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JMST-1084; No. of Pages 6
ARTICLE IN PRESS
Journal of Materials Science & Technology xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Journal of Materials Science & Technology
journal homepage: www.jmst.org

Direct joining of oxygen-free copper and carbon-fiber-reinforced plastic by friction lap joining

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ARTICLE INFO

Article history:
Received 3 April 2017
Received in revised form 25 April 2017
Accepted 29 April 2017
Available online xxx

Keywords:
Friction lap joining
Metal
Plastic
Carbon-fiber reinforced thermoplastic
Dissimilar materials joining

ABSTRACT

Oxygen-free copper (Cu) was successfully joined to carbon-fiber-reinforced thermoplastic (CFRTP, polyamide 6 with 20 wt% carbon fiber addition) by friction lap joining (FLJ) at joining speeds of 200–1600 mm/min with a constant rotation rate of 1500 rpm and a nominal plunge depth of 0.9 mm. It is the first time to report the joining of CFRTP to Cu by FLJ. As the joining speed increased, the tensile shear force (TSF) of joints increased first, and decreased thereafter. The maximum TSF could reach 2.3 kN (15 mm in width). Hydrogen bonding formed between the amide group of CFRTP and the thin Cu_2O layer on the Cu surface, which mainly contributed to the joint bonding. The influence factors of the TSF of the joints at different joining speeds were discussed. The TSF was mainly affected by the joining area, the degradation of the plastic matrix and the number and the size of bubbles. As the joining speed increased, the influence factors varied as follows: the joining area increased first and then decreased; the degradation of the plastic matrix and the number and the size of bubbles decreased. The maximum TSF was the comprehensive result of the relatively large joining area, small degradation of the plastic matrix and small number and sizes of bubbles.

1. Introduction

Nowadays, carbon-fiber-reinforced plastic (CFRP) materials have been increasingly used as structural materials in aerospace, automobile, and electronic industries for a reduction of fuel consumption, because of their light weight, high specific strength and very low corrosion rate [1]. Among CFRP materials, carbon-fiber-reinforced thermoplastic (CFRTP) materials, which are highly processable, especially draw lots of attentions. However, the inferior thermal and electrical conductivities of CFRTP materials have largely limited their application. As we know, metals are characterized by the high thermal and electrical conductivity and superior specific strength [1–3]. Therefore, the hybrid joining of plastics including CFRTP and metals are highly demanded for the structural applications where plastics and metals can compensate each other for various advantages to achieve a more flexible structural design, high performance, cost saving, etc [4–6].

However, it is not easy to join plastics and metals since there is a huge difference on physical and chemical properties. Adhesive bonding and mechanical fastening have been commonly reported to apply for the joining of plastics to metals, and relatively strong hybrid joints could be obtained [7]. However, some drawbacks always exist for these conventional joining methods. For example, adhesive bonding is always involved with environmental issues and inferior long-term stability, and mechanical fastening are usually associated with inflexible design challenges and stress concentrations [7]. To solve these problems, researchers have been dedicating on the exploring of some novel joining techniques, such as laser welding [2,8,9], friction stir spot welding [6,10], and ultrasonic welding [3,11].

Katayama and his co-workers [2,8,12,13] have made some good reports on the laser welding of different plastics including CFRP to metals such as steel and Al alloys. They found that the joints for CFRP to different metals could all achieve a high tensile shear force (TSF) of more than 3 kN (20 mm in width) by the chemical or physical bonding on atomic, molecular or nano-sized level between the melting plastic and the oxide of the metal surface, as well as the mechanical bonding. During laser welding, the large pressure produced by the expansion of bubbles was benefit for the bonding of plastics with metals. Therefore, laser welding shows a great potential for the joining of plastics and metals, however, most of previous investigations have focused on the laser welding of plastics to Al, Mg, Ti and steel. So far, there are only limited preliminary papers on the joining of plastic to Cu.

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https://doi.org/10.1016/j.jmst.2017.10.019
1005-0302/

It is well known that Cu is widely used in electronic components and air-conditioning condenser pipes. The joining of Cu to polymer is of great significance since the Cu-polymer hybrid joints can reduce the weight of the components purely made of Cu, which reduce the energy-consuming, thereby reducing the products costs. Different from that strong laser welds of plastic to Al or steel were usually obtained, not so strong plastic-Cu joints were produced by direct laser welding and also the energy input largely increased [14]. Tamrin et al. [7] pointed out that the feasibility of laser welding was largely dependent on the laser absorptivity of materials. It is much more difficult for the joining of plastics to Cu materials compared to Al and steel, since Cu has high reflectivity and conductivity. Therefore, other joining methods are needed to be applied to join plastics and Cu materials. Although the joining of plastics and metals has been also found to be feasible by friction stir spot welding or ultrasonic welding [3,6,11,15], yet, dimensions and geometries of the joints are limited. Besides, so far, no results on the joining of plastics to Cu materials using friction stir spot welding or ultrasonic welding have been reported.

In order to solve the shortage of all these joining methods of the joining of plastics to Cu materials, friction lap joining (FLJ) seems to be a potential one. FLJ, a new variation of friction stir welding (FSW) which is widely applied in various metals and composites [16,17], has been recently developed for the joining of plastics and metals [1,18,19]. The main difference between FLJ and FSW is that during FSW, a stir pin attached to a tool is usually used to assist the material flowing, while no stir pin for FLJ. FLJ mainly involves that friction heat between metals and tool is transferred into plastics, resulting in the melting of plastics near the interface, and then the joining of plastics and metals is achieved under the pressure of the tool and clamping apparatus after solidification of plastics [1,18].

