FULL PAPER

Dissimilar welds between Al_2O_3 and AZX612-Mg alloy by friction stir spot welding

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Dissimilar welds between Al_2O_3 and AZX612-Mg alloy were obtained easily by a friction stir spot welding method with a machining center and a drilling machine. We analyzed the interface with scanning transmission electron microscopy energy dispersive X-ray spectrometry. The results suggested that the rotating tool induced the diffusion of Mg and Ca from the AZX612-Mg alloy, which reacted with Al_2O_3 , forming Mg, Al, and Ca compounds and creating a strong welding interface at low temperatures.

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1. Introduction

Welding techniques for joining ceramics and metals are required for electronic devices and biomaterials.^{1),2)} It is important to weld stronger, faster, and simpler. Recently, according to Fukumoto et al., the welds of Al_2O_3 and 5052-Al alloy were obtained by a friction stir spot welding (FSSW).³⁾ The welding can be performed in the atmosphere, without an insert material, and fast.⁴⁾⁻⁷⁾ Previously, we welded Al_2O_3 and 5052-Al alloy by FSSW and investigated the interface by scanning transmission electron microscopy (STEM) and energy dispersive X-ray spectrometry (EDS).⁸⁾ Mg was segregated into regions several dozens of nanometers wide along the interface. The welds of Al_2O_3 and 5052-Al alloy achieved with FSSW were strong owing to the formation of a compound containing Mg. If Al_2O_3 and metal containing Mg have been welded chemically by the FSSW, Al_2O_3 and AZX612-Mg alloy containing a large amount of Mg may be also welded strongly in the atmosphere and the short time. However, the study for the welds between Al_2O_3 and AZX612-Mg alloy obtained by the FSSW has not been reported yet. Therefore, Al_2O_3 and AZX612-Mg alloy have been welded with a machining center and a drilling machine and have been investigated the interface by STEM and EDS.

2. Experimental procedures

Al_2O_3 with high relative density of 99.5%, a purity of 99.5%, and a specimen size $50 \times 25 \times 5$ mm was used.

The welded surface of Al_2O_3 was mirror finished and the roughness, R_a , was $0.045 \mu\text{m}$. The composition of the AZX612-Mg alloy was Mg:Al:Ca:Zn:Mn:Si:Cu:Ni:Fe = 90.789:5.948:2.001:1.011:0.226:0.018:0.005:0.001:0.001 (mass %), and the AZX612-Mg alloy specimen size was $60 \times 30 \times 1$ mm. The specimen was as rolled and the roughness, R_a , was $0.776 \mu\text{m}$. The AZX612-Mg alloy was firmly anchored on Al_2O_3 . A machining center (Dura Vertical 5060, DMG MORI Co., Ltd.) using a 12 mm diameter tool with no probe or a drilling machine (B13, Hitachi) using an 8 mm diameter tool with no probe was used to obtain welds (Fig. 1). Tools were made of carbon steel. The bottoms of tools were flat. The bottom edge of the tool of the 12 mm diameter tool was not sharp, whereas that of the tool of the 8 mm diameter tool was sharp. For the machining center, the welding conditions were a tool rotation speed of 2000 rpm, a plunge rate of 1.7×10^{-3} mm/s, a tool holding time of 60 s, and a probe plunge

Fig. 1. Photographs of the machining center (a) and drilling machine (b).

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depth of 0.4 mm. For the drilling machine, a tool rotation speed was 3000 rpm. The rotating tool was inserted just above Al_2O_3 . The plunge depth was 0.5 mm when we measured after welding. The maximum temperature of the welding area for the drilling machine during welding was monitored by an infrared thermography camera (C2, FLIR). A tensile-shear test was performed with a tension tester (Instron Japan Co., Ltd., Instron 5582) to investigate the welding interface strength at room temperature. The welds were strained parallel to the welding interface. The loading speed was 1.7×10^{-1} mm/s.

A specimen welded by the machining center was used for examining the welding interface. A thin specimen was made with a focused ion beam apparatus (FB2200, Hitachi). The processing was performed by gallium ions with the acceleration voltage of 40 kV. The finish processing was performed at 10 kV. The welding interface was observed with STEM (HD-2700, Hitachi). The acceleration voltage for STEM-EDS was 200 kV. The detection angle for scattered electrons for the high-angle annular dark field (HAADF)-STEM image was $70 \text{ mrad} \leq \beta \leq 370 \text{ mrad}$. The elemental analysis of the welding interface was performed by EDS. The drift correction was not performed.

