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Ultrasonic dissimilar joining of aluminum alloy and polymer with the composite material of ABS polymer doping carbonized rice husk

Chin-Pao, Cheng*, Chun-Hu Cheng, I-Wen Wang Yu-Chen Chen, Yang-Sheng You

Dept. of Mechatronic Engineering, National Taiwan Normal University, Taiwan, R.O.C.

Abstract. The metal housing is typically jointed with plastic fittings by conventional gluing method or embedding injection molding to produce this type of devices. We propose to improve this new technique with more practical approach. In plastic-aluminum substrate dissimilar joining, the 5052 aluminum plate coarsening process was performed to increase the porosity of the permeable dissimilar phase. The ABS polymer plus carbonized rice husk powder was later induced or deposited on the microstructure to improve the bonding effect. The plastic -aluminum substrate dissimilar joining is completed by the final step of ultrasonic welding. The finished substrate will be tested on the properties of tensile strength to ensure its quality. According to the simulation analysis and measuring results, the maximum temperature between the interface of ABS polymer and 5052 aluminum alloy is about 400~450℃ during ultrasonic welding, which can make the surface of ABS polymer to be melted. Furthermore, after drilling micro-hole array and covering ABS plus carbonized rice husk powder, the 5052 aluminum alloy shows better joining effect with ABS polymer sheet by ultrasonic welding. This improved approach does not require mold or injection molding machinery to produce the high quality plastic -aluminum bonding parts.

1 INTRODUCTION

Because of features such as excellent texture, anti-electromagnetic waves, heat dissipation, and high strength, metal cases can be used to mobile devices to make them shatterproof and shockproof as well as display a luxurious texture【1】. However, metal cases must be assembled with the internal plastic parts of mobile devices【2】. Light metals and plastics are commonly used together because of the demand for lightweight transportation, and the bonding between them is receiving increasing attention. Past conventional bonding methods include mechanical fastening and adhesive bonding, which possess some limitations such as stress concentration, a requirement for large bonding areas, differences in the nature of dissimilar materials, and harmful gas emissions【3】. In addition, when metals are bonded to polymers, their interfaces do not produce interfacial reaction layers similar to intermetallic compounds, and generally require intermolecular bonding forces such as van der Waals or electrostatic forces to achieve bonding effects. However, these bonding forces are relatively weak and possess stress concentration problems, with the plastic parts prone to falling off under external forces. New bonding technology for metal and plastic undergo constant innovation to enhance bonding quality. The Japanese company Taisei Plas proposed the Nano Molding Technology (NMT) for metal–plastic bonding, wherein a metal sheet is first processed using a special solution to form nano-holes on its surface【4,5】. It is then placed into a mold and subjected to injection molding for plastics to enter the nano-holes and solidify, thereby achieving the bonding of metal and plastic. The bonding can be applied to consumer electronics such as mobile phone cases or the internal mechanism designs of battery back covers. However, the process involves high temperature and high pressure effects that can deform the thin metal plates, whereas the use of plastic molds and injection molding machines also increases production costs.

Welding is another viable bonding method, with the early application of ultrasonic welding being mainly used for the bonding of plastic materials; it has also been used to bond dissimilar aluminum alloy and plastic materials in recent years【6,7】. Balle *et al*. used ultrasonic welding to bond aluminum plates and carbon fiber reinforced polymer, achieving satisfactory bonding effect. In this study, a micro-hole array was first fabricated on the aluminum alloy surface, after which the processed aluminum and plastic was bonded using ultrasonic welding, which resulted in occlusion between the plastic and the coarsened metal surface【7】.

To strengthen the bonding interface, rice husks were subjected to high temperature firing and pulverized, after which charcoal was removed, and remnants were mixed with plastic powder and placed in the bonding interface between the plastic and aluminum alloy. The joint was then subjected to tensile strength analysis after ultrasonic welding. The aim was to achieve a simplified process

[a] Corresponding author: cpcheng@ntnu.edu.tw

with reduced production costs and enhanced bonding strength. Rice husks are low-priced agricultural waste from rice grain production, and mixing them with plastic following their carbonization to form composite materials can improve part strength.

