major concern for Ni_3Al [5]. It's obvious that weld-ability of Ni_3Al alloys may possibly increase the use of these alloys in engineering applications [6, 7]. Earlier studies on the welding of Ni_3Al have focused mainly on fusion weldability using gas tungsten arc welding (GTAW) and electron beam welding (EBW). These studies showed that the cracking susceptibility strongly depends on the alloy composition. In addition, there are several studies on diffusion welding of Ni_3Al alloys in recent years [5–7].

Friction welding is one of the available joining techniques and this welding process has been used successively in steels, aluminum, titanium, nickel, and magnesium alloys and intermetallics [8–13]. There are many parameters affecting the friction welding quality. The most important ones are friction speed, friction duration and friction pressure. In the present study, Ni_3Al alloys have been welded by friction welding and the affects of the welding parameters on the welding interface, microstructure and mechanical properties have been investigated.

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2 Experimental

The alloy Ni_3Al was prepared by vacuum arc melting under argon atmosphere from nickel and aluminum with 99.95 and 99.9 wt% purity, respectively. To prevent oxidation, the furnace was evacuated to 5×10^{-2} millibar and then filled with pure Argon. The alloy was melted in a copper crucible cooled with water and cast in a sand mould which was fixed to the crucible. The samples were then homogenized at 1000 °C for 50 h and cooled in a furnace. The samples were machined to cylindrical form in diameters of 8 mm.

Prepared samples were welded by friction welding. The friction welding experiments were carried out by continuous drive friction welding machine [14] at the friction pressure of 50, 100, 150 MPa, the friction times of 20, 25, 30 s, the friction speeds of 300, 600, 1000 rpm and the forging pressure of 150 MPa. The welding conditions and burn-offs of the samples are shown in Table 1.

The welded samples were cut perpendicular to the welding interface. The surfaces of the samples were ground with 1200 grinding paper and polished with 3 µm diamond paste, then the samples were etched with a mixture of H_2O (30 ml), HNO_3 (30 ml), HCl (20 ml) and HF (20 ml). The microstructures were observed with a light microscope and scanning electron microscopy (SEM). The chemical composition of the alloy was determined by using energy dispersive spectroscopy (EDXS) (Fig. 1). Microhardness values were measured from the center of the welding interface to the matrix by means of Vickers indenter with a load of 100 g, and 15 s dwell time. The shear tests were performed to determine the strength of the weld interface using an electromechanical universal test machine (Shimadzu AG-IS-250) at room temperature. The schematic view of the test apparatus to determine the shear strength is shown in Fig. 2 [15]. Three tests were performed for each experiment condition. The mean values were calculated.

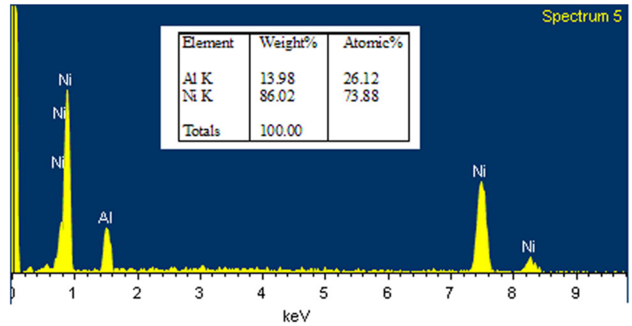

Fig. 1 SEM-EDXS analysis of the Ni_3Al alloy

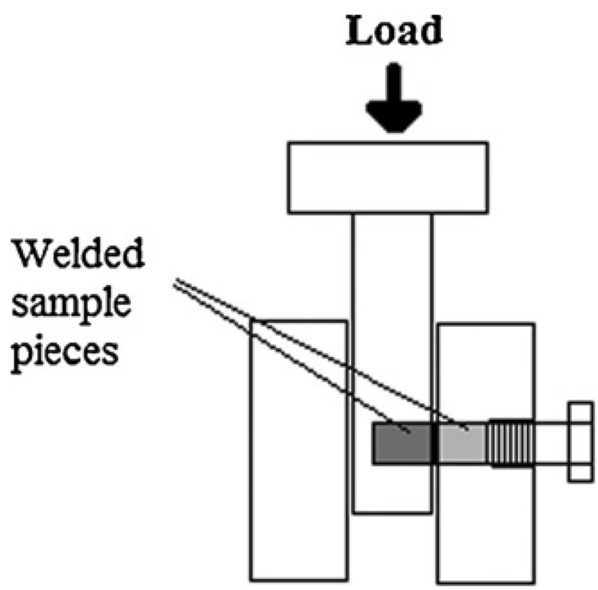

Fig. 2 Schematic view of shear test apparatus

3 Results and Discussion

3.1 Structure

The macrostructures of friction-welded samples are shown in Fig. 3. As seen from the macrographs, the flash

