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Development of ultrasonic direct joining of thermoplastic to laser structured metal

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ABSTRACT

This work reports on an improved ultrasonic welding process for the direct joining of thermoplastic and metal. A metal thin plate was structured with grid arrays on a micro-scale level by laser irradiation. A thermoplastic part was placed on the structured region, and ultrasonic welding or ultrasonic hot welding was applied. The thermoplastic was locally melted and re-solidified in the structured grooves with very low energy input due to the tiny initial contact area of the grid tips. Single lap shear specimens and boss specimens were used to study the feasibility and performance of hybrids made by this joining method. Both shear strength and normal tensile strength were affected by changes in the grid structures and welding parameters, and the experimental results show that the micro-structure geometry of the metal plate is a major factor in the joining strength. Successful welds required that process cycle times be less than 1 s. Furthermore, the mold holding the metal sheet was heated in the ultrasonic hot welding experiments, and the heated mold significantly enhanced the joint quality. Ultrasonic hot welding appears to be a fast, low cost, and reliable method to produce plastic/metal hybrid products for electronics and other industrial applications.

1. Introduction

Thermoplastic based materials, lightweight metallic materials, and their hybrids are widely used to produce strong, light components in industries such as electronics and automobiles. Currently joints of metal and plastic are manufactured primarily by adhesive bonding. However, this approach has several disadvantages, including long curing time, environmental issues caused by the adhesives, and unstable quality [1]. To solve these problems, direct joining methods have been investigated. A common method is assembling plastic and metal by injection molding. The joining between plastic and metal components is created when plastic part is formed during injection molding. Several variations on this method were reviewed by Grujicic et al. [2], and direct adhesion based on interlocking between two materials was considered the most promising method. Fusion bonding methods such as induction bonding, laser joining, friction spot joining (FSJ), and friction lap welding (FLW) have also been investigated. The joining processes and bonding principles of these methods are similar. The metal part is heated by a heat source, causing the thermoplastic adjacent to the metal interface to melt. The plastic–metal bond is obtained when the plastic solidifies and interlocks with the metal surface [1,3–5].

Surface treatments such as anodizing and laser structuring are often used to process the metal surface before the joining processes for better joint quality [6–9]. These improvements take advantage of micro-mechanical interlocking. Several studies have discussed the effect of micro-mechanical interlocking on the adhesion strength of polymer-metal interfaces [6,10].

Another approach to plastic–metal bonding is ultrasonic welding. Ultrasonic plastic welding (UPW) is widely used to bond plastic-to-plastic, while ultrasonic metal welding (UMW) is used for metal–metal bonds. Ultrasonic welding offers short processing time and low input energy because the heat is generated at the joining interface by interfacial friction or viscoelastic heating. Kruger et al. [11] attempted to bond PA-12/E-glass composite and $AlMg_3$ sheet by UPW and UMW. The substrates were bonded in both experiments but damaged by the high welding energy. However, the unique heat process of ultrasonic welding results in challenges when joining plastics on metals. Because the thermal conductivity of the metal is generally from 100 to 1000 times higher than plastic, the thermal energy is led off immediately and the molten plastic solidifies without flowing into the metal surface [12]. Consequently, previous studies used energy directors or precoating polymer layers on the metal surface to realize the bond [12–14]. In addition, UPW is divided into far-field welding in which the horn is placed more than 6 mm from the joint interface, and near-field welding in which the distance between the horn and the joint interface is 6 mm or less [15,16]. Far-field welding is

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more difficult than near-field since the thick plastic dampens the transmission of energy.

In this study, a lap joint of thermoplastic parts and metal thin plates was achieved by a two-step UPW process. The thermoplastic parts did not form energy director structures on the bond region. Surface pretreatment of the thermoplastic parts was not performed and no additional polymer layer was pre-coated on the metal plates. Instead, the metal thin plates were micro-structured by laser before joining. A generally used ultrasonic plastic welding process was applied. The acceptable process time was under 1 s and very low energy input was needed. Nevertheless, the process window was small. The best resulting lap shear strength was low, and an adhesive fracture was observed on the metal surface after a single lap shear test. To address these issues, several developments including enhanced laser patterns and ultrasonic hot welding process were proposed to achieve higher joint strength. With these developments, a 15 mm high plastic boss part was successfully joined on the same metal plate via far-field welding. Both lap shear strength and normal tensile strength of the hybrid were studied.