3. Results and discussion

A load applied by the tool during processing for the machining center was shown in **Fig. 2**. The load was increased monotonically to approximately 3100 N (27 MPa) in the tool tip location (z -axis) range of $-0.06 \leq z \leq 0$ after the tool made contact with the AZX612-Mg alloy. The load was decreased to approximately 1800 N (16 MPa) in the location range of $-0.12 \leq z < -0.06$. No large change in load was observed in the location range $-0.4 \leq z < -0.12$. Al_2O_3 and AZX612-Mg alloy were welded and the welds showed no cracks in the Al_2O_3 . The drilling machine also welded the two materials. The maximum temperature of the welding area during processing was 116°C ; however, although the temperature of the welding area was low, that of the welding interface may have been higher. The lower

Fig. 2. A load applied by the tool during processing for the machining center.

processing temperature prevented the dissimilar materials from cracking due to the difference in the coefficients of thermal expansion. The welds obtained with the machining center and the drilling machine are shown in **Fig. 3**.

As the result of the tensile-shear test, the specimens welded with the machining center and the drilling machine broke at 1383 and 655 N, respectively. The specimens after the tensile-shear test are shown in **Fig. 4**. Some Al_2O_3 was still attached to the AZX612-Mg alloy, indicating that the welding interface strength was higher than the breakdown strength of the Al_2O_3 .

An HAADF image of the welding interface is shown in **Fig. 5(a)**. The Al_2O_3 and AZX612-Mg alloy welds formed an interface with no voids or nanosized cracks. EDS line analysis of the welding interface was performed. Al, Mg, O, and Ca were detected at the welding interface [**Fig. 5(b)**]. It was considered that Ca was diffused into the interface by the rotating tool, Ca also reacted with Al_2O_3 , and Ca was segregated at the interface. Since Al, Mg, O, and Ca were coexisted around the welding interface, Mg, Al, and Ca compounds might be formed around the interface. It was speculated that these compounds contributed to the high strength of the welds.

4. Conclusion

Al_2O_3 and AZX612-Mg alloy were welded with a machining center and a drilling machine and the welding interface was investigated by STEM and EDS to study if

Fig. 3. Photographs of specimens welded with the machining center (a) and the drilling machine (b).

Fig. 4. Photographs of specimens welded with the machining center (a) and the drilling machine (b) after a tensile-shear test.

Fig. 5. HAADF image of the welding interface (a) and EDS line analysis of the welding interface (b). The white line in (a) indicates the scan area.

Al_2O_3 and AZX612-Mg alloy containing a large amount of Mg were strongly welded in the atmosphere and the short time. As the result of the tensile-shear test, the specimens welded with the machining center and the drilling machine broke at 1383 and 655 N, respectively. Some Al_2O_3 was still attached to the AZX612-Mg alloy, indicating that the welding interface strength was higher than the breakdown strength of the Al_2O_3 . The welds between Al_2O_3 and AZX612-Mg alloy were welded strongly with machine tools. STEM showed that the interface had no voids or cracks and EDS showed that Al, Mg, O, and Ca coexisted around the welding interface. It was considered that Ca was diffused into the interface by the rotating tool, Ca also reacted with Al_2O_3 , and Ca was segregated at the interface. Since Al, Mg, O, and Ca were coexisted around the welding interface, Mg, Al, and Ca compounds might be formed around the interface. It was speculated that these compounds contributed to the high strength of the welds.

References

- 1) 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).
- 2) C. Bertrand, Y. LePetitcorps, L. Albingre and V. Dupuis, *Br. Dent. J.*, **190**, 255–257 (2001).
- 3) M. Abbasi, A. Abdollahzadeh, B. Bagheri and H. Omidvar, *J. Mater. Eng. Perform.*, **24**, 5037–5045 (2015).
- 4) G. Faraji, O. Dastani and S. A. A. A. Mousavi, *J. Mater. Eng. Perform.*, **20**, 1583–1590 (2011).
- 5) F. Khodabakhshi, H. G. Yazdabadi, A. H. Kokabi and A. Simchi, *J. Mater. Sci. Eng. A*, **585**, 222–232 (2013).
- 6) S. H. Chowdhury, D. L. Chen, S. D. Bhole, X. Cao and P. Wanjara, *J. Mater. Sci. Eng. A*, **562**, 53–60 (2013).
- 7) Y. Bozkurt and M. K. Bilici, *Mater. Design*, **51**, 513–521 (2013).
- 8) H. Sonomura, T. Ozaki, K. Katagiri, Y. Hasegawa and T. Tanaka, *J. Ceram. Soc. Jpn.*, **127**, 127–130 (2019).