Interface microstructure observation for welds of an alumina ceramics and an aluminum alloy with friction stir spot welding

Hirosuke SONOMURA¹,³, Tomoatsu OZAKI¹, Kazuaki KATAGIRI¹, Yasunori HASEGAWA¹ and Tsutomu TANAKA¹

¹Osaka Research Institute of Industrial Science and Technology, 7–1 Ayumino-2, Izumi, Osaka 594–1157, Japan

A 5 mm thick alumina ceramic plate and a 1 mm thick aluminum alloy plate were welded together by a friction stir spot welding technique. The welding was performed at tool rotation rate of 2000 rpm, plunge time of 0.4 mm, dwell time of 60 s, and plunge rate of approximately 0.1 mm/min. The interface microstructure of the welds was investigated by a scanning transmission electron microscope and energy dispersive X-ray spectrometry analysis to study the welding mechanism. A magnesium element was detected along the interface. It was expected that the alumina ceramic plate and the aluminum alloy plate were welded via magnesium oxide or a magnesium–aluminum–oxygen compound.

©2019 The Ceramic Society of Japan. All rights reserved.

Key-words : Friction stir spot welding (FSSW), Interface microstructure, Scanning transmission electron microscope image, Ceramics, Aluminium alloys

[Received May 29, 2018; Accepted November 20, 2018]

1. Introduction

Ceramics have good heat resistance, wear resistance, and insulation performance. However, they are difficult to work with compared with metals. Thus, it is difficult to make a large and complex structure using only ceramics. A welding technique for a ceramics and a metal is necessary. The friction stir spot welding (FSSW) technique is rapid and easy welding process since sound welds are obtained by local heating in the atmosphere without the use of a furnace.¹⁻⁶

As reported by Fukumoto et al., the welding of an Al₂O₃ ceramic plate and aluminum alloy A5052 plate with the FSSW technique was obtained.⁷ They also discussed the welding mechanism. According to the results of cross-section observation, A5052 was trapped in gaps on the Al₂O₃ ceramic surface, which were likely caused by mechanical bonding. On the other hand, in case of liquid phase welding with vacuum heating reported by Kumamoto et al., MgO formed along the interface which contributed to the welding.⁸ During the welding, a magnesium element of aluminum alloy A6063 was diffused to the interface and, reacted with Al₂O₃ on the AlN surface, forming MgO along the interface. Since A5052 also contains a magnesium element, MgO may form along the interface with the FSSW technique as is the case with the vacuum heating technique. However, an elemental analysis of the interface with the FSSW technique has not been investigated.

Thus, we have investigated the elemental mapping of the interface with the FSSW technique by a scanning transmission electron microscope (STEM) and an energy dispersive X-ray spectrometry (EDS) analysis to discuss the welding mechanism for the welds of Al₂O₃ and A5052 with the FSSW technique.

2. Experimental procedures

The Al₂O₃ ceramic plate used in experiment had a purity grade of 99.5%, relative high density of 99.5%, and specimen size 50 mm × 25 mm × 5 mm. The welded surface of the Al₂O₃ ceramic plate was a mirror finished to avoid mechanical bonding. The composition of the A5052 plate used in experiment was Al:Mg:Fe:Cr:Si:Zn:Cu:Mn:others = 96.81:2.60:0.27:0.17:0.08:0.02:0.01:0.01:0.03 (mass %). The A5052 plate size was 60 mm × 30 mm × 1 mm. Two A5052 plates lined up against each other were set on the Al₂O₃ ceramic plate, and were firmly anchored. For the FSSW, a machining center (DMG MORI CO., LTD., DURA VERTICAL 5060) was used. The photograph of the tool is presented in Fig. 1. This tool was often used for the friction stir butt welding between metals. The tool had a probe with diameter and length of 5 and 4.9 mm, respectively. The welding conditions were fixed at tool rotation speed of 2000 rpm, tool holding time of 60 s, and probe plunge depth of 0.4 mm. The rotating tool was inserted just above the interface between the A5052 plate and the Al₂O₃ ceramic plate. The plunge rate was approx-
approximately 0.1 mm/min. The lowest rate of the machining center was used to suppress an occurrence of the crack of the Al$_2$O$_3$ ceramic plate surface. It avoids mechanical bonding.

In the welding, A5052 of a plastic flow state caused by the rotating tool was pressed against the Al$_2$O$_3$ ceramic plate, and the Al$_2$O$_3$ ceramic plate and the A5052 plate were welded together.

A tensile shear test was performed at room temperature by a material testing machine (A&D CO., LTD., MCT-2150) to confirm the welding interface intensity. The load was applied in the longitudinal direction of the specimen and the loading speed was fixed at 10 mm/min.

Thin specimen was prepared by a focused ion beam (FIB) system (HITACHI, FB2200) with the specimen after the tensile shear test to observe the interface. The acceleration voltage of gallium ions was 40 kV during processing. The cross-section surface was finished processing at 10 kV. The interface microstructure observation specimen was obtained by cutting from the center of the welding area. The interface microstructure observation was performed by STEM (HITACHI, HD-2700). The presence or absence of magnesium compounds along the interface was investigated by EDS analysis. The acceleration voltage on STEM-EDS was 200 kV. The detection angle for scattered electrons for an annular dark field (ADF)-STEM image was 70 mrad $\leq \beta \leq$ 370 mrad. A drift condition was not performed.

