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Direct joining of plastic to copper by friction lap joining*

by Lihui Wu **, Kimiaki Nagatsuka ** and Kazuhiro Nakata **

Pure copper (Cu) were joined to polyamide 6 (PA6) directly by friction lap joining (FLJ) at the joining speed of 200-1600 mm/min with a constant rotation rate of 1000 rpm. As the joining speed increased, the tensile shear force increased first, and decreased thereafter, and the maximum tensile shear force at 800 mm/min could approach to 1 kN. The effect of the joining area, the strength of the melting plastic matrix, and the bubbles on the tensile shear force was discussed.

Key Words: Friction lap joining, metal, plastic, carbon-fiber reinforced thermoplastic, dissimilar materials joining

1. Introduction

Plastics and metals are widely used in many fields such as aerospace, automobile, and electronic industries due to their excellent properties, such as the light weight character of plastics and the superior specific strength of metals[1-5]. The hybrid joining of plastics to metals has drawn lots of attentions for the structural applications, due to the combination of both the advantages of plastics and metals. Conventional joining techniques including mechanical fastening and adhesive bonding have been commonly applied for the joining of plastics to metals. However, these joining processes are usually associated with some problems such as a long joining time and environmental pollution[1,5]. To solve these problems, some advanced joining techniques, such as laser welding[1-3], friction stir spot welding[4, 5], and ultrasonic welding[6, 7] have been explored.

Katayama and his co-workers[1-3] have reported a good result on the laser welding of plastics, such as polyethylene terephthalate, and metals such as steel and Al alloys. They found that plastics could join strongly with metals via the chemical or physical bonding between the melting plastic and the oxide of the metal surface, as well as the mechanical interlocking effect. The high pressure resulted from the rapid expansion of bubbles was benefit for the formation of the bonding between the plastic and oxide[1, 3]. Chan et al[8] reported that the hybrid joining of plastic to Ti for the medical application could be successfully achieved by laser transmission joining. They defined and quantified the contact area between the plastic and metal, which facilitated calculation of the mechanical shear stress of the hybrid joints. Goushegir et al[4] found that a strong hybrid joint of 2024 Al and carbon-fiber-reinforced plastic (CFRP) with a tensile shear strength of 27 MPa was achieved by direct friction spot joining. Belle and Wagner et al[6, 9-11] has reported the feasibility of plastics and metals by ultrasonic welding, and the tensile shear strength of the joint of 2024 Al and CFRP could even achieve 58 MPa[6]. All the advanced joining techniques above showed a great potential for the joining of plastics and metals, while these joining methods are now still in the developing stage, and more investigations are needed to enlarge the knowledge range of the joining of plastics and metals.

Recently, friction lap joining (FLJ), a new variation of friction stir welding, has recently been developed to join plastics and metals, and previous studies showed that FLJ can successfully join plastics and metals such as Al, Mg alloys[12-14]. For example, Liu et al[12, 13, 15] reported the successful joining of Mg alloys with MC Nylon-6 and polyethylene. Nagatsuka et al[3] found that for the FLJ joint of A5052 alloy and CFRP, CFRP and A5052 Al alloy were joined well via an interfacial magnesium oxide layer. And the tensile shear force (TSF) of the joint could even achieve 5000 N (15 mm in width) and they fractured at the base material of CFRP via a silane coupling treatment on the Al sheet surface[16]. Therefore, FLJ shows a big advantage for the joining of plastic to Al and Mg alloys.

Pure copper (Cu) has been extensively applied in thermal and electronic industries because of its very superior thermal conductivity and electroconductivity. The joining of Cu to plastic has been highly demanded to reduce the cost and increase the design flexibility. However, no paper on the FLJ of Cu and plastic has been reported so far. In order to expand the advantage of FLJ into the joining of plastic to Cu, in this study, the feasibility of FLJ of Cu to polyamide 6 (PA6) was explored.

2. Experimental procedure

The as-received materials were PA6 sheets with dimensions of 150×75×3 mm^3, and pure copper sheets with dimensions of

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**Member, Joining and Welding Research Institute Osaka University

150×75×2 mm^3. Acetone and ethanol were used to clean the surfaces of PA6 and Cu, respectively before FLJ. The PA6 sheets were friction lap joined to Cu at a rotation rate of 1000 rpm and a transverse speed of 200-1600 mm/min. A steel tool of a shoulder diameter of 15 mm without a pin was used. The lap width of 30 mm, the tilt angle of 3^o and the plunging depth of 0.9 mm were set.