Now FLJ has been reported to successfully join plastics and metals such as Al, Mg alloys and steel [1,18,19]. For example, MC nylon-6 could directly join with Al and Mg alloys by FLJ [18,19]. It was also found that similar to that in laser welding, bubbles could be observed in the joints, and strong FLW joints was obtained when the area fraction of bubbles was less than 8% via welding process optimization [19]. Besides, during direct FLJ of CFRTP and 5052 Al alloy, hydrogen bonding formed between the plastic matrix and an oxide of 5052 Al sheet surface, which contributed mainly to the joint bonding [1]. Furthermore, it was found that by a chemical surface treatment (i.e. silane coupling) on the Al sheet surface before FLJ, the tensile shear strength of the joint could even be over 20 MPa and an efficiency of the joint of 97% could be obtained with the joint fracturing at the base material of CFRTP [20]. Therefore, FLJ shows a big potential for the joining of plastics to Al, Mg alloys and steel, however, the feasibility of the FLJ of plastics to Cu materials still remains unknown.

Since the joining of plastics and metals are now still in the developing stage, in order to enlarge the knowledge of the plastic-metal hybrid joining, the joining of CFRTP to Cu was conducted by FLJ at different joining speeds in this study. The objective is to explore the feasibility of directly joining of plastics to Cu materials, to evaluate the joint characteristics, and to clarify the influence of the joining speed on the tensile shear properties of the joints.

2. Materials and experimental procedure

The as-received materials were 3-mm-thick CRFTP sheets (polyamide 6 (PA6) with 20 wt% carbon fiber addition) made by injection molding, and 2-mm-thick oxygen-free copper sheets. The diameter and length of the carbon fibers were 10 μm and about 500 μm, respectively. The average tensile strengths of the CFRTP were 140 MPa in the flow direction and 117 MPa in the transverse direction, and about more details on the CFRTP, please refer to the previous work [1]. Before FLJ, the Cu sheets were ground in the flowing water with #800 emery paper, and CFRTP sheets were dry-ground with #80 and #800 emery paper. The CFRTP sheets were friction lap joined to Cu at joining speeds of 200–1600 mm/min with a constant rotation rate of 1500 rpm. A tool plunge depth of 0.9 mm, a tilt angle of 3 degree, and a lap width of 30 mm was used by a steel tool with a shoulder diameter of 15 mm without a stir pin. For the temperature measurement during FLJ, a K-type thermocouple was inserted at Cu sheet/CFRTP sheet interface at the center of the joined area.

The specimens for microstructural observation were first cut perpendicular to the joining direction, mounted in epoxy resin, and ground and polished with silica solution. The microstructural observation of these specimens was then performed via optical microscopy (OM) and transmission electron microscopy (TEM). To test the TSF, specimens were cut perpendicular to the joining direction with a width of 15 mm. Tensile shear tests were carried out in a regular tensile machine at the crosshead speed of 0.5 mm/min. For each joining condition, three tensile specimens were tested, and in order to reduce the effect of travel position on the microstructure and mechanical properties, the specimens were all cut from the travel distance of 60–120 mm. The fracture surfaces of the tensile shear specimens were observed using OM, SEM with energy dispersive X-ray spectroscopy (EDS). The residual CFRTP areas on the fractured surface of Cu were measured manually using Photoshop software.

3. Results and discussion

After FLJ, Cu could successfully join with CFRTP at all the joining speeds, and the typical surface morphologies of FLJ joints of Cu to CFRTP at 200 and 1600 mm/min are shown in Fig. 1. The advance side (AS) and retreating side (RS) were located at the CFRTP side and Cu side, respectively. At all the joining speeds, the joints could not be separated apart by human hand force, which suggested that CFRTP should have joined well with Cu at all the joining speeds.

The variation of the TSF of the CFRTP-Cu FLJ sheets with the joining speed is shown in Fig. 2. It was obvious that as the joining speed increased, the TSF increased first, and then decreased. The TSF of the joints achieved the maximum of 2.3 kN at 600 and 800 mm/min at a nominal plunge depth of 0.9 mm. Therefore, it is feasible to join CFRTP to Cu directly by FLJ.

In order to explain the variation trend of TSF with the joining speed, the temperature profiles at the joint center line at different joining speeds were measured, as shown in Fig. 3. At each joining speed of 200 to 1600 mm/min, the maximum temperature was all over the thermal decomposition temperature (350 °C) and the

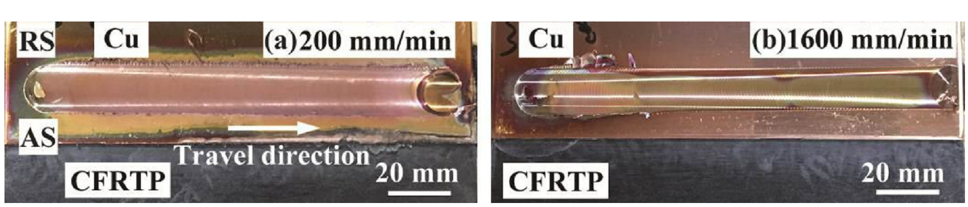

Fig. 1. Typical marostructural morphologies of friction lap joints of CFRTP to Cu at (a) 200 and (b) 1600 mm/min.

Please cite this article in press as: L.H. Wu, et al., J. Mater. Sci. Technol. (2017), https://doi.org/10.1016/j.jmst.2017.10.019