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Effect of Hook Morphology on Joint Strength of Friction Stir Spot Welded A5052 Aluminum Alloy/C1100 Copper Joint

Mitsuhiro Watanabe[1,a], Yuhao Pan[2,b], Yu Noguchi[3,c], Kazunori Yoshida[3,d]
[1]Department of Precision Machinery Engineering, College of Science and Technology, Nihon University
7-24-1 Narashinodai, Funabashi-shi, Chiba 274-8501, Japan
[2]Graduate student, Department of Precision Machinery Engineering,
Graduate School of Science and Technology, Nihon University
7-24-1 Narashinodai, Funabashi-shi, Chiba 274-8501, Japan
[3]Machining Technology Center, College of Science and Technology, Nihon University
7-24-1 Narashinodai, Funabashi-shi, Chiba 274-8501, Japan
[a] watanabe.mitsuhiro@nihon-u.ac.jp ; [b] csuk23029@g.nihon-u.ac.jp ;
[c] noguchi.yuu@nihon-u.ac.jp ; [d] yoshida.kazunori@nihon-u.ac.jp

Abstract – Lap welding of an A5052-H34 aluminum alloy plate and a C1100 pure copper plate was performed using friction stir spot welding. The aluminum alloy plate was overlapped on the copper plate. A high-speed rotating welding tool, which composed of a shoulder and a probe, was inserted from the aluminum alloy plate side and the probe tip of the welding tool was held at the position of 0.3 mm below the lapped interface. The dwell time of the welding tool was controlled in the range from 5 s to 30 s. The joint strength was evaluated by using tensile-shear test at room temperature. The microstructure of the joint was examined by using an optical microscope. The spot welding was accomplished at the tool dwell time more than 10 s. A doughnut-shaped welded area was observed at the periphery of the hole fabricated by plunging of the welding tool to the copper plate. The formation of hook of copper rising toward the aluminum alloy was observed at the bottom edge of the hole. The morphology of the hook varied with the tool dwell time. The fracture load of the joint evaluated by using the tensile-shear test decreased with increading the hook height divided by the hook width. It is assumed that a strong joint are formed when the hook height divided by the hook width is approximately 1.

Keywords**:** friction stir spot welding, aluminum alloy, copper, joint strength, hook formation

1. Introduction

Friction stir spot welding is a solid-state spot welding technique developed based on friction stir welding [1], in which a high-speed rotating cylindrical welding tool with a projection at the tip is plunged into the lapped base metals. This process results in metal softening due to generation of friction heat and plastic flow. The temperature during the welding process is usually lower than the melting point of the base metals, which is considered a significant advantage in controlling the formation of brittle intermetallic compounds which are usually produced in case of welding of dissimilar metals such as Al and Cu [2].

We previously studied relationship between the plunge depth and joint strength of friction stir spot welded Al/Cu joint, and reported that high joint strength is obtained at deep plunge depth [3]. Also, hook formation was observed in the strong joint. This is considered to mean that the hook formed at the bonding interface act as resistance to the shear load applied to the welding interface. Also, it is also reported that the joint strength changed when the dwell time of the welding tool is varied [4]. However, the relationship between the interfacial microstructure and joint strength is still unclear. In the present study, the relationship between hook morphology and joint strength of friction stir spot welded Al/Cu joint was investigated by changing the dwell time of the welding tool at the fixed plunge depth of the welding tool.

2. Experimental Procedure

An A5052-H34 aluminum alloy (called Al alloy, hereafter) plate and a C1100 pure copper (called Cu, hereafter) plate were used as the welding material. The thickness of each plate was 2.0 mm. Mechanical polishing using a #1000 waterproof abrasive paper was performed as the surface treatment before welding process. After the surface polishing, each plate was treated in acetone using an ultrasonic cleaner. An SKH51 high-speed tool steel bar was used as the welding tool material. The shape of the welding tool used in the present study is shown in Fig. 1. The present welding tool was consisted of a cylindrical shoulder and probe, and an M4 screw shape was fabricated on the side of the probe. The diameter of the shoulder and probe was 8.0 mm and 4.0 mm, respectively. The length of the probe was 2.3 mm.

