Development of Disc Friction Joining and its Application to Dissimilar Butt Joining of Aluminum and Resin Plates

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We have developed a joining process which we named disc friction joining (DFJ). DFJ is a solid state butt joining method that utilizes a rotating disc that is sandwiched and compressed by two plates to be joined. Frictional heat generated at the contact interfaces effectively softens the materials to be plasticly deformed by the compression force applied, yielding a joint interface once the disc is withdrawn and the plates make contact. The feasibility of DFJ was examined by joining commercial pure aluminum and polyethylene terephthalate (PET) plates. These materials were successfully joined, and the joint exhibited a tensile fracture stress of 17.1MPa at room temperature.

Key Words: dissimilar joining, rotating disc, aluminum, polyethylene terephthalate, interfaces, tensile strength

1. INTRODUCTION

Joining and welding are essential technologies fabricating industrial products. Solid-state joining methods, such as diffusion bonding1), rotary friction welding2), ultrasonic welding3), friction stir welding (FSW)4), friction stir spot welding5), and linear friction joining6, 7) are widely utilized for materials such as aluminum alloys or dissimilar materials, since they are not easily welded by conventional fusion welding8).

Dissimilar joining is a key for realizing the Sustainable Development Goals (SDG’s)9), since energy-conscious engineering such as the production of cutting-edge high-mileage-vehicles, requires “multi-material-structures” composed of light and functional materials. Welded joints inevitably possess peculiar microstructures near the joint interface that are different from that of the base metal because of the heat and plastic deformation caused by the welding process. This results in discontinuities of the mechanical properties of the joints. In particular, FSW produces a unique microstructure called onion rings5). Although FSW is a suitable linear welding technique for metallic plates, it modifies the microstructure of a large portion of the joint. Thus, there is a need to develop a novel joining method to achieve linear welding with minimal effects on the joint microstructure.

We have designed a new welding method based on friction welding which was presented in a previous report on the use of a rotating disc to join bars. However, no attempt was made to join plates10). The present welding method is applicable for the continuous and linear butt joining of plates. Furthermore, it is possible to join metals to resins, which is difficult to achieve with fusion welding and FSW.

The present study was the first to examine the feasibility of disc friction joining (DFJ) for the dissimilar joining of metals to resins, such as an aluminum plate to a polyethylene terephthalate (PET) resin plate.

2. EXPERIMENTAL PROCEDURE

2.1 Disc Friction Joining

DFJ comprises two fundamental processes, friction and forging, which are schematically shown in Fig.1 (a). The friction process generates frictional heat between the rotating disc and contacting plates, which are compressed perpendicularly to the disc. The subsequent process is called forging, where the plates meet each other under compression just after passing the periphery of the disc.

The outline of the DFJ process is shown schematically in Figs.1-(b) - (f). Two plates are firmly fixed on the sliding apparatus of the joining machine (b). Subsequently, a disc sandwiched by these plates begins to rotate by a servo-motor with a fixed rotation speed (c). The disc is simultaneously compressed by the plates via a gas-pressure module (d). The plate materials are partially softened near the contact interface due to frictional heating. After a few seconds of frictional heating, the rotating disc is withdrawn from the plates (e), and a joint between the plates forms (f). The welding direction is the withdrawing direction of the disc.

2.2 Joining conditions and evaluation of joints

The materials used were commercial pure aluminum A1070-H24 and PET resin plates. The specimens for the joining tests had 2mm thicknesses, 30mm lengths, and 10mm widths. A disc made of SKH51 steel with a 140nm diameter and 0.5mm thickness was used with rotation...
speeds up to 2000 rpm. The gas pressure to provide a compression force of 23 N on the joint interface was applied for the entire joining.

After 2 s of frictional heating, the rotating disc was quickly withdrawn to allow the plates to contact under pressure. K-type thermocouples were spot welded to record the temperature history at points 1mm from the joint interface during joining. The temperatures on both sides of the plates were measured.

An optical microscope was used to examine defects and evaluate the microstructures of the joints after mechanical polishing of the cross-sections with emery papers and diamond paste. Tensile tests of the joints were carried out at ambient temperature with an initial strain rate of 5.6 x 10^-4 s^-1 after removing the burr. The tensile specimens were prepared after removing the burr followed by polishing to yield flat surfaces, and the dimension was 8mm x 55mm x 1.6mm. The actual gauge length was 30mm. The fractured surfaces of the tensile tested specimens were observed with a low-vacuum scanning electron microscope, (Hitachi Miniscope TM3030).

### 3. RESULT AND DISCUSSION

The top and bottom views and cross-section of an A1070/PET joint produced by DFJ are shown in Fig.2. The top view (a) of the joint, in which 1070 aluminum is on the right side, clearly shows that a burr of the resin formed along the direction of motion of the rotating disc, i.e. the welding direction as indicated by the arrow. The bottom view (b) of the same joint also shows the burr. Based on this observation, the joint formation is mainly attributed to the deformation or flow of resin at the contact surfaces during the forging process.

Fig.2 Top and bottom views and cross-section of A1070/PET joint produced by DFJ. (a) top view, (b) bottom view, (c) macroscopic view of cross section, and (d) magnified image of the white circle in (c), showing an uneven interface.

No significant defects such as tunnels or grooves, were observed, in the macroscopic and magnified images shown in Figs.2 (c) and, (d). The mark on the right top side in Fig.2 (c) indicates the welding direction perpendicularly towards the other side. Thus the DFJ produced a high quality joint with no defects throughout the thickness. The magnified view of the interfacial region shows a zig-zag shape of the interface, i.e., asperities with sizes of several tens of micrometers on the joint interface. This implies that joining is due to an anchoring effect caused by the resin being injected into the pits on the aluminum side, while other mechanisms, such as chemical bonding, should also be considered to fully understand the joining mechanisms of DFJ.

Figure 3 shows temperature histories of the aluminum and the resin, which were measured 1 mm from the disc in both materials. On the aluminum side, the temperature increased monotonically as the friction heating occurred and reached a maximum temperature of 576.6K after 2 s. As commercial grade aluminum is softened above around
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