Table 1 Welding conditions and burn-off of samples

Friction pressure (MPa)	Friction speed (rpm)								
	300			600			1000		
	Friction times (s)								
	20	25	30	20	25	30	20	25	30
50	0	0	0	0	0	0*	0.3	0.3	0.4
100	0	0	0*	1	1.2	1.6	1	1.5	2
150	0	0	Failed	4.6	Failed	Failed	1.5	2.1	5.9

0: not joined, * not joined at 50 s also

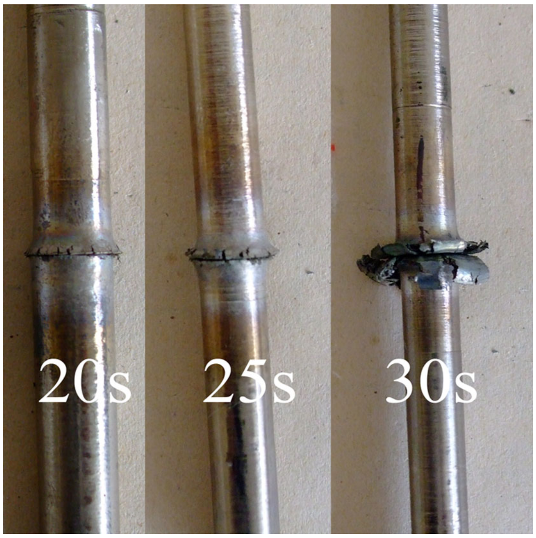

Fig. 3 Macrographs of the welded samples. Friction speed of 1000 rpm and friction pressure of 150 MPa

formation was observed in all welded samples because of plastic deformation during welding. The friction pressure and the friction time played an important role in the flash formation. With an increase in the friction time, friction pressure and friction speed, heat input increased at the weld interface. Thus, more plastic deformation occured. As a result of this situation the burn-off (axial shortening) increased.

The optical microscope images of some welded samples are shown in Fig. 4. As seen in the optical micrographs, all welded samples were bonded successively. The dynamic recrystallization zone was observed in the interface of all the welded samples. The width of dynamic recrystallization zone for all of the welded samples was approximately 150–220 μm. With respect to the matrix, the grain size of the dynamic recrystallization zone seemed relatively smaller. Also, the larger grain size was observed between the dynamic recrystallization zone and the matrix for some samples (Fig. 4a). In the literature, a plastic deformation zone next to recrystallization zone at the welding interface for the friction welding of the ductile materials was reported [12, 16]. However, due to low ductility of intermetallic compounds, the plastic deformation zone was not observed in the interface of the welded samples. In addition, with an increase of the friction pressure, time and speed, heat generated at the interface increased. As a result of this situation, the grain size in the dynamic recrystallization zone was coarsened (Fig. 4b). As seen from the figures the grain size at the center of welding interface was coarser than interface sides. The heat generated at the center of interface was the highest and the cooling rate was the lowest. Therefore, a slight coarsening occurred at the center of the interfaces.

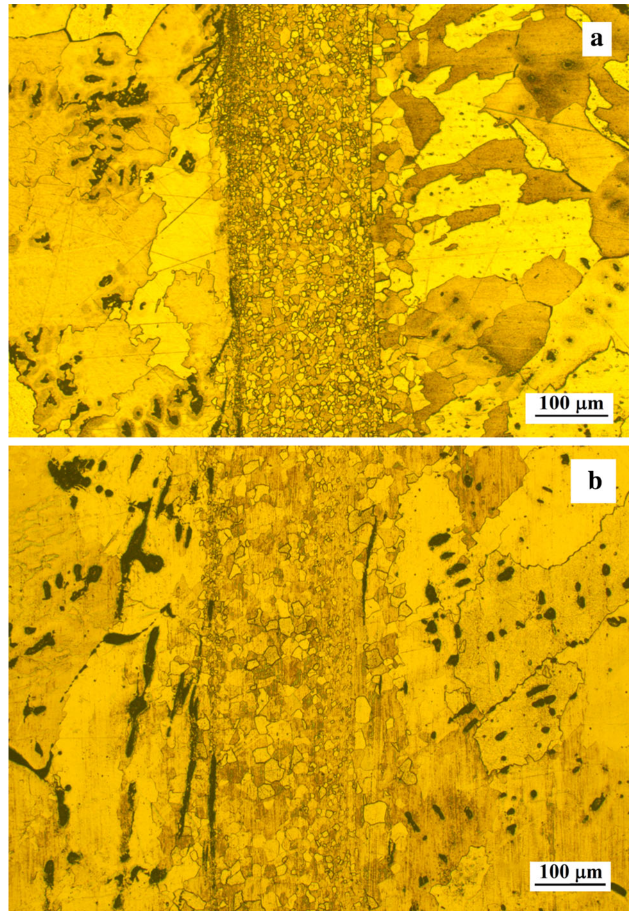

Fig. 4 Microstructure of welded samples. **a** 1000 rpm, 50 MPa 25 s, **b** 1000 rpm, 100 MPa, 25 s

