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Direct joining of carbon-fiber–reinforced plastic to an aluminum alloy using friction lap joining

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ABSTRACT

A carbon-fiber–reinforced thermoplastic (polyamide 6 with 20 wt.% carbon fiber addition) and an aluminum alloy (A5052) were joined using friction lap joining. The joint characteristics were evaluated to investigate the effects of A5052 surface treatments and the joining speed on the joint properties. Carbon-fiber–reinforced thermoplastic and A5052 were joined via an interfacial magnesium oxide layer. Surface grinding of the A5052 generated the aluminum hydroxide on the alloy surface and increased the tensile shear strength of the joint. The tensile shear strength increased as the joining speed increased from 100 to 1600 mm min^{-1}, and decreased thereafter.

1. Introduction

Polymeric/plastic materials are extensively utilized in many industries to achieve significant weight reduction, superior thermal and electrical insulation, design flexibility, and good corrosion resistance in manufactured components [1]. Carbon-fiber–reinforced plastics (CFRPs) have been introduced recently as structural materials in aircraft and automobiles, where they can reduce fuel consumption and CO_2 emissions by virtue of their light weight and remarkable mechanical properties [2–6]. In particular, carbon-fiber–reinforced thermoplastics (CFRTPs), made by adding carbon fibers to thermoplastic matrix materials such as polyamide, polyphenylene sulfide, and polyethylene have large specific tensile strengths compared to conventional metal materials and retain several key polymer materials properties. In addition, CFRTPs are highly processable since they can be formed using mold-injection methods [4–6]. Because of these advantages, dissimilar joining techniques for attaching CFRTPs to metals have been developed to expand the range of applications for CFRTPs and improve their manufacturing production and performance characteristics. However, the direct joining of CFRTPs to metal materials is difficult because of their fundamentally different chemical and physical properties [1,7].

Adhesive bonding and mechanical fastening are conventional processes for joining plastic materials, including CFRTPs, to metals [8–14]. However, these joining techniques have several drawbacks. Adhesive bonding produces environmental pollutants in the form of volatile organic compounds emitted during processing, requires long processing times for efficient bonding, and provides non-uniform and/or insufficient joint strengths. Mechanical fasteners not only produce stress concentrations, reduce air-tightness, and increase weight, but are also not suitable for many mass production schemes. Other approaches to the direct joining of plastic materials to metals have been investigated recently, such as a laser joining [7,12–17], ultrasonic welding [18–20], and friction spot joining [21,22]. Katayama et al. [12–16] developed a laser-based direct-joining process for metals and plastics. In this process, a metal and a plastic material are joined using the heat produced by laser irradiation of the metal substrate. This technique can join plastics and various kinds of metal materials directly at high speed. The limitations of this process include the high cost of the laser unit, deterioration of the joined materials, and the complex welding parameters involved. Ultrasonic lap welding and friction spot joining can also form joints between plastics and metals; however, the dimensions and joint geometry are restricted.

These problems can be solved or mitigated by employing the friction lap joining (FLJ) method, which is a novel direct joining method capable of joining plastic materials, including CFRTPs, to

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metals [23,24]. Fig. 1 shows the FLJ technique schematically. FLJ can be carried out using a friction stir welding (FSW) apparatus [25,26], and uses the heat energy generated by friction between the rotating tool and metal surface. A reusable rotating tool is pressed into the surface of the metal plate and dragged along the overlap region. The tool not only heats the materials to be joined but also applies pressure at the joint interface [23,24]. The appearance of a FLJ joint is similar to that of a FSW joint. The tool in FSW incorporates a stirring probe to assist material flow, but the tool in FLJ does not. Heat transfer (via conduction) from the heated metal to the plastic component produces a narrow melted region in the plastic material near the interface. Joining of the metal and the plastic is complete after the melted plastic, under pressure produced by the contact with the metal substrate, solidifies. Given these advantages, FLJ has the potential to generate interfaces with strong joint strengths without any damage to the base materials, high-cost apparatus, or design limitations imposed on the joint geometry. In addition, there are significantly fewer joining parameters in FLJ – only four variables: tool dimension, rotation speed, plunge depth, and joining speed have to be controlled – and FLJ is an energy-saving and environmentally friendly process. This technique would further expand the applications for plastic materials, including CFRTPs, combined with metals.

As the metal in a joined plastic/metal component, Al alloys offers weight reduction, high strength, and good formability, all of which are important considerations in the fabrication of automobiles and aircraft [26]. The purpose of this study was to confirm the possibility of directly joining CFRTPs and Al alloys using the FLJ technique and to evaluate the joint characteristics, including the joint strength, interface structure, and fracture behavior. Also, the effect of grinding the surface of the Al alloy on the joint strength was investigated, since the condition of the surfaces plays an important role in the direct joining of these materials [17,27]. Finally, the effect of the joining speed during FLJ was investigated using ground Al specimens. The joining speed is an important parameter which affects both the interface temperature and heating interval, as well as the industrial applicability of the process.