Fig. 2 shows principle of friction stir spot welding. The friction stir spot welding was performed using a conventional vertical-type milling machine. The Al alloy and Cu plates were used as the upper and lower plates, respectively. Namely, the Al alloy plate was overlapped on the Cu plate, and they were fixed on the working table of the milling machine. The welding tool attached to the chuck of the milling machine was rotated at high speed and then was plunged from the upper Al alloy plate. The probe tip was dwelled at a certain plunge depth for a certain time, and then was retracted from the Al alloy plate. The rotational speed and plunge speed of the welding tool were fixed at 1735 rpm and 0.4 mm/s, respectively. The tip of the welding tool was plunged to a depth of 2.3 mm below the surface of the upper Al alloy plate. The tool dwell time was changed in the range from 5 s to 30 s, respectively.

To observe the microstructure of welding interface, the obtained joint was cut in cross section at the welded area and mirror-polished using mechanical polishing. An optical microscope was used to observe the microstructure. Tensile-shear test was used to evaluate the strength of the joint. The test was performed at room temperature at a tensile speed of 0.25 mm/min.

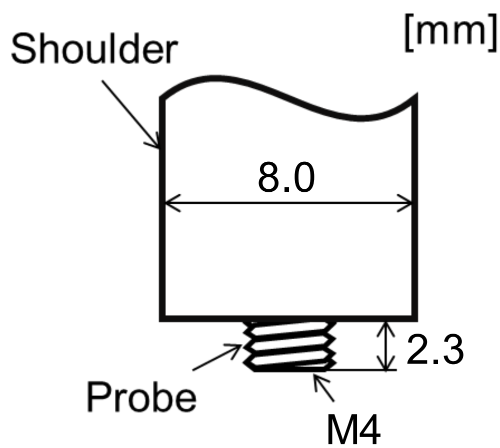


Fig. 1 Schematic illustration of welding tool.

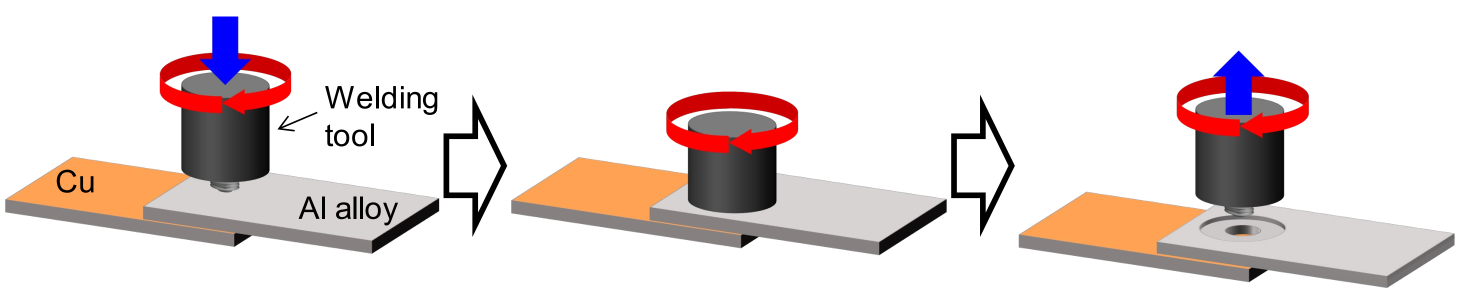


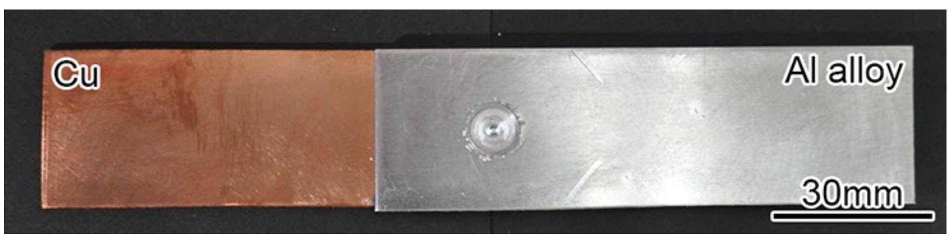
Fig. 2 Schematic diagram of principle of friction stir spot welding.