3.2 Mechanical Properties

The shear strengths of the welded samples are given in Fig. 5. As seen from Fig. 5a, the samples were not joined at 50 MPa friction pressure and 600 rpm friction speed. Friction pressure of 50 MPa was insufficient to generate enough heat for joining of samples. The shear strengths of the welded samples were increased with the friction time at 100 MPa friction pressure. An unusual behavior was observed at 150 MPa friction pressure. The samples were welded in 20 s but destroyed in 25 and 30 s. This alloy had a limited ductility at the ambient temperatures but had a good ductility at higher temperatures [17, 18]. In these welding conditions, it was thought that the heat generated in the interface was sufficient for welding but insufficient for enough ductility. The friction pressure was too high and the friction speed was too low.

As seen from Fig. 5b, at 1000 rpm friction speed, the shear strength values of the welded samples increased up to 25 s and then decreased with increasing time. However, the shear strengths increased with an increase in the friction

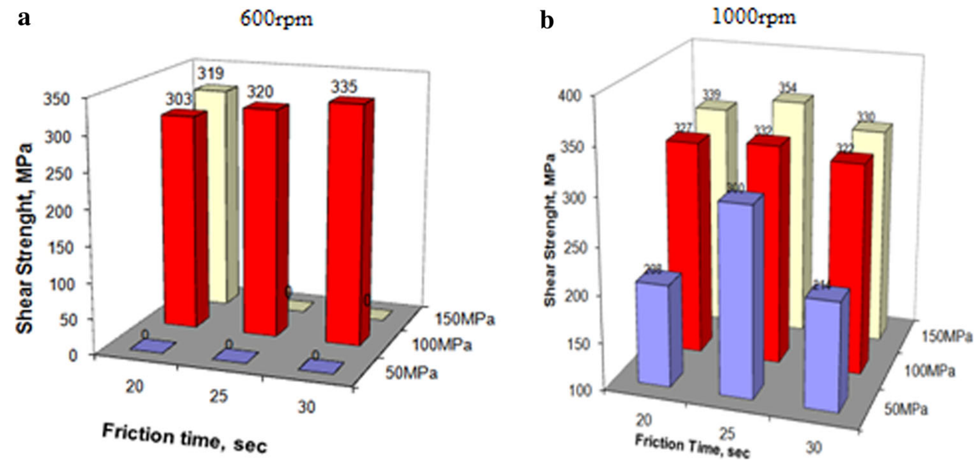

Fig. 5 The shear strengths of the welded samples

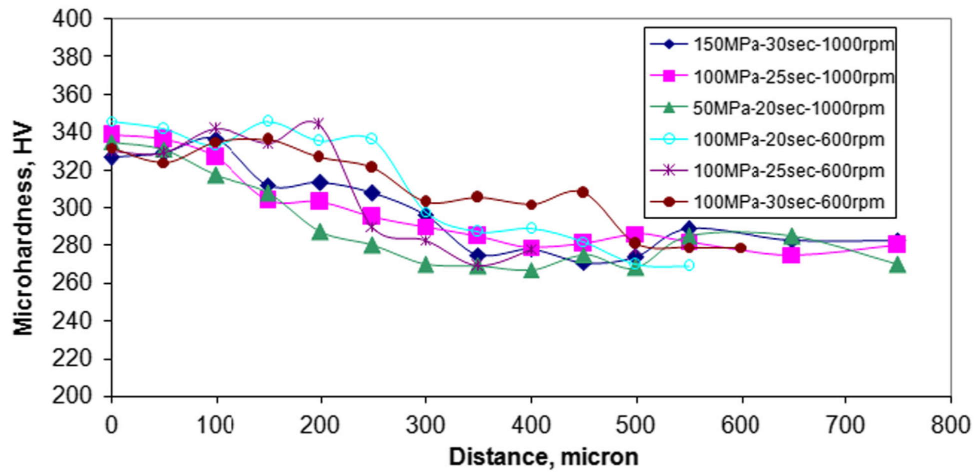

Fig. 6 Hardness profile from the center of welds to matrix

pressure. The highest shear strength of 354 MPa was obtained at friction pressure of 150 MPa and the friction time of 25 s. This value was very close to 355 MPa, which was the shear strength value of Ni_3Al alloy. Higher shear strength values were observed at high friction pressure. The weld strength was related to the heat generated at the welding interface during the process. For a given friction speed, the increase in the friction time and pressure increased the heat input at the interface. The increase of temperature at the welding interface provided a better joining. Relatively low shear strengths were observed as a result of lower heat input at low friction pressures. When the friction time was too high, due to annealing effect, the grain size in the dynamic recrystallization zone was coarsened. Therefore, the shear strengths got reduced with increase in friction time up to 30 s, at the 1000 rpm friction speed.

