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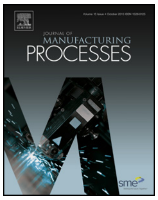

Technical Paper

Joining steel studs and steel plates by solid-state stud welding and estimation of temperature near the joint interface

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ABSTRACT

In solid-state stud welding, joining is completed within a few milliseconds by using a large discharge current and pressure. Materials with high electrical resistivity are candidates for producing higher Joule heat from the same electric discharge energy. In this study, the suitability of solid-state stud welding for joining steel studs to steel plates was examined. Steel studs were successfully joined to steel plates at charged voltages of 125–200 V without distortion of the plate and tarnish marks on the back surface. The joint interface between the projection and plate was arc-shaped. The deformation behavior was notably different from that in previous reports of joining aluminum alloy studs to aluminum alloy plates or magnesium alloy plates. Observation of the joining area revealed that the projection and plate deformed and spread along the plate surface, squeezing the plate material. The projection and plate deformed more severely as the charged voltage increased. The original shape of the projection tip was partially retained in the joints formed at 125 and 150 V. The amount of martensite observed near the joint interface increased with the charged voltage. The ferrite was not observed above 175 V in the center, and above 150 V inside and outside of the projection near the joint interface. To estimate the maximum temperature reached during joining, the microstructures of the stud and plate heated at various temperatures were compared with those of joint specimens. Because ferrite and martensite was observed near the joint interface, the maximum temperature reached during joining could be estimated by the presence or absence of the ferrite and martensite. The region where the temperature increased above the A_1 point extended only about 500 μm around the joint interface. Because the majority of the specimen was room temperature and removed heat rapidly from the joint interface, martensite was formed despite the air cooling after joining. The tensile fracture load increased with the charged voltage. The stud and plate were joined strongly enough for the base plate to fracture partially during the tensile test.

1. Introduction

Common stud welding method is widely used for joining metallic studs, such as pins or screws, to metal plates. This conventional method generates excess heat input for melting the joint materials during the welding process. A solid-state stud welding method has recently been developed to suppress the excess heat input. In this method, joining is completed within a few milliseconds by using a large capacitance discharge current and pressure. A specially designed stud having a circular projection at its bottom is pressed against a plate surface. The discharge current is introduced from the upper part of the stud. Local heating can be achieved by a high current density at a contact point between the projection and plate. The projection and plate are deformed by local heating and pressure. Since the deformed projection and plate make contact at a bare surface newly formed by the removal of the oxide film, joining can be achieved at the contact point in solid state. Because the projection shape, electrode shape, and current path are contrived, a sound joint is obtained, suppressing excess heat input. An advantage of the method is that, unlike conventional fusion welding (e.g., arc stud welding and resistance spot welding), it does not distort thin plates or tarnish its back surface, and thus is suitable for joining studs to thin plates and surface-treated or painted plates. Kumai et al. reported that solid-state stud welding joined AA2024-T3 aluminum alloy studs to AA5052-H34 aluminum alloy plates strongly without the back surface of the plate becoming tarnished [1]. Takaya et al. also reported joining AA2024-T3 aluminum alloy studs to AA6N01-T6 aluminum alloy plate [2]. A softened zone

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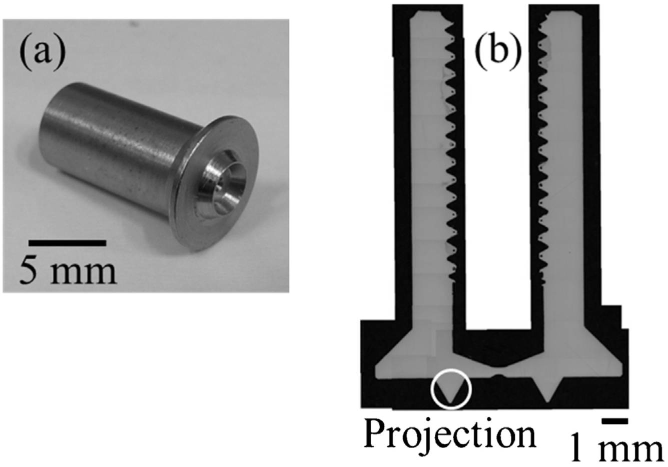

Fig. 1. (a) Photograph of appearance and (b) cross-sectional view of stud.

appeared at the plate adjacent to the joint interface. The hardness of the softened zone recovered to that of the AA6N01 aluminum alloy upon post-joint aging. This finding indicates that softening is caused by the dissolution of β" precipitates in the aluminum matrix due to the welding heat input. Harada et al. reported that in the dissimilar joining of AA2024-T3 aluminum alloy studs to AZ80-F magnesium alloy extruded plate, the aluminum alloy projection penetrated the magnesium alloy plate [3]. As the charged voltage increased, the projection bent toward the outer side of the stud, along the main current route. Refined AZ80 magnesium alloy grains were observed near the joint interface. This revealed that local plastic deformation and heating induced dynamic recrystallization within the plate. A 1-μm-thick layer of $Mg_{17}Al_{12}$ and Al_3Mg_2 was observed along the joint interface.

