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Joining of metal to plastic using friction lap welding

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ABSTRACT

Friction lap welding (FLW) is a new conception of joining method developed in Joining and Welding Research Institute (JWRI). The efficiency of joining metal and plastic using FLW was demonstrated through a case study on aluminium alloy AA6061 and MC Nylon-6. The lap joints with high shear strength were obtained over a wide range of welding parameters. A linear relationship was observed between FLW parameters $(R/v)^{0.5}$ and the thickness of melted nylon (H). The influences of FLW parameters on bubbles and shear strength were investigated. The morphologies of the fractured surfaces of AA6061 alloy fell into seven types based on the scanning electron microscopy examination. Statistical analysis showed that the contribution to shear strength of these regions followed such an order: region II > region V > region VI > region VII > region IV > region I or III.

1. Introduction

Plastics-based materials have been widely and are expected to be more extensively used in automobile, aerospace, and electronic industries due to their low weight, considerable strength, excellent corrosion resistance, thermal and electrical insulation, and design flexibility [1,2]. This has led to high demands on and research interesting in joining dissimilar materials involving plastics and metallic materials for structural applications. Such joining enables engineers to utilize the hybrid components in sections where high stiffness and strength can be exploited, and plastic material offers excellent functional integration.

Joining a metal and a plastic is often difficult and the combined behaviours are grossly not fully understood. This is because of the difference in mechanical and physical properties between the metal and plastic materials, and the limited joining methods available for this type of hybrid materials [3]. Mechanical fastening and adhesive bonding are commonly applied in joining between polymer and metal. These approaches are usually associated with some drawbacks such as long processing time, accidental disassembly, and susceptibility to degradation by environmental factors [4,5]. In order to solve these problems, several welding methods, such as laser joining, ultrasonic welding and friction spot joining have been investigated to exploit the possibility of obtaining high quality hybrid joints of plastics and metals.

Recently, Katayama et al. have developed a laser direct joining process for metals and plastics [1,5,6]. In this process, metal and plastic were part overlapped initially, and then laser beam was irradiated on the overlapped region. The metal was heated up by the moving laser beam, resulting in that the plastic in a narrow region adjacent the heated metal was melted and re-solidified during the laser joining process. The metal and plastic were bonded together during this process. This technique has been proved to have the potentials in producing high performance joints between plastics and various kinds of metallic materials [1,5–10]. The limitation of this process is that there are too many welding parameters, such as laser power, welding speed, pulse mode, focus shape and size, beam quality, polarization and keyhole shielding gas which can influence the quality and reliability of the eventual joint.

In the past few years, Balle et al. [11–13] have investigated ultrasonic lap welding of aluminium alloys and fibre reinforced polymers. The tensile shear strength of these joints reached up to about 21–24 MPa and typical cohesive failures were observed on the fracture surface of aluminium alloys [11,12]. The welding time for ultrasonic welding was a few seconds which made the process ideal for mass production. It should however be noted that this joining technique is limited to small components with weld lengths typically not exceeding a few centimetres.

Some newly raised research works have demonstrated that friction spot joining (FSJ) also is an alternative joining technology for plastic-metal hybrid joints [14,15]. The plastic-metal joints obtained by FSJ exhibited a higher joint strength as compared to adhesive joining [14]. The main advantages of this technique include: short joining cycles, absence of emissions, operation simplicity, available of commercial equipment and good mechanical performance [14]. Only overlap configurations and spot geometry joint design limit its application.

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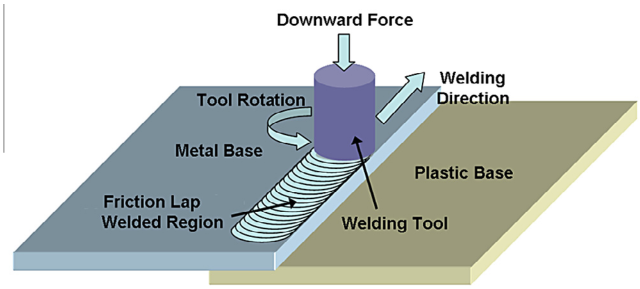

Fig. 1. Schematic illustration of joining metal and plastic through FLW.

Table 2
Mechanical and physical properties of AA6061-T6 and MC Nylon-6.

	AA6061-T6	MC Nylon-6
Ultimate tensile stress (MPa)	318	81
Yield stress (MPa)	289	–
Modulus of elasticity (GPa)	68.9	2.79
Elongation at break (%)	11	26
Density (g cm^{-3})	2.70	1.15
Melting temperature (°C)	582–652	216
Glass transition temperature (°C)	–	50
Thermal conductivity (W m^{-1} K^{-1})	167	0.25
Coefficient of thermal expansion, linear 20 °C (μm m^{-1} K^{-1})	23.6	90
Specific heat capacity (J g^{-1} K^{-1})	0.90	1.65

All these emerging technologies for joining metals and plastics have their own advantages alongside of disadvantages. New joining techniques for metal and polymer hybrid joints which offer better joint properties and increased design flexibility compared to existing techniques are highly required.