3. Results and Discussion

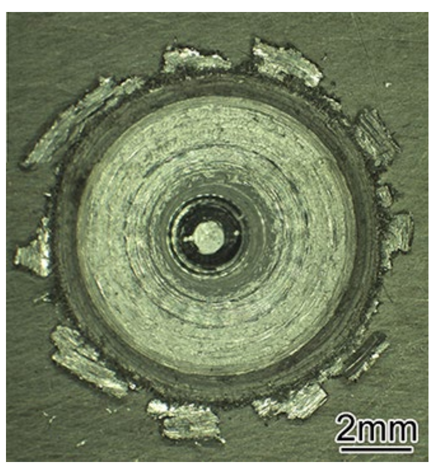
3.1. Macroscopic Appearance of Joint and Microstructure of Welded Area

Figure 3(a) shows a typical macroscopic appearance of friction stir spot welded Al alloy/Cu joint. The long plate on the on the right is the Al alloy and the long plate on the left is the Cu. The Al alloy and Cu plates overlap in a 40 mm × 30 mm mm area near the center. The spot welding was performed in the center of the area where the Al alloy and Cu plates overlapped, resulting in the imprint formation of the shape of the welding tool tip onto the Al alloy surface (Fig. 3(b)).

Figure 4 shows optical micrographs of cross section of welded area in the joints obtained by using the tool dwell time of (a) 10 s, (b) 15 s, (c) 20 s, (d) 25 s and (e) 30 s. The upper plate is Al alloy and the lower plate is Cu plate. In the present study, although we tried to weld the Al alloy and Cu plates by several tool dwell time, the welding was accomplished at the tool dwell time more than 10 s and was not achieved at the tool dwell time of 5 s. The shape of the welding tool tip was obviously imprinted to the Al alloy plate, as well as top view observation. The tip of the welding tool was plunged into a depth of 2.3 mm below the surface of the upper Al alloy plate. This indicates that the welding tool tip was plunged beyond the area of the Al alloy plate to a depth of 0.3 mm on the Cu plate side, since the thickness of the Al alloy plate is 2.0 mm, as described in Section 2. Regardless of the tool dwell time, a doughnut-shaped welded area was observed at the periphery of the hole fabricated by plunging of the welding tool to the Cu plate. The width of the welded area was approximately 800 μm, independent of the tool dwell time. The formation of hook of Cu rising toward the Al alloy was observed at the bottom edge of the hole, as indicated by arrows in the figures. The morphology of the hook varied with the tool dwell time. For the tool dwell time of 10 s, the hook was formed along the side of the welding tool. In the range of the tool dwell time from 15 s to 20 s, the tip of the hook moved away from the welding tool with increasing the tool dwell time. For the tool dwell time longer than 20 s, the hook was observed along the side of the welding tool.



(a)



(b)

Fig. 3 Macroscopic appearance of joint. (a) Joint observed from Al alloy side.
(b) Imprint formed by plunging of welding tool into Al alloy surface.