2. Materials and methods

2.1. Materials

An $18 \times 45 \times 1.5\ \mathrm{mm}^3$ 5052 aluminum alloy thin plate was used as the metal part. The laser structuring was achieved by a fiber laser system (MARS-50J, Han's Laser) with a wavelength of 1064 nm. The structures were treated with an output of 25 W and a line speed of 750 m/s. The structured area of 10 mm × 10 mm was incised with a grid pattern. The width of the laser route, measured form the top of the structure, was 40 μm at these settings.

In the studies of adhesion between plastic and laser structured metal, the proportion of plastic in the joint interface primarily affected the shear strength [6,8]. We thus describe the specimens by their structure density (SD), following Holtkamp [8]. The SD is defined as the groove area divided by the total area, which is assumed to be equal to the proportion of plastic at the welded plastic/metal interface. The grid structures were varied by changing the pitch of the array. All specimens were treated 5 times using identical settings to obtain the undercut structure, and the depth of the fabricated grid structure was approximately 120 μm. However, the recast layer will pour and cover the structured grooves when the laser routes are too close, because of the limitations of our laser. The micro-structures made with lower pitches could not be used in the joining experiments. Hence, for higher structure density, we extend the groove width by treating the same region twice. In the second treatment, the same patterns were structured with a shift. The depth of the extended grooves was under 100 μm, affected by the recast layers. The dimensions and calculated structure density of the different grid structures are shown in Table 1.

The thermoplastic ABS (Acrylonitrile butadiene styrene) is widely used in the electronics and automotive industries and easily transmits ultrasonic energy. Therefore, the plastic parts used in this study were made of ABS (PA747, CHIMEI). The tensile strength of this material is 39 MPa. To investigate the bonding strength along different directions, two different types of plastic parts were used: a $10 \times 45 \times 1.5\ \mathrm{mm}^3$ board and a plastic boss (⌀8 mm × 15 mm) formed by injection molding. The overlap length of the ABS board and laser structured AA5052 plate was 5 mm, to avoid undesirable fractures in the plastic part. This overlap with an area of $50\ \mathrm{mm}^2$ was used in the calculation of the resulting shear strength. Likewise, the joint area of the boss specimen is $50.265\ \mathrm{mm}^2$, which is used in the calculation of the normal tensile strength. The dimensions of the laser region on the metal part and the two type specimens are shown in Fig. 1.

2.2. Ultrasonic welding device and joining processes

The experiments conducted in this study consisted of two plastic/metal joining process, ultrasonic welding (UW) and ultrasonic hot welding (UHW). In the UHW method, the mold holding the metal plate was heated during the joining process. The two experiments were both performed using a KWD2020 ultrasonic plastic welder provided by k-sonic. The frequency was around 20 kHz and the maximum output power was 2 kW. The horn and mold were made of 6061 aluminum alloy. Two sets of horn and mold were prepared for producing different type specimens. In addition, the molds were equipped with a heater and a thermocouple to control the mold temperature during the joining process for the UHW experiment. The setup for the ultrasonic welding is shown in Fig. 2.

The metal part was placed in the mold and the plastic part was placed on it. The metal part was set as the lower adherend only, because direct contact between the horn and the metal part might

Table 1
Laser grid structure parameters.

Structure density (SD)	Pitch (μm)	Groove width (μm)	Grid width (μm)
0.23	320	40	280
0.27	280	40	240
0.36	200	40	160
0.42	170	40	130
0.58*	200	70	130
0.68*	230	100	130

* SD0.58 and SD0.68 were treated twice.

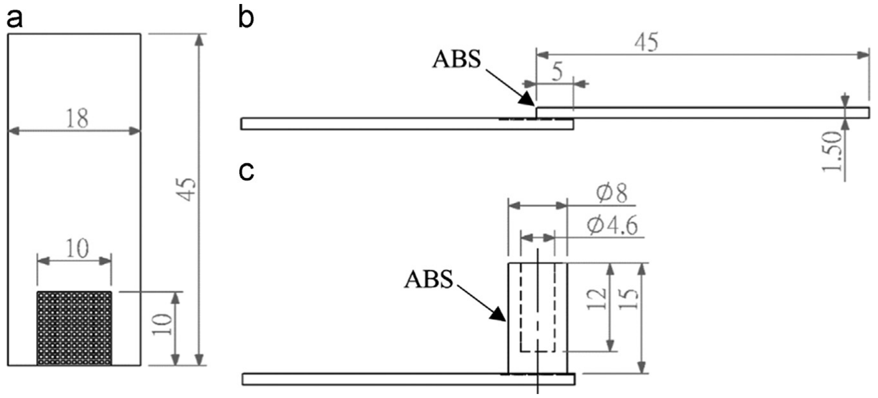

Fig. 1. Schematic illustration of (a) laser structured metal plate, (b) lap shear specimen and (c) boss specimen (unit: mm).