The cross-sections for joint interface examination were mechanically ground, polished with 6 and 3 μm diamond paste, and subjected to optical microscopy (OM) and scanning electron microscopy (SEM) examinations. To test the TSF, specimens were cut perpendicular to the joining direction with a width of 15mm from the travel distance of 65-115mm to reduce the effect of tool position. Tensile shear tests were carried out using a regular tensile test machine at the crosshead speed of 0.5 mm/min. For each joining condition, three tensile specimens were tested. The fracture surfaces of the tensile samples were analyzed by OM and SEM attached with energy dispersive X-ray spectrometer (SEM-EDS). In order to measure the residual plastic area, the residual plastic profiles were first marked manually on the OM images of the fractured surface on Cu sides and the areas were then measured by the Photoshop software. Advancing and retreating sides are simplified as AS and RS, respectively.

3. Result and discussion

After FLJ, PA6 can be joined with Cu at all the parameters, and the typical surface morphologies with both front and back sides of Cu/PA6 FLJ joint at a joining speed of 800 mm/min are shown in Fig. 1. It is obvious that a large melting zone could be observed viewed from the back side, and near the positions of tool plunging in and pulling out, a larger melting zone showed compared to that during travelling, which was the result of longer staying time at these two positions.

The cross sections of Cu/PA6 FLJ joints at 200, 800 and 1600 mm/min are shown in Fig. 2. It shows that PA6 was melted in the narrow region near the Cu/PA6 interface during FLJ, and a re-solidified plastic layer formed under the pressure of the weld tool after FLJ. As the joining speed increased, the thickness of the melting zone decreased, from ~584 μm for 200 mm/min to ~175 μm for 1600 mm/min. Besides, in the re-solidified layer, a number of bubbles were observed, which should mainly come from the thermal decomposition of plastic[13]. As the joining speed increased, the total area of bubbles decreased. At 200 mm/min, numbers of bubbles with a size of about 500 μm were found, while at 1600 mm/min, at the center of the joint, there was even no bubble although large bubbles (more than 1.5 mm) were still observed at the edge.

Fig. 3a shows the variation of the TSF of the Cu/PA6 FLJ joints with the joining speed. It was obvious that, as the joining speed increased, the TSF increased first, and thereafter decreased. And the TSF of the joints achieved the maximum of 0.99 kN at the joining speed of 800 mm/min. It indicates that it is feasible to join Cu and the plastic using FLJ. The associated tensile shear fracture surfaces of the FLJ welds in Fig. 3b showed that on the Cu side, each fracture surface consisted of a naked Cu surface and a region covered with residual materials. EDS on Fig. 4 showed that on the naked Cu surface, C was seldom observed, while C element could be observed at the region covered with residual materials, which suggested that the materials adhere to the Cu sheet surface was plastic. Most of the residual plastic exhibited a deformation character with a distorted morphology where some plastic was even stretched into silks, as shown in the magnified SEM in Fig. 4b, while some residual plastic seemed to fracture along the bubbles without any distorted deformed characteristics (Fig. 4c). Fig. 5 shows the variation trend of the total and deformed residual plastic area per unit length along the joining direction with the joining speed. As the joining speed increased, both the residual plastic areas increased first, and exhibited a decreased trend thereafter at 800 mm/min.

It is reported that plastic can join well with metals via strong chemical or physical bonding, or mechanical interlocking effect, and the chemical bonding is generally formed between plastic and the oxide on the metal surface[1, 14]. The high TSF and the residual plastic on the Cu sheet after fracture suggested that PA6 might have been well joined with Cu sheets via strong chemical bonding. According to Liu et al[12], the deformed residual plastic contributed the most to the strength of the joint, while those fractured along the bubbles contributed little to the joint strength. In this study, the residual plastic area fractured along bubbles took up a small fraction of the total residual plastic area, and the variation trend of TSF was roughly similar to that of both the total and deformed residual plastic areas although there was a small data scatter at 1600 mm/min (Fig. 3a and 5).

