Advanced High-Speed Solid-State Joining of 2024 Aluminum Alloy Studs to 5052 Aluminum Alloy Plates*1

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Cylindrical 2024-T3 aluminum alloy studs were welded to 5052-H34 aluminum alloy plates by using an advanced high-speed solid-state joining method. Double cylindrical copper tubes, an assembly consisting of an inner tube and an outer tube, were used as electrodes. A stud having a circular ridge projection at its bottom was mounted at the end of the inner tube. The stud was then pressed against the plate surface. A discharge current was next introduced to the stud through the inner tube, whereupon the current flowed through the plate surface to the outer tube, which acts as a ground. The welding was completed within a few milliseconds without a notable increase in temperature of the joint. Subsequent examination revealed that the circular ridge projection had crushed and spread along the plate surface. Asymmetrical deformation occurred on both the inner side and outer side of the projection. The deformed area on the inner side of the projection consisted of a compacted grain structure. In contrast, the deformed area on the outer side exhibited a refined grain structure. These results indicate that the outside region was subjected to a higher temperature than the inside region. The joint was next investigated by tensile testing to evaluate its strength. The fracture surface of the joint region on the inner side of the projection exhibited a relatively flat surface with a limited number of dimples. On the other hand, that on the outer side was entirely covered with small dimples. Fracture stress was calculated by dividing the measured tensile fracture load by the dimple fracture area. The fracture stress thus obtained was found to be equivalent to the UTS of 5052-H34 alloy.

Keywords: stud welding, solid-state joining, aluminum alloy, fracture stress, microstructure

1. Introduction

Stud welding is a widely used technique for joining a metallic stud, such as a pin or screw, to a metallic plate. With conventional stud welding, however, heat generated during the process often causes distortion of the plate and tarnishing on its back surface. These can be serious problems when the plate is thin or when the plate has been painted or surface-treated for decorative purposes. Such problems can be avoided, however, through the use of a recently developed stud joining method, described here and in reference.1) This joining mechanism is one reason why we refer to the method as “advanced high-speed solid-state joining”. Through its use of a specially designed stud and a controlled discharge current path, the method minimizes the temperature increase at the welding surface and heat input to the weld joint, thereby making it possible to join strongly dissimilar aluminum alloys without plate distortion or tarnishing2,3) (see Figs. (a) and (b)).

In this study, we welded cylindrical 2024 aluminum alloy studs to 5052 aluminum alloy plates. We next investigated the microstructure of the joint interfaces and the fracture strength of the joints. On the basis of these results, we discuss the welding mechanism.

2. Experimental Procedure

2.1 Joining principle

The basic principle behind this joining method is to instantaneously run a large current through the local contact point between the stud and the plate by means of a discharge circuit. The discharge circuit includes a specially designed electrode. We also used a specially designed stud having a circular ridge projection at its bottom. Figure 2 shows a schematic illustration of the joining procedure. We begin with a double cylindrical copper tube, consisting of an inner tube and outer tube that together serve as a pair of electrodes (Fig. 2(a)). The stud is mounted at the end of the inner tube. The stud is then pressed against the plate surface by air pressure, as shown in Fig. 2(b). Next, as shown in Fig. 2(c), a discharge current is introduced to the stud through the inner tube, whereupon current flows through the plate surface on to the outer tube, which acts as a ground. High-density current running through the contact point acts to increase the local temperature. This promotes plastic deformation and enhances atomic diffusion at the contact point. As a result, the stud welded joint is obtained (Fig. 2(d)).

The welding is normally completed within a few milliseconds, which is another reason why we refer to this method as “advanced high-speed solid-state joining”. The joint is cool enough to touch immediately after welding; that is, the temperature increase of the joint is negligible.
2.2 Materials

Materials used in the present study were 2024-T3 aluminum alloy studs and 1.5-mm-thick 5052-H34 aluminum alloy plates. Figure 3(a) shows a general view of a stud. The stud is basically a wide-based cylindrical tube with circular ridge projection at the bottom. It is also provided with an internal thread. Figures 3(b) and (c) show a partial cross-sectional view of the stud and a close-up of the cross section of the circular ridge projection.

2.3 Joining conditions

Joining experiments were performed with a stud-welding machine developed by Akebono Kikai Ltd. Optimal joining conditions differ according to the physical and mechanical properties of the alloys to be joined. The electric conductivity and hardness of an alloy depend on its chemical composition, degree of cold working and heat treatment conditions. The size and morphology (shape) of the stud and plate also affect welding conditions. Numerous preliminary tests were performed in advance to establish optimal operating conditions, and thereby we determined the type of electrode, level of applied air pressure and the capacitance of the discharge capacitor which were best suited for the present alloy combination. In this study, joining experiments were performed under three different discharge voltage conditions (415, 445 and 475 volts), with all other parameters kept constant.