3. Results and discussion

Figure 2 shows the applied load of the tool during processing. In the tool tip location (z-axis) range $-0.16 \leq z \leq 0$, the load was increased monotonically up to approximately 1000 N after the tool made contact with the A5052 plate. In the location range $-0.4 \leq z < -0.16$, the maximum load peak of approximately 1500 N was observed at $z = -0.27$. As a result, cracks on the Al$_2$O$_3$ ceramic plate were not observed during processing. The tensile shear test showed that the welds were broken at 151 N. This value was nearly equal to the value of the previous report. The broken-out section after the tensile shear test is presented in Fig. 3. The attached Al$_2$O$_3$ ceramics of approximately 3 mm$\varphi$ was observed on the A5052 plate. It indicates that welding interface intensity is higher than the breakdown intensity of the Al$_2$O$_3$ ceramic plate.

Figure 4 shows microstructure images of (a) high-angle annular dark-field (HAADF) image, (b) BF image, and (c) SE image near the welding interface. As seen in figures, the welds of the A5052 plate and the Al$_2$O$_3$ ceramic plate formed a good interface. In the interface there might be voids, but there was no gap. EDS mapping images of aluminum, magnesium, iron, chromium, oxygen, and gallium elements are shown in Fig. 5. The gallium element caused by FIB processing was detected in A5052. Loss of an aluminum element and segregation of a magnesium element were detected along the welding interface. Segregation of an iron element was partially detected near the interface. Since the iron element was not detected for another interface observation point, it was considered that...
Segregation of the iron element did not contribute largely to the welding interface. Segregation of a chromium element was partially detected in the grain of A5052. Segregation of the chromium element also did not contribute. EDS line profile across the welding interface with SE signal, aluminum Kα signal, oxygen Kα signal, and magnesium Kα signal is shown in Fig. 6. The magnesium element was detected in the width of several dozens of nm near the welding interface. Since aluminum and oxygen elements were also detected in the same range, magnesium oxide or a magnesium–aluminum–oxygen compound was more likely to exist. It is expected that the Al₂O₃ plate

Fig. 4. Microstructure images of (a) HAADF image, (b) BF image, and (c) SE image near the welding interface.

Fig. 5. EDS mapping images of aluminum, magnesium, iron, chromium, oxygen, and gallium elements. The mapping conditions were the dwell time of 200μs and 371 frames for scanning.

Fig. 6. EDS line profile across the welding interface with SE signal, aluminum Kα signal, oxygen Kα signal, and magnesium Kα signal.
and the A5052 plate are welded via magnesium oxide or the magnesium–aluminum–oxygen compound.

According to the report for liquid phase welding, it was considered that the magnesium element in aluminum alloy was diffused to the interface and, reduced Al₂O₃. MgO was sequentially formed after the formation of MgAl₂O₄ and Al metal as the diffusion of the magnesium element to the interface progressed. The interface obtained by the FSSW technique is expected to be occurred similar reaction. More detailed interface information such as composition, crystal structure, and crystallinity needs to be investigated by TEM in the future. The interface information may change by the condition of interface temperature, tool pressurization, and plastic flow state.

4. Conclusion

The elemental analysis of the interface for the welding of the Al₂O₃ ceramic plate and the aluminum alloy A5052 plate with the FSSW technique was performed to discuss the welding mechanism. The results were summarized as follows;

(1) As the result of the tensile shear test, the welds were broken at 151 N. This value was nearly equal to the value of the previous report.⁷

(2) Segregation of a magnesium element in the width of several dozens of nm near the welding interface was detected along the welding interface. Since aluminum and oxygen elements were also detected in the same range, magnesium oxide or the magnesium–aluminum–oxygen compound was more likely to exist. It was expected that the Al₂O₃ plate and the A5052 plate were welded via magnesium oxide or the magnesium–aluminum–oxygen compound.

References

1) D. Mitlin, V. Radmilovic, T. Panc, J. Chena, Z. Feng and M. L. Santella, J. Mater. Sci. Eng. A, 441, 79–96 (2006).
2) Y. Uematsu, K. Tokaji, Y. Tozaki, T. Kurita and S. Murata, Int. J. Fatigue, 30, 1956–1966 (2008).
3) Z. Zhang, X. Yang, J. Zhang, G. Zhou, X. Xu and B. Zou, Mater. Design, 32, 4461–4470 (2011).
4) K. Tanaka, M. Kumagai and H. Yoshida, J. Jpn. Inst. Light Met., 56, 317–322 (2006).
5) S. H. Chowdhury, D. L. Chen, S. D. Bhole, X. Cao and P. Wanjara, Mater. Sci. Eng. A, 562, 53–60 (2013).
6) J. M. Piccinia and H. G. Svoboda, Prog. Mater. Sci., 9, 504–513 (2015).
7) M. Fukumoto, “Bull. Ceram. Soc. Jpn., The Ceramic Society of Japan”, Ed. by S. Shimura, Japan (2016), 51, pp. 66–69.
8) A. Kumamoto, N. Shibata, K. Nayuki, T. Tohei, N. Terasaki, Y. Nagatomo, T. Nagase, K. Akiyama, Y. Kuromitsu and Y. Ikuhara, Sci. Rep., 6, 22936 (2016).