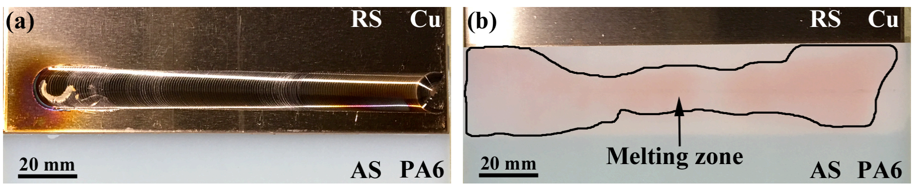

Fig. 1 Typical macrostructural surface morphologies of the FLJ joints of Cu to PA6 at 800 mm/min: (a) front side, (b) back side

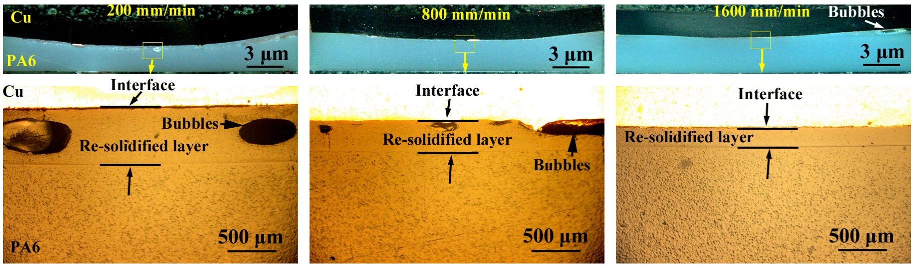

Fig. 2 Cross sections of the FLJ joint of PA6/Cu at joining speeds of 200, 800 and 1600 mm/min. The images at the bottom were the magnification of yellow rectangles of the cross sections at the top

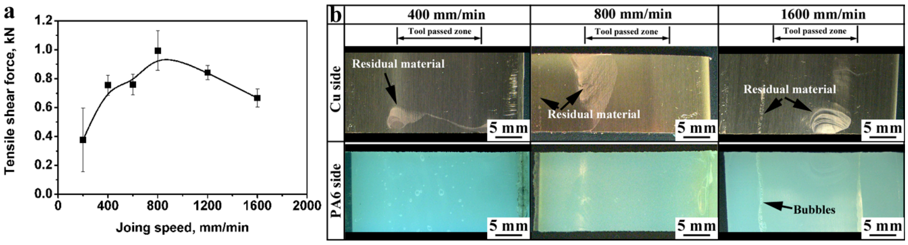

Fig. 3 (a) The variation of tensile shear force of the FLJ joints with joining speed of Cu to PA6, and (b) the associated macrostructures of the opposing tensile shear fracture surfaces

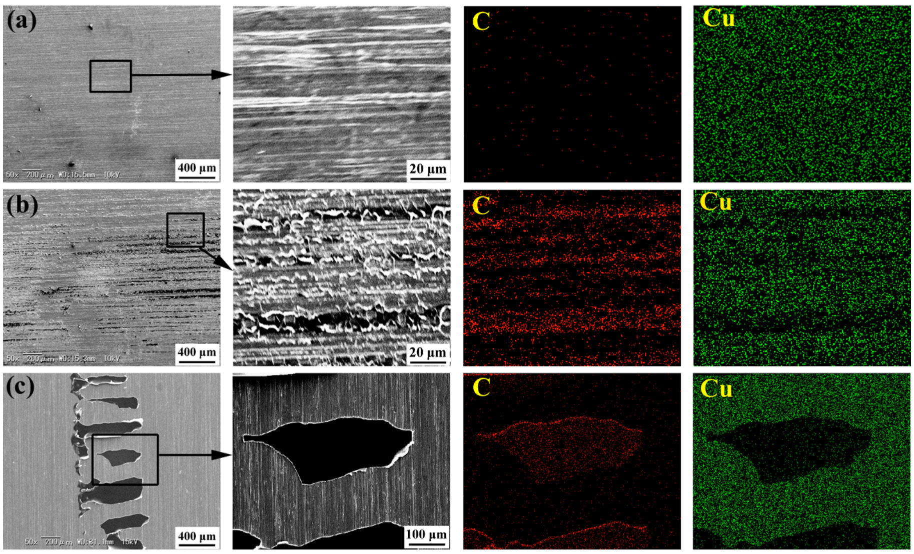

Fig. 4 Typical SEM images of fracture surface on the Cu side and the corresponding EDS element map distributions of the FLJ joint: (a) on the naked Cu surface, (b) and (c) on the region covered with residual materials at 800 mm/min and 1600 mm/min, respectively

In order to explain the trend for the TSF with the joining speed, the temperature curves at 400, 800 and 1600 mm/min were measured, as shown in Fig. 6. It is obvious that as the joining speed increased, both the welding temperature and the staying time at high temperature decreased. The time above the melting point and thermal decomposition temperature of PA6 decreased from 9.7s to 0.9s and from 3.8s to 0s, respectively.