2.4 Microstructural analysis

The microstructure of the joint interface was observed under an optical microscope. To observe the grain structure of the 2024 alloy, a polished metal surface was etched with Keller’s reagent (HF: 1.0, HCl: 1.5, HNO₃: 2.5, H₂O: 95 (vol%)) at room temperature. Also, back-scattered electron imaging (BEI) was also carried out on a scanning electron microscope (SEM). The hardness change at the joint interface was examined by nano-indentation (load: 200 mgf). The change of chemical composition across the joint interface was investigated using an electron probe microanalyzer (EPMA) under an acceleration voltage of 20 kV, a beam diameter of 1 μm and a measurement interval of 1.5 μm.

2.5 Tensile testing and fractography

The joined stud was loaded in tension perpendicular to the joining interface at a crosshead speed of 0.1 mm/s (Fig. 4). A load-displacement curve was recorded until fracture. For some specimens, the tensile test was interrupted at arbitrary displacements to observe the progress of fracture. Fracture surfaces were observed using a stereomicroscope and SEM at an acceleration voltage of 20 kV. For fracture stress calculation, the area of the fracture surface covered with dimples was also measured.

3. Results and Discussion

3.1 Morphological change of the projection on the plate

We examined the morphological change of the tip of the circular ridge projection after joining. Figures 5(a) and (b) show optical micrographs of macroscopic cross-sectional views of the stud before and after joining. Figures 6(a) to (c) show close-ups of areas within the framed portion of Fig. 5(b). These photographs show deformation behavior of the projection at each discharge voltage—415 V (Fig. 6(a)), 445 V (Fig. 6(b)) and 475 V (Fig. 6(c)). From these photographs we can see that (i) the tip of the projection was pressed onto the plate and crushed over the plate surface; (ii) deformation becomes more severe with increasing discharge voltage; and (iii) the manner of deformation was different at the “inside” of the projection (inner side; left side in the photographs) and the “outside” of the projection (outer side; right side in the photographs).
3.2 Microstructural change at the joint interface

We next examined the microstructures more precisely. We polished a cross section of the joint, and to reveal the microstructure of the 2024 aluminum alloy stud, etched the cross section with Keller’s reagent. Figure 7 shows the grain structure of the stud (Keller’s reagent does not readily etch 5052 aluminum alloy, so the polished surface of the plate remained essentially intact). The original microstructure of the projection is characterized by columnar grains, as apparent in the upper part of Fig. 7. This is because the stud was machined from an extruded bar. Below, we describe the most notable characteristics for three regions at the joint interface: “Central” (frame B), “Inside” (frame C) and “Outside” (frame D).

3.2.1 Central region

The very tip of the projection kept its original macroscopic shape and grain structure even upon being embedded in the plate, as apparent in the area indicated by arrow A in Fig. 7. See Fig. 3(c) for comparison. Figure 8(a) shows an SEM-
The joint interface on the outer side of the projection is a wavy interface, sometimes with clear gaps, between the 2024 alloy (stud) and 5052 alloy (plate). The wavy interface corresponds to the cross section of the original machined surface of the projection, as shown in Fig. 8(b). This shows that although the tip of the projection was pressed into the plate, no bonding took place in this region.

3.2.2 Inner and outer sides of the projection

In contrast to the central region, remarkable microstructural change was detected at both the inner and outer sides of the projection, areas indicated as frame C and frame D, respectively, in Fig. 7. We note asymmetrical deformation at the inner and outer sides of the projection.

Figure 9(a) shows a close-up of a portion of frame C. The deformed area inside of the projection consists of compacted grains. The grains have been flattened and their alignment drastically altered.

As shown in Fig. 9(b), the deformed area on the outer side (frame D) was etched heavily and exhibited refined grain structure. Also, in the protruded area (knot-like area indicated by arrow E in Fig. 7), a dendritic structure was observed. This shows that the area melted and then solidified.

Additional microstructure analyses were conducted to highlight differences between areas at the outer and inner sides of the projection.

Figure 10(a) is a BEI (composition) image of the joint interface within frame C of Fig. 7. There is a clear difference in contrast across the joint interface; no alloyed region can be observed. In addition, secondary particles dispersed in the 2024 alloy matrix (particles showing bright contrast in the figure) were present in the stud before and after joining.

We observe a wavy interface, sometimes with clear gaps, between the 2024 alloy (stud) and 5052 alloy (plate). The wavy interface corresponds to the cross section of the original machined surface of the projection, as shown in Fig. 8(b). This shows that although the tip of the projection was pressed into the plate, no bonding took place in this region.

3.3 Origin of microstructural differences between inner side and outer side of the projection

Let us consider why microstructure and deformation manner would be different at the inner side and the outer side of the projection. The mechanism of the joining method is considered to be as follows. A high-density discharge current runs from the inner copper cylinder through the narrow contact point between the projection tip and the plate. The discharge current generates Joule heat, which increases the local temperature. This temperature increase causes softening of the materials at the joint interface and promotes local plastic deformation. Shear deformation at the projection tip breaks through the oxide layers on the original aluminum alloy surfaces, producing a fresh surface on each. This promotes metallic bonding between the alloys. The temperature increase also significantly enhances atomic diffusion at the contact point. For these reasons, high-speed solid-state joining with the present method is possible.