Materials of the stud or plate used in the previous works were aluminum alloy and magnesium alloy. Steel is one of the important materials, but there is no reported example of using this welding technique. Since the physical characteristics, such as electrical resistivity and melting point, of steel is quite different from that of aluminum and magnesium, it is unclear whether this welding technique can be applied or not. If this technique is possible also applied to steel, that will be applicable to many of the industrial products in the world. In solid-state stud welding, the projection and plate are deformed by Joule heat generated at the contact point. Materials with a high electrical resistivity are expected to produce higher Joule heat with the same electric discharge energy, and steels have higher electrical resistivity than aluminum alloys. For example, JIS-SS400 steel has a resistivity of $16.9 \times 10^{-8}\ \Omega$ m, whereas AA2XXX aluminum alloy has a resistivity of $5.75 \times 10^{-8}\ \Omega$ m at 20 °C. Therefore, in this work we focused on joining steel studs to steel plate.

Table 1
Chemical compositions of materials used in this study (mass%).

C	Si	Mn	P	S	Fe
(a) SS400 steel stud					
0.20	0.05	0.84	0.025	0.040	Bal.
(b) SPCC steel plate					
0.03	0.01	0.15	0.013	0.004	Bal.

Temperature near the joint interface is very important factor for the welding. However, it is difficult to measure that with a thermocouple during solid-state stud welding, because a high discharge current flows into the thermocouple. According to the Fe–C binary phase diagram [4], the phase transformation from ferrite to austenite occurs above the A_1 point (727 °C), and martensite is formed by rapid cooling of austenite. Therefore, steel is a suitable material for estimating the maximum temperature reached during joining by observing the microstructural changes near the joint interface. Here, we examine the applicability of solid-state stud welding to joining steel studs to steel plate and estimate the maximum temperature reached during welding.

2. Experimental procedures

2.1. Materials

The materials used in this study were specially designed steel (JIS-SS400) studs and steel (JIS-SPCC) plate (thickness: 2 mm). The chemical compositions of the materials are listed in Table 1. Fig. 1(a) and (b) shows a photograph of appearance and a cross-sectional view of a stud. The stud has a 1-mm-high circular projection at the bottom, and the projection tip diameter is 4 mm.

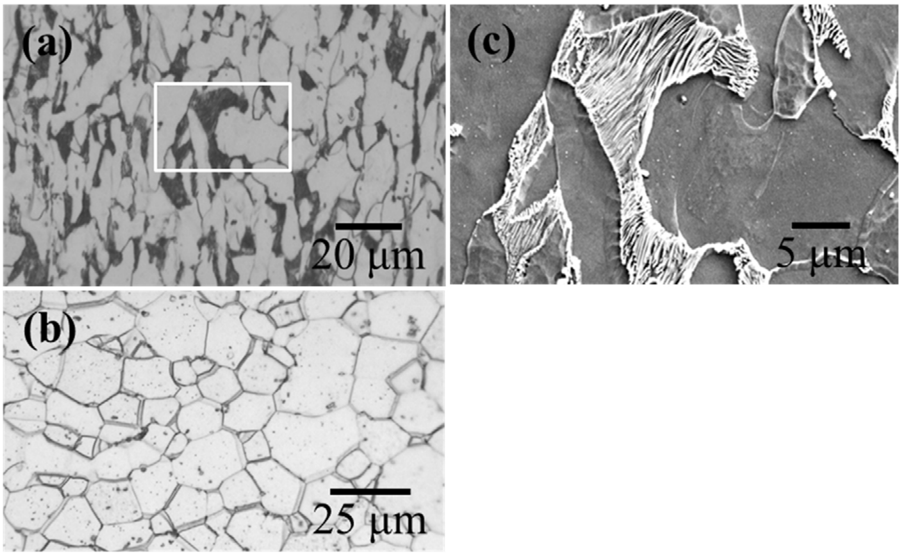

Fig. 2. Microstructures of (a) stud and (b) plate before joining. Magnified SEM-SEI image of the framed area in (a) is shown in (c).