2. Material and methods

Experiments were carried out on injection-molded CFRTP plates (80 mm × 80 mm × 3 mm) made of polyamide 6 with 20 wt.% short-cut carbon fiber addition and A5052 Al alloy plates (150 mm × 75 mm × 2 mm) with a composition of 2.4 mass% Mg and 0.18 mass% Cr. The diameter and length of these carbon fibers were 10 μm and approximately 500 μm, respectively. The A5052 plates were used in both the unground/as-received condition and after wet-grinding with #800 emery paper. The surfaces of both the unground and ground A5052 plates were analyzed using X-ray photoelectron spectroscopy (XPS, Quantera SXM, Physical Electronics, Inc., Chanhassen, MN, USA).

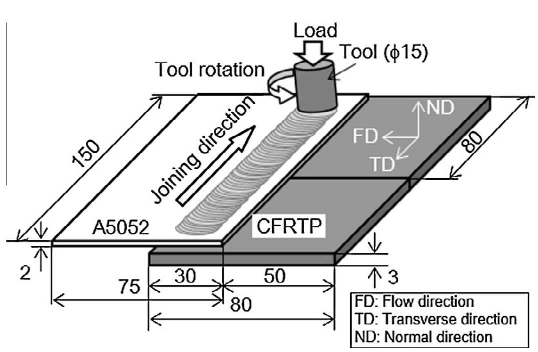

Fig. 1. Schematic illustration of the friction lap joining process indicating dimensions and directions. (All dimensions in mm.)

The CFRTP plates exhibit an anisotropic tensile strength due to the orientation of the carbon fibers. To determine these strengths, the CFRTP plates were cut into dumbbell-shaped tensile specimens parallel to both the flow direction (FD) and the transverse direction (TD) in injection molding. Tensile tests were carried out using a precision universal tester at a crosshead speed of 0.5 mm min^{-1}. The average tensile strengths of the CFRTP were 140 MPa in the FD and 117 MPa in the TD. The FD of the CFRTP plate was oriented toward the joining line. Two CFRTP plates were placed in a row and the ground surface of A5052 plate was placed facing the CFRTP plates, as shown in Fig. 1. FLJ was used to join the A5052 plate to the two CFRTP plates using a rotating tool made of SKD tool steel. The tool had 15 mm diameter shoulder (without probe) and was tilted at an angle 3° forward from the vertical. A tool plunge depth of 0.9 mm and a tool rotation speed of 2000 rpm were used, as determined by preliminary experiments. Different joining speeds in the range 100–2000 mm min^{-1} were employed for the ground-A5052/CFRTP joints, but the speed was fixed at 1600 mm min^{-1} for the unground-A5052/CFRTP joints. The temperature during FLJ was monitored using a K-type thermocouple inserted at the ground-A5052 plate/CFRTP plate interface at the center of the joined area. The normal load on the tool during travel was monitored by force sensors (9047C, Kistler Japan Co., Ltd., Tokyo, Japan).

The FLJ-joined specimens were cross-sectioned and mounted in epoxy resin before they were ground with #220 SiC paper and polished with diamond paste. Observations of the macrostructure and microstructure of the joined interface were then performed using optical microscopy (OM) and a transmission electron microscopy (TEM, 2100F, JEOL, Ltd., Tokyo, Japan).

A gel permeation chromatography (GPC) analysis was carried out to evaluate the molecular weight changes in the polyamide 6 in the CFRTP by sampling the CFRTP near the FLJ joint in samples joined at speeds of 100 and 1600 mm min^{-1}. The GPC analysis employed a differential refractometer detector (Shodex RI104, Showa Denko K. K., Tokyo, Japan); the column (Shodex HFIP-606 M, Showa Denko K. K., Tokyo, Japan) was held at a temperature of 313 K, and hexafluoroisopropyl alcohol with 5 mol m^{-3} of trifluoroacetic acid sodium salt at a flow rate of 3.3 mm^3 s^{-1} was used as the solvent. The molecular weight was determined relative to that of polymethyl methacrylate.

To evaluate the joint strength, the FLJ joints were cut into strips perpendicular to the joining direction with a width of 15 mm. Tensile shear tests were carried out using a precision universal tester at a crosshead speed of 0.5 mm·min^{-1}. Three strips were tested for each joining condition. The fracture surfaces of the tensile shear specimens were observed using OM, scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDS).

3. Results

3.1. Effect of grinding the A5052 plate

Fig. 2 shows the bright-field images and distributions of the elements Al, Mg, O, and C at the interface for both the unground- and ground-A5052/CFRTP joints. No voids or gaps were observed at the adhered interface. The CFRTP and A5052 alloy were joined via an oxide layer that consisted of Mg and O. A selected-area diffraction analysis identified the oxide layer as MgO.

Fig. 3 shows the tensile shear strengths of the unground- and ground-A5052/CFRTP joints and the macrostructures of the matching fracture surfaces of the unground A5052, ground A5052, and CFRTP surfaces. The tensile shear strength of the