That said, these phenomena are presumably common to both sides of the projection. From where, then, does the difference arise? The important point here is the position of the outer copper cylinder, which acts as a ground and thus draws the dominant current toward the outer side along the very surface of the plate. Thus, the local temperature increase, together with the resultant plastic deformation, is inferred to be much larger at the outer side of the projection. This thus explains why an alloyed region forms at the interface and why secondary particles within the matrix are reduced in terms of both size and volume fraction. Similarly, the excess temperature increase at the outer side of the projection can cause partial melting of the projection, the molten region of which is then extruded.

It should also be noted that the characteristic local and instantaneous current, because of the narrowness of its path and its short duration, acts to forestall an increase in temperature throughout the stud and plate as a whole.
**Fig. 10** Change in microstructure, hardness and chemical composition across the joint interface inside of the projection. (a) BEI of the joint interface inside of the projection in the frame “C” in Fig. 7 (b) Hardness change across the joint interface (c) Chemical composition change across the joint interface.

**Fig. 11** Change in microstructure, hardness and chemical composition across the joint interface outside of the projection. (a) BEI of the joint interface inside of the projection in the frame “D” in Fig. 7 (b) Hardness change across the joint interface (c) Chemical composition change across the joint interface.
3.4 Fracture behavior of the joint

Figure 12 shows a typical load-displacement curve obtained by the tensile test. In the course of loading, a pop-in was observed. Final fracture takes place after further loading from that point. Figure 13 shows the relationship between fracture load and applied discharge voltage. We see that fracture load increases with increasing discharge voltage.

Differences in the microstructure of the regions led to differences in their fracture behavior. Figure 14 shows a cross-sectional view of the stud projection after tensile testing. The tip of the projection, which was embedded in the plate, keeps its original shape, which means that no joining occurred in this region (see also Fig. 3(c) (region before joining) and Fig. 7 (region before tensile testing)). The fracture surface within this region on the inner side of the projection tip, indicated by frame A in Fig. 14, is shown as Fig. 15(a). The fracture surface is relatively smooth; there are only a few small pieces of 5052 alloy (bright contrast) adhering to the fracture surface. As shown in Fig. 15(b), on the other hand, the fracture surface within this region on the outer side of the projection tip, indicated by frame B in Fig. 14, is rough and covered with a large amount of 5052 alloy.

Interrupted tensile tests revealed that the pop-in in the load-displacement curve, shown in Fig. 12, can be attributed to a somewhat brittle fracture of the joining area on the inner side of the projection. Final fracture took place in the area on the outer side of the projection. Figure 16(a) shows an SEM micrograph of the fracture surface of the fractured projection of Fig. 14. The fracture surface on the inner side has a flat appearance with a limited number of dimples. In contrast, the fracture surface on the outer side is relatively rough. Detailed SEM observation of the location indicated by frame B of Fig. 14 is presented in Fig. 16(b). Here, we can see that the...
Fracture surface was entirely covered with small dimples, indicating that ductile fracture occurred.

3.5 Fracture stress of the joint

Because the final fracture load corresponds to the fracture over the region on the outer side of the projection, we can consider the fracture strength (load) of the stud joint to be dependent on the quantity of the joint area in this region. We thus measured the area covered with dimples to obtain a total fracture area.

Figure 17(a) shows the relationship between the area covered with dimples and discharge voltage. The area increases with discharge voltage. We divided the fracture load values obtained in tensile testing (Fig. 13) by the measured fracture areas to determine fracture stress values. These are presented for each discharge voltage in Fig. 17(b).

The fracture stress values thus obtained are constant and equivalent to the UTS of 5052-H34 alloy of the plate (260 MPa). This demonstrates that strong stud joints were obtained with the method described in this paper. These results also provide insight into how joint strength can be further increased; that is, by enlarging the joining area on the outer side of the projection, we should be able to increase the fracture load.

4. Summary

Cylindrical 2024-T3 aluminum alloy studs with a circular ridge projection at the bottom were welded to 5052-H34 aluminum alloy plates using what we refer to as “advanced high-speed solid-state joining”. The welding was achieved within a few milliseconds without a notable temperature increase of the joint. This stud-welding method, based on solid-state joining, was quite useful in obtaining high-strength, damage-free stud welds. We attribute this capability to the special design of the studs and the use of a unique tubular electrode arrangement. Microstructural observation revealed that the tip of the projection spreads over the plate surface upon joining. Asymmetrical deformation occurred at the inner and outer sides of the projection because of a difference in current flow at those two locations. An investigation of fracture surfaces after tensile testing revealed the fracture surface on the inner side of the projection to be relatively flat, whereas the fracture surface on the outer side of the projection was entirely covered with small dimples. Fracture stress, that is, the strength of the stud/plate joint, was found to be equivalent to the UTS of the 5052-H34 plate.

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