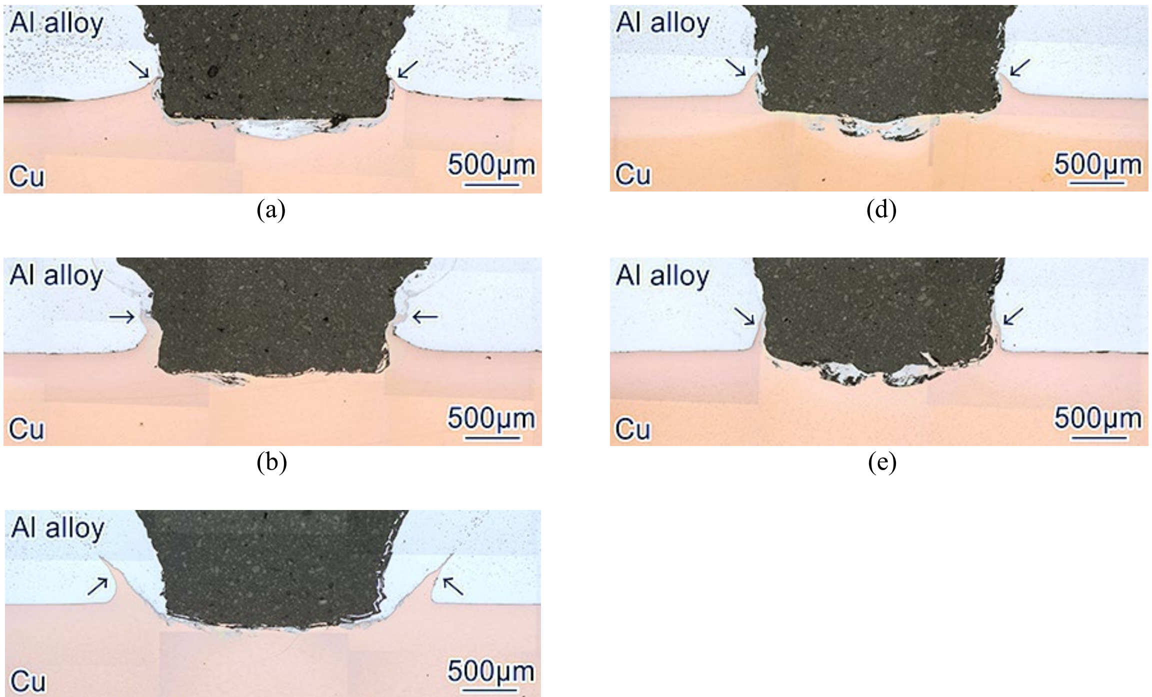
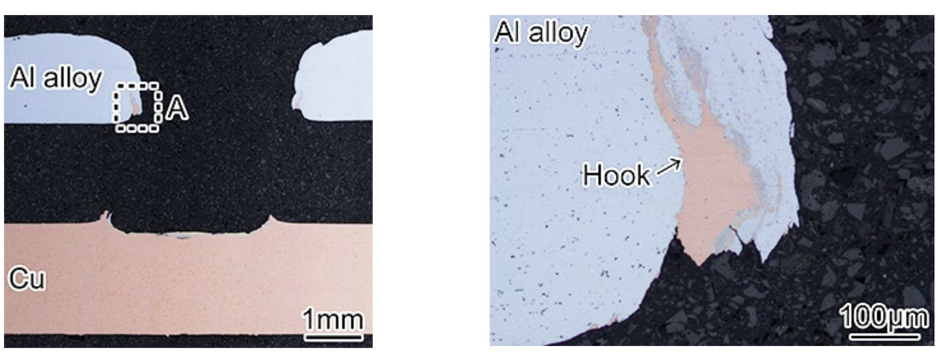


Fig. 4 Cross section of welded area in joints obtained by using each tool dwell time.
(a) 10 s. (b) 15 s. (c) 20 s. (d) 25 s. (e) 30s.

3.2. Joint Strength

Cross section of joint after tensile-shear test is shown in Fig. 5(a). The fracture by the tensile-shear test occurred at the welded area in the joint. In addition, the hook was fractured by shear load (Fig. 5(b)). This fracture at welded area was similar for the joints obtained at any tool dwell time. Figure 6 shows the relationship between the fracture load obtained by the tensile-shear test and the tool dwell time. In the range of the tool dwell time from 10 s to 20 s, the fracture load increased with increasing tool dwell time. On the other hand, in the range of the tool dwell time longer than 20 s, the fracture load decreased with increasing tool dwell time.



(a) (b)

Fig. 5 (a) Cross section of joint. (b) Enlarged image of area A indicated in (a).

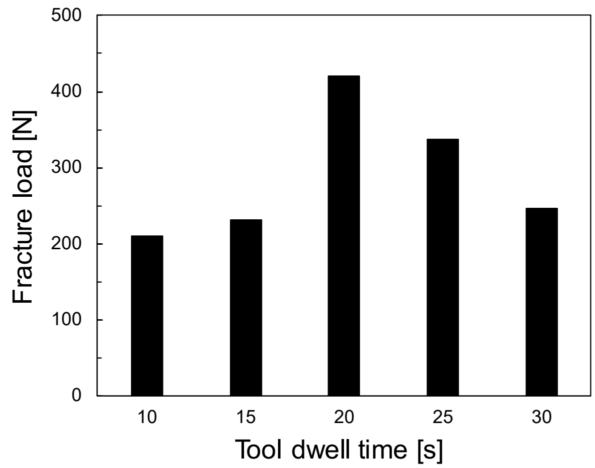


Fig. 6 Relationship between fracture load evaluated by tensile-shear test and tool dwell time.