As we know, fracture usually occurs at the weakest region, and during the tensile shear test, four regions might act as the fracture sites, they are the interface of the plastic and metal, the plastic in the re-solidified layer, the bubbles or even the plastic base material. (In this study, no evidence showed the joint fractured at the plastic base material, and thus it will not be discussed next.) When there is no joining between the plastic and metal, or the joining bonding is very weak, the joint will fracture preferentially along the interface of the plastic and metal, which resulted in a naked Cu surface. It is well-known that the decomposition of plastic at high temperature results in the decrement of weight-averaged molecular weight, and thus reduces the plastic strength[14)]. The larger the temperature and decomposition time are, the larger the decrement of the plastic strength is. Therefore, the melting plastic strength itself increases as the joining speed increases. For bubbles, it has a complex influence on the joint strength. On one hand, bubbles would produce a large pressure and push the melting plastic into the metal, which is benefit for the joining of metal and plastic[1]. On the other hand, large numbers and large sizes of bubbles themselves will reduce the joint strength since they acted as fracture pass sites, and only the small sizes of the bubbles are benefit for increasing the joint force[17, 18].

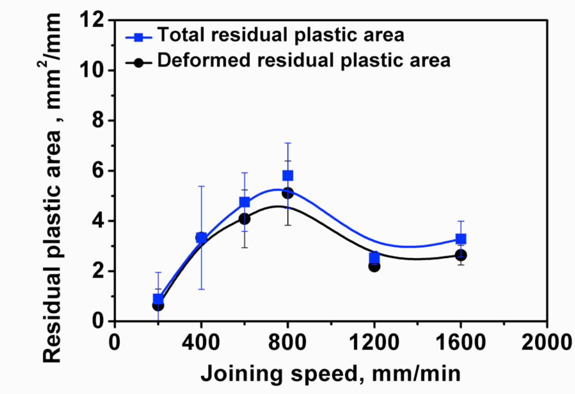

Fig. 5 The variation of residual plastic area per unit length along the joining direction with the joining speed

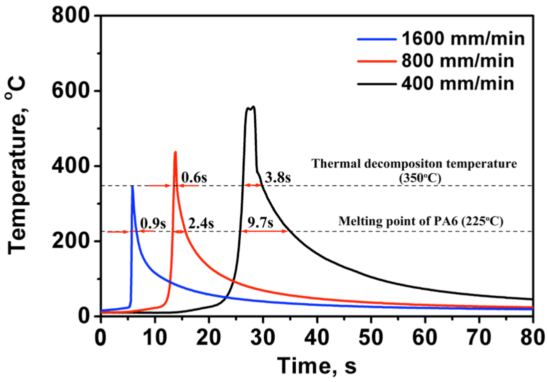

Fig. 6 The temperature curves of the FLJ joints at 400, 800 and 1600 mm/min

In this study, for the too hot or cold parameters, it was not benefit for the formation of a strong joint. For the too hot parameters (e.g. 200 mm/min), the plastic was largely decomposed, and thus large numbers of large bubbles formed and the melting plastic strength largely decreased. For the too cold condition (e.g. 1600 mm/min), the joint cooled down rapidly, and thus there was not enough time for the formation of chemical or physical bonding (Fig. 6). Therefore, the maximum TSF at 800 mm/min (Fig. 3a) should be the comprehensive result of the relative large joining area, the relative small decrement of plastic matrix strength, and the small sizes of bubbles.

4. Conclusion

As the joining speed increased, the TSF increased first, and decreased thereafter. The maximum TSF could approach to 1 kN at 800 mm/min, which was the comprehensive result of the relative large joining area, the relative small decrement of the plastic matrix strength, and the small sizes of bubbles.

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