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1. Main Research Results

1) Interfacial microstructure and strength of Al/metallic glass lap joints fabricated by magnetic pulse welding

Magnetic pulse welding, which is a kind of impact welding, was applied to lap joining of pure aluminum and several kinds of metallic glass. In tensile test of the lap joint, fracture occurred at the Al matrix close to the welding interface, indicating that strong lap joints were obtained. The welding interface exhibited characteristic wavy morphology, as well as that of metal/metal joints. The intermediate layer was also observed along the wavy interface. TEM observation and TEM-EDS analysis revealed that the intermediate layer consists of fine grains of Al and amorphous phase with different composition from original metallic glass. Also, it is found that the metallic glass matrix retained the amorphous structure.

2) Growth behavior of intermetallic compound layer produced at friction stir welded Al/steel interface

Lap joining of an aluminum plate and a low carbon steel plate was performed using friction stir spot welding. The rotating tool was inserted from the Al plate-side which was overlapped on the steel plate and the tip of the tool was held above the Al/steel interface. The holding time was controlled in the range from 3 s to 60 s. In a condition of all holding time, strong lap joint was obtained. The welded area increased with increasing holding time. Intermetallic compound layer was produced along the welding interface. Thickness of the intermetallic compound layer increased with increasing holding time. Precise SEM-BEI observation indicates that the two contrasts were observed in the intermetallic compound layer. SEM-EDS analysis revealed that $Al_{13}Fe_4$ phase was produced at the Al side and Al_5Fe_2 phase was produced at the steel side. Thickness of the $Al_{13}Fe_4$ phase did not almost change in all holding time. On the other hand, thickness of the Al_5Fe_2 phase increased with increasing holding time. Such a characteristic growth manner of the IMC is considered to be due to increment of heat input induced by stirring of Al and friction heat generated between the Al and the rotating tool.

3) Interfacial microstructure and strength of stud welded aluminum alloy joint

Cylindrical 2xxx aluminum alloy studs were welded to 5xxx aluminum alloy plates using an advanced high-speed solid-state joining process. The welding machine has an electrode consisting of a double cylindrical copper tube. The stud was mounted at the end of the inner tube and was pressed against the 5xxx aluminum alloy plate. The end of the outer tube was also pressed against the plate. Then a discharge current was introduced to the stud through the plate surface and flew to the outer tube, which played the role of ground. The welding was achieved within a few milliseconds without temperature increase. Asymmetrical deformation took place for inside and outside of the circular ridge. The deformed area inside the ridge consists of a bundle of squashed grains. In contrast of that, the deformed area outside the ridge exhibited refined grain structure. This indicates that the outside was subjected to higher temperature rather than the inside. This attributed to that the discharge current mainly passed through the outside of the ridge. The stud

welded perpendicular to the plate surface was loaded in tension and joint strength was examined. Fracture surface of the joint region inside the circular ridge exhibited relatively flat surface with a limited number of dimples. On the other hand, fracture surface of the joint region outside the circular ridge was covered with small dimples entirely. Fracture strength was calculated using the measured tensile fracture load and the dimple area. The obtained fracture strength was equivalent to the tensile strength of 5xxx alloy.

2. List of Publication (original article, comment/book)

Original Paper

1) Mitsuhiro Watanabe and Shinji Kumai: "Interfacial Morphology of Magnetic Pulse Welded Aluminum/Aluminum and Copper/Copper Lap Joints", *Materials Transactions*, 50, 286-292, (2009).
2) Mitsuhiro Watanabe, Shinji Kumai, Go Hagimoto, Qingsheng Zhang and Koji Nakayama: "Interfacial Microstructure of Aluminum/Metallic Glass Lap Joints Fabricated by Magnetic Pulse Welding", *Materials Transactions*, 50, 1279-1285, (2009).
3) Mitsuhiro Watanabe and Shinji Kumai: "High-Speed Deformation and Collision Behavior of Pure Aluminum Plates in Magnetic Pulse Welding", *Materials Transactions*, 50, 2035-2042, (2009).
4) Mitsuhiro Watanabe, Go Hagimoto, Shinji Kumai, Hisamichi Kimura and Akihisa Inoue: "Microstructure of magnetic pulse welded metal/metallic glass interface", *Proceedings of the 18th International Symposium on Processing and Fabrication of Advanced Materials (PFAM XVIII)*, 4, 1981-1988, (2009).
5) Shinji Kumai, Mitsuhiro Watanabe, Keigo Okagawa and Tomokatsu Aizawa: "Similar- and dissimilar-metal joining using magnetic pulse welding", *Proceedings of the 18th International Symposium on Processing and Fabrication of Advanced Materials (PFAM XVIII)*, 4, 1933-1942, (2009).

3. Invited/Plenary Talk in Conference

International Conference or Workshop

1) Mitsuhiro Watanabe, Shinji Kumai, Qingsheng Zhang, Koji Nakayama and Hisamichi Kimura: "Intermediate Layer Produced at Magnetic Pulse Welded Aluminum/Metallic Glass Interface", The 3rd International Conference on the Characterization and Control of Interfaces for High Quality Advanced Materials, and Joining Technology for New Metallic Glasses and Inorganic Materials (ICCCI 2009), Kurashiki, Japan, 2009. 9. (Poster presentation)
2) Mitsuhiro Watanabe, Go Hagimoto, Shinji Kumai, Hisamichi Kimura and Akihisa Inoue: "Microstructure of magnetic pulse welded metal/metallic glass interface", The 18th International Symposium on Processing and Fabrication of Advanced Materials (PFAM XVIII), Sendai, Japan, 2009.12. (Oral presentation)
3) Shinji Kumai, Mitsuhiro Watanabe, Keigo Okagawa and Tomokatsu Aizawa: "Similar- and dissimilar-metal joining using magnetic pulse welding", The 18th International Symposium on Processing and Fabrication of Advanced Materials (PFAM XVIII), Sendai, Japan, 2009. 12. (Keynote lecture)

Domestic Conferences

1) Keisuke Hayashida, Mitsuhiro Watanabe, Shinji Kumai: "Strength and interfacial microstructure of stud

welded aluminum alloy joint", The 116th Spring Meeting of The Japan Institute of Light Metals, Noboribetsu, Japan, 2009. 5. (Oral presentation)

2) Keyan Feng, Mitsuhiro Watanabe, Shinji Kumai: "Interfacial microstructure and strength of friction stir spot welded aluminum alloy/plated carbon-steel lap joints", The 145th Fall Annual Meeting of The Japan Institute of Metals, Kyoto, Japan, 2009. 9. (Oral presentation)
3) Mitsuhiro Watnabe, Keyan Feng, Shinji Kumai, Yoshio Nakamura: "Interfacial microstructure and strength of friction stir spot welded aluminum/steel lap joint", The 117th Fall Meeting of The Japan Institute of Light Metals, Tokyo, Japan, 2009. 11. (Oral presentation)
4) Keyan Feng, Mitsuhiro Watanabe, Shinji Kumai: "Friction stir spot welding of aluminum alloy plates and plated carbon-steel plates", The 117th Fall Meeting of The Japan Institute of Light Metals, Tokyo, Japan, 2009. 11. (Oral presentation)
5) Keisuke Hayashida, Mitsuhiro Watanabe, Shinji Kumai: "Welding mechanism and strength of stud welded aluminum alloy joint", The 117th Fall Meeting of The Japan Institute of Light Metals, Tokyo, Japan, 2009. 11. (Oral presentation)