Here, the joint strength as it varied with the tool dwell time is discussed. As shown in Fig. 6, the fracture load varied with the tool dwell time. Whereas the variation of the fracture load is assumed to depend on microstructural evolution in the welded area because the fracture ocurred in the welded area, precise observation indicated that the similar width of the welded area was formed regardless of the tool dwell time. On the other hand, the morphology of the hook formed at the bottom edge of the hole varied with the tool dwell time, as shown in Fig. 4. Therefore, the relationship between the morphology of the hook and the joint strength was investigated. For the quantitative evaluation of the morphology of the hook, the width from top of the hook to the side of the hole, *W*, and the height from the top of the hook to the original Cu surface, *H*, were measured and their ratio, *H/W*, was used, as shown in Fig. 7. This evaluation method of hook has been proposed by previous study [3]. Table 1 shows the relationship between the average *H/W* value and the dwell time. In most case, the *H/W* value larger than 1 was estimated. Figure 8 shows the relationship between the *H/W* value and the fracture load. The fracture load decreased with increading the *H/W* value. Li *et al.* investigated the relationship between joint strength and *H/W* value [3] and we can deduce from the results that a higher *H/W* value results in a higher fracture load. In the present study, the fracture load decreased with increasing the *H/W* value, which is opposite to the tendency reported by the previous study. This is assumed to be due to the difference in the range of *H/W* value. In the previous study, the formed hook had larger width than height, resulting in the *H/W* value smaller than 1. On the other hand, in most case in the present study, the hook with larger height than width were obtained, resulting in *H/W* value larger than 1. Therefore, the combined results of both study suggest that the strong joint are formed when the *H/W* value is approximatele 1.

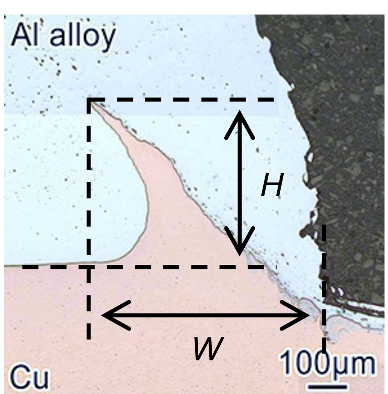


Fig. 7 Definition of hook morphology.

Table 1 Average *H/W* value of hook formed by using each tool dwell time.

Tool dwell time [s]	Average *H/W* value
10	5.1
15	2.8
20	0.7
25	2.2
30	12.3

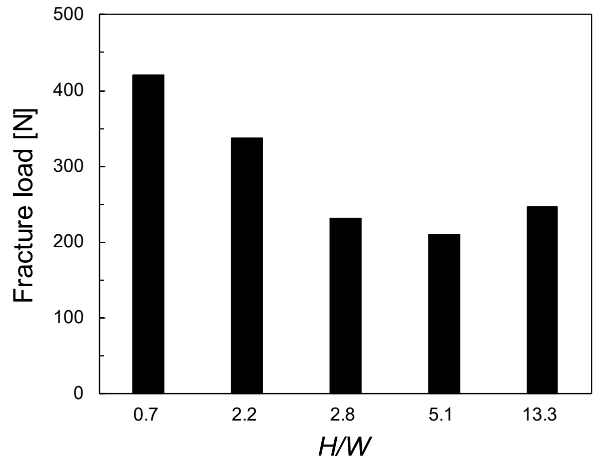


Fig. 8 Relationship between *H/W* value and fracture load.

4. Conclusion

Friction stir spot welding of A5052-H34 aluminum alloy plate and C1100 pure copper plate was performed with various dwell time of the welding tool. The spot welding was accomplished at the tool dwell time more than 10 s. A doughnut-shaped welded area was formed at the periphery of the hole fabricated by plunging of the welding tool to the copper plate. The Cu hook was formed at the bottom edge of the hole. The fracture load of the joint decreased with increading the hook height divided by the hook width. It is assumed that a strong joint are formed when the hook height divided by the hook width is approximately 1.

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