2 Experimental Process

The aluminum alloy 5052 and the plastic acrylonitrile butadiene styrene (ABS) were adopted as the experimental materials for this study. Both were first processed into 120 mm × 40 mm × 3 mm sheets before welding, with a joint area of 30 mm × 30 mm, after which they were bonded in an overlapping fashion. A micro-hole array was adopted in this study to stabilize and quantify the coarsening of the aluminum alloy surface. Within the 30 × 30 mm2 range of the aluminum alloy bonding area, 20 holes with a diameter of 1.0 mm were each drilled along the length and width of the alloy using a computer numerical control (CNC) machine at a fixed distance. The array contained 400 holes in total, each having a depth of 2 mm (Fig. 1), and the aluminum alloy was then bonded with the ABS using ultrasonic welding. For the plastic to be fully filled into the holes, ABS powder was added to the bonding interface. In addition, to strengthen the bonding interface, carbonized rice husk powder and ABS powder were further mixed to a specific proportion (Fig. 2) and added to the interface area, after which ultrasonic welding was performed (Fig. 3) and its effectiveness was evaluated.

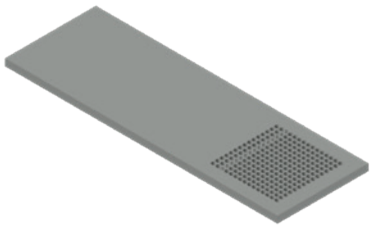

Fig.1 Micro-hole array on the aluminum alloy surface

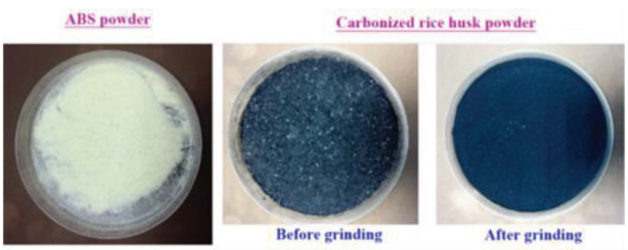

Fig.2 ABS and carbonized rice husk powder

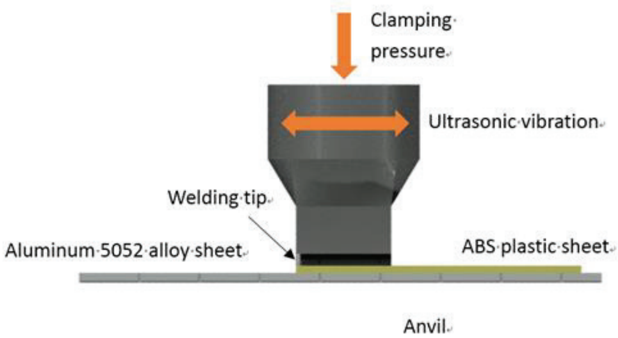

Fig. 3 Ultrasonic welding of two overlapping test pieces

First, an aluminum alloy sheet with a processed surface was placed at the bottom of a fixture, and an overlapping plastic sheet was placed on top of it (Fig. 3). Ultrasonic energy was transmitted to the plastic through the horn, and a high temperature was produced in its internal molecules because of friction. When the temperature exceeded the melting point of the plastic, the ABS underwent local melting and was squeezed through the holes of the coarsened metal where mechanical interlocking was achieved after it cooled down. The fixed parameters for the ultrasonic welding in this experiment were a frequency of 20 025 Hz, a vibration amplitude of 20 μ, a delay time of 0.8 s, a curing time of 1.5 s, and a welding time of 2~4 s. To explore the quality of the dissimilar bonding interface, the bonding strength of aluminum alloy and ABS was tested under various conditions using a tensile testing machine. Two pieces of 3 mm material were adhered to the end of both test pieces during the experiment for the tensile force to be exerted on the centerline of the test pieces during the tensile test (Fig. 4).