Hardness profile from the center of welds to the matrix was shown in Fig. 6. The hardness of matrix was 280 HV and hardness of the dynamic recrystallization zone was about 330 HV. The hardness increase in the dynamic recrystallization zone was due to the finer grain size.

3.3 Fractography

Figure 7 shows the SEM fractograph of fractured surface of the sample welded at 1000 rpm friction speed, pressure of 100 MPa and friction time of 25 s. The SEM image showed that very fine grain structure formed during the friction welding. It was obviously seen that the fracture originated from dynamic recrystallization zone and occurred chiefly at the grain boundaries.

Figure 8 shows the XRD patterns of Ni_3Al alloy as cast and after shear test. As seen in Fig. 7, Ni_3Al phase was produced and after welding there was no phase transformation at the welding interface. According to Ni–Al phase diagram, there was no phase transformation for Ni_3Al up to 1385 °C. For phase transformation, the atomic ratios of elements should be changed. The phase transformation did

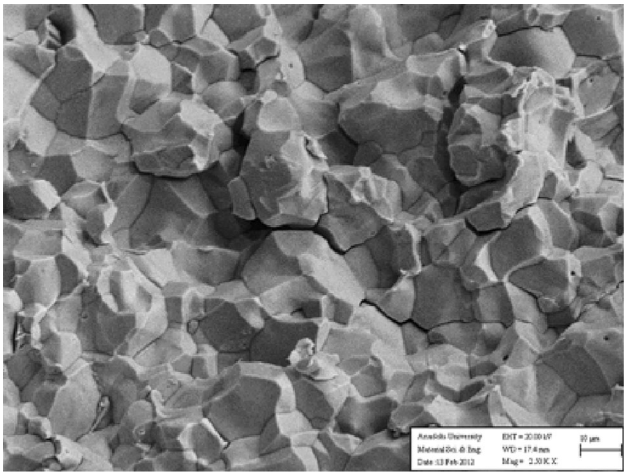

Fig. 7 SEM fractograph of fractured surface of the sample welded at 1000 rpm friction speed, pressure of 100 MPa and friction time of 25 s

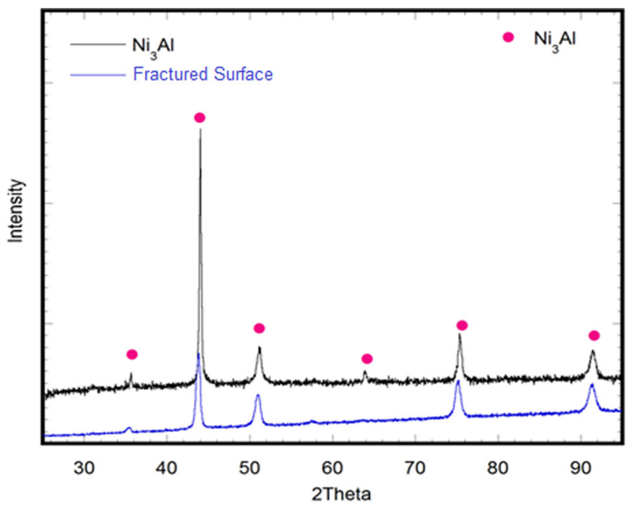

Fig. 8 XRD patterns of Ni_3Al alloy as cast and after shear test

not occur during the welding process because the chemical composition did not change.

4 Conclusions

In this study, joining of the cast Ni_3Al alloy was carried out successively by friction welding. Welding interface of all samples had finer grain structure than matrix as a result of dynamic recrystallization. The quality of the welding depended on the friction time, speed and pressure. The heat input at the interface increased with increase in all parameters. Increasing heat input at the interface resulted higher quality of welding. However, the grain size of welding interface coarsened when the friction time was too much. As a result, the strength of welding interface got decreased due to annealing affect. The welding interfaces of all treated samples had a higher hardness due to their finer grain structure, and the welding parameters did not affect the hardness profiles clearly. Fractured surface XRD analysis showed that there was no phase transformation at the interface during welding process.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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