In this study, the authors firstly showed the feasibility of joining metal to plastic using friction lap welding (FLW) through a case study on two commercially available materials, aluminium alloy AA6061 and MC Nylon-6. In addition to the joint interfaces, the fractography of the tensile specimens and the factors which influence the quality of the FLW hybrid joints have been investigated.

2. Friction lap welding

Friction lap welding which is developed in JWRI, Osaka University [16] is a new conception of joining method for metal–plastic hybrid joints. As shown in Fig. 1, a non-consumable rotation tool is pressed on the surface of metal matrix and travels long the overlap region. The appearance of the FLW process is similar to the friction stir welding (FSW) [17,18]. The main difference between the FLW and FSW is that the FLW tool does not have a stir pin, and therefore, the primary function of the rotation tool is not to cause materials flow around the stir pin but to press and heat up the metal workpiece. The localized heating is accomplished by friction between the tool shoulder and the metal workpiece. The heat transfers via conduction from the heated metal component to the plastic component and consequently melts the plastic materials in a narrow region adjacent to the interface. Bonding between the metal and the plastic can be finished after the melted plastic is solidified under the pressure provided by the pressed metal component.

3. Materials and experimental procedures

Aluminium alloy (A6061) and monomer casting nylon (MC Nylon-6) sheets with dimensions of 150 × 75 × 2 mm were prepared. The chemical composition of the AA6061 is listed in Table 1. The MC Nylon-6 was prepared by the alkali-catalyzed anionic ring-opening polymerization of caprolactam. Compared with normal Nylon-6, MC Nylon-6 has the advantages of a simple preparation procedure, high crystallinity, high molecular weight and excellent properties. The physical properties of the AA6061 and the MC Nylon-6 are compared in Table 2. FLW processes were conducted using a FSW machine with a specially designed cylindrical tool. The diameter of the tools used in this study was 15 and 20 mm, respectively. During FLW, a position control system was employed, and the plunging depth was set to 0.3 mm. The cylindrical tool remained perpendicular to the workpiece surface during FLW. The rotation rate (R) was varied from 1000 to 3000 rpm and the welding speed (v) was varied from 200 to 1500 mm/min. The FLW samples were designated using a series digital format. For example, sample 1000–200 denotes the sample which was subjected to FLW at a rotation rate of 1000 rpm and a welding speed of 200 mm/min.

After welding, the FLW samples were cut into strips perpendicular to the welding direction for joint interface examinations and tensile shear test. The width of the strips is about 20 mm. The cross sections for joint interface examinations were mechanically ground and polished with 1 μm diamond past. The thickness of re-solidified layer and non-melted layer of nylon plates was measured at the middle of the weld zone. Tensile shear test was carried out using a tensile test machine (SHIMAZU) at a tensile speed of 0.5 mm/min. The grip inserts were used so that the centreline of the grip assembly is aligned with the bonded interface. The fracture surfaces of the tensile samples were subjected to optical microscopy (OM), scanning electron microscopy (SEM) and SEM–EDS (energy dispersive X-ray spectrometer) analyses.

4. Results and discussion

4.1. Joint produced using a 20 mm diameter tool

A cylindrical tool with dimension of 20 mm in diameter and an overlap of 22 mm were initially used to join the AA6061 plate to the MC Nylon-6 plate. The selected processing parameters were: a rotation rate of 2000 rpm, a traverse speed of 600 mm/min and a plunge depth of 0.3 mm. Fig. 2 shows the typical joint samples processed by FLW before and after tensile test. The semi-circular patterns which were generally observed in the friction stir welded/processed samples [19] were clearly observed on the surface of processed AA6061 (Fig. 2a). The FLW sheets did not show apparent welding distortion and warping. This is especially attractive for structural applications in manufacturing industries because the cost and time required for distortion correcting can be saved.

Tensile test showed that the FLW samples did not fail through the weld interface but failed across the nylon sheet near the edge of the weld zone, as shown in Fig. 2c. Such a strong joint was produced by FLW without any treatment on the surface of the AA6061

Table 1
Chemical composition of AA6061-T6 plate (wt.%).

	Al	Mg	Si	Fe	Cu	Cr	Mn	Ti	Zn	Others
AA6061	Balance	1.05	0.63	0.29	0.27	0.17	0.07	0.02	0.01	<0.01