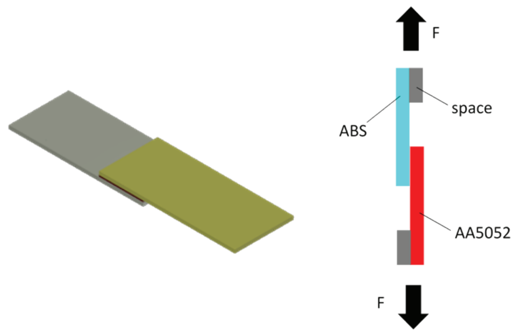

Fig. 4 Schematic diagram of the tensile test

3. Results and Discussion

3.1 Temperature Distribution

To understand the interfacial temperature changes of the aluminum alloy and ABS using ultrasonic welding, the temperature measurement was conducted directly using a thermocouple and then the change during the bonding process was recorded. Fig. 5 shows the laying position of the thermocouple. First, a groove 1.1 mm wide and 20 mm long was added to the top of the aluminum alloy, wherein a K-type thermocouple with a 1 mm diameter was placed every 6 mm starting from the centerline. A temperature recorder was connected to measure the temperature distribution at different positions to analyze the possible changes in the material properties during the bonding process.

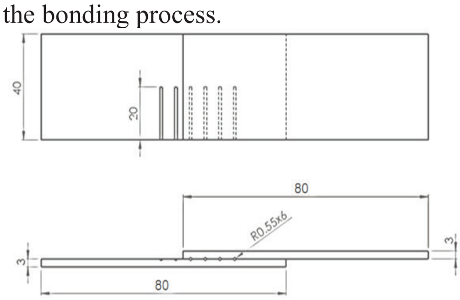

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Fig. 5 Schematic diagram of the temperature measurement position

Fig. 6 shows the temperature change curves for each part after the measurement; the melting time was 2 s, and the instantaneous maximum temperature at the center reached approximately 450 °C. The maximum temperature 18 mm from the center was also about 400 °C, which is higher than the melting point of the ABS and was sufficient for the melting of the plastic surface despite the very short time.

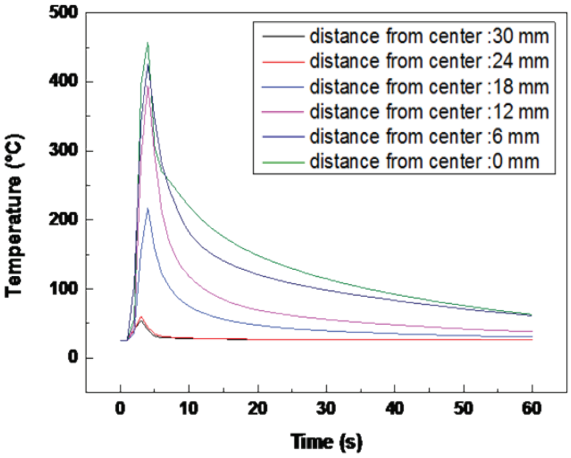

Fig. 6 Temperature change curves for multiple positions

The second part of this study conducted a simulation analysis using the finite element analysis (FEA) software Abaqus/CAE student edition. The value of the heat source generated during the ultrasonic welding process had to be obtained before the analysis. According to Elangovan *et al.*, the heat source causing the temperature change during the ultrasonic welding process can be divided into two categories: that generated by deformation, and that by the friction between the two test piece surfaces. At the early stage of welding, the temperature rapidly spread to the deformation zone because of the high thermal conductivity of the aluminum alloy. This can be regarded as a uniform distribution of the total power produced in the deformation zone【8】.

The heat flux due to deformation form Eq. (1)

$$Q_w = \frac{\sqrt{(Y_T/2)^2 - ((F_N/A_{DZ})/2)^2} \times A_{DZ} \times 4 \times \xi_0 \times fw}{A_W} \quad (1)$$

The area involved in friction is given

$$\mathrm{A_{FR}} = \mathrm{A_R} - \mathrm{A_W} \quad (2)$$

Heat flux by friction will become

$$\mathrm{Q_{FR}} = \frac{\mu \times \mathrm{F_N} \times 4 \times \xi_0 \times fw}{\mathrm{A_{FR}}} \quad (3)$$

Table I List of symbols

A_{DZ}	area of deformation zone (mm^2)
f_w	welding frequency (Hz)
F_N	normal force (N)
A_W	heat flux due to deformation (W/mm^2)
Y_T	temperature dependent yield strength(N/mm^2)
ξ_0	sonotrode amplitude (μm)
μ	static friction
A_{FR}	area of friction zone (mm^2)
A_R	Area involved in friction(mm^2)
Q_w	heat flux due to deformation (W/mm^2)
Q_{FR}	heat flux due to friction (W/mm^2)

According to the simulation analysis results (Fig. 7), the maximum temperature in the central region of the contact surface was more than 400 °C, which is close to the result of the previous thermocouple measurement. In addition, because the thermal conductivity coefficients of the ABS and aluminum alloy were vastly distinct, and the base of the fixed test piece was also of aluminum alloy material, an obvious temperature gradient change was observed in the lower aluminum alloy plate. A high temperature was only produced on the surface of the upper ABS plate, and the melting effect was produced on the plastic surface during ultrasonic welding. In the thermal analysis model, the interface contact of the horn and ABS, as well as that of the ABS and aluminum alloy, was in an ideal condition. However, under actual circumstances, full contact cannot be achieved because of thickness changes and surface roughness. A complete bond can only be obtained by increasing the welding time, as well as the molten plastic used to fill the gap between the two adherents.

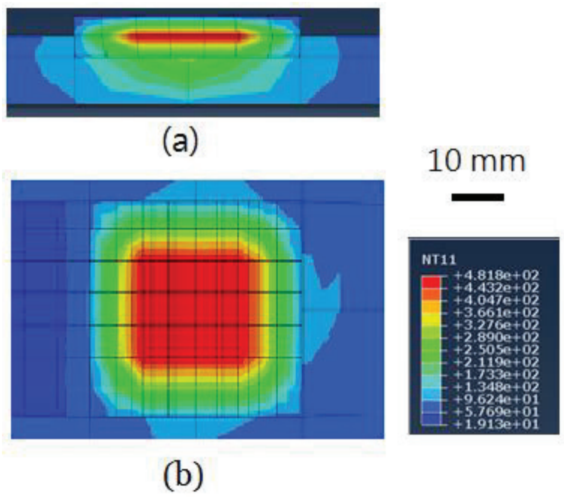

Fig. 7 Predicted temperature distribution for the 2 s bonding of the weld symmetry plane: (a) Z-axis profile; (b) X-Y plane

3.2 Ultrasonic Welding

The carbonized rice husk used in this study was produced by introducing high temperature and dry distillation at 900 °C to attain high silicon dioxide (SiO2) content and low carbon content. Based on the electron microscope images of the carbonized rice husk in Fig. 8, the rice husks were mainly irregular particles, identified as SiO2 under X-ray diffraction (XRD) analysis after the removal of the charcoal (Fig. 9). This study hopes to encourage the use of this waste resource because of its relatively low cost. In subsequent experiments, the high-temperature-fired carbonized rice husks were added to the bonding interface of the ABS with the hope of achieving a strengthening effect.

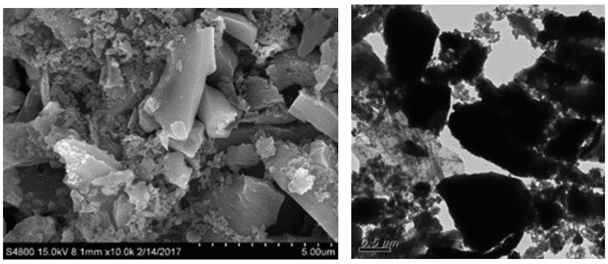

Fig. 8 Electron microscope images of carbonized rice husks

An aluminum alloy surface with a micro-hole array was placed into mixed powder of ABS and carbonized rice husk, after which it was subjected to ultrasonic welding. Fig. 10 shows that the aluminum alloy and the plastic achieved a bonding effect after the mixed powder was melted and filled into the holes. The bonded test pieces were then subjected to tensile testing, and the tensile strength changes following distinct bonding times are shown in Fig. 11. The test pieces had a lower bonding strength with a bonding time of 2 s, mainly because of the insufficient time, during which the mixed powder was incapable of fully melting and effectively filling the holes. The bonding strength of the test pieces decreased at a long bonding time of 4.5 s, a result that could be caused by the excessively long bonding time that resulted in the softening and deformation of the ABS. The bonding strength of the specimens with bonding time 3~4 s was close to the ABS base material, and the addition of mixed powder with carbonized rice hull particles also enhanced the bonding strength of the test pieces. These results indicate that under sufficient bonding conditions, the fracture positions of the stretched test pieces were all located at the ABS base material instead of on the bonding interface, thus demonstrating a satisfactory bonding effect.

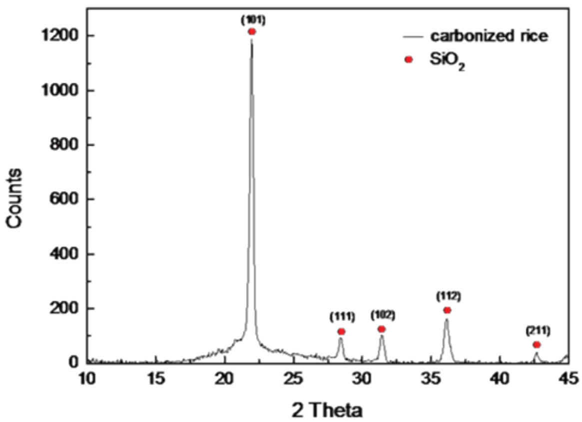

Fig. 9 XRD analysis of carbonized rice husks

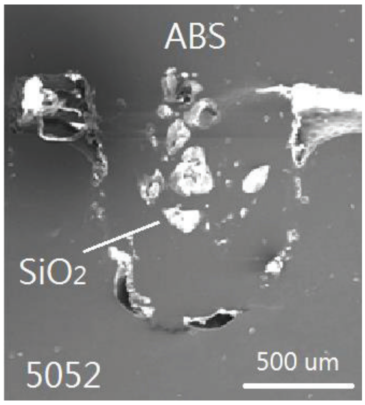

Fig. 10 Mixed powder of ABS and carbonized rice husk, melted and filled into the hole

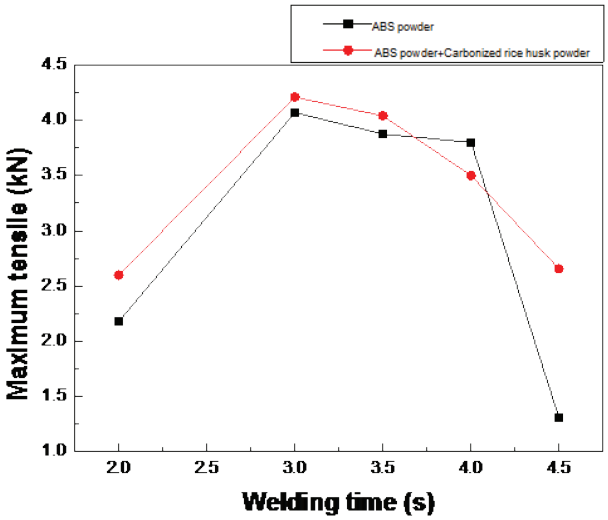

Fig. 11 Relationship between the tensile loading and bonding time after the bonding of the test pieces

4 Conclusions

This study conducted a dissimilar bonding of 5052 aluminum alloy and ABS using ultrasonic welding. A micro-hole array was produced at the junction of the aluminum alloy to increase the rate of dissimilar agents entering the holes, and the mixed powder consisting of ABS and carbonized rice husk was added at the interface to improve the bonding effect. The experiment obtained the following results:

1. The bonding interfacial temperature changes for the ultrasonic welding of the aluminum alloy and ABS were measured using a thermocouple, which showed that the maximum temperature at the bonding region was approximately 400~450°C when the welding time was 2 s. A similar result was also obtained using finite element simulation analysis, and a more obvious heat transfer effect was produced on the aluminum alloy side.
2. Regular holes were produced on the aluminum alloy surface using a micro-hole array, and ABS mixed with SiO_2-based carbonized rice husk was added to the bonding interface, after which it was subjected to ultrasonic welding with ABS. The tensile test results indicated that the fracture position of the test pieces

was on the ABS base material when the bonding time was 3~4 s, and a maximum load of approximately 4 kN was obtained, indicating a satisfactory bonding effect. A bonding time exceeding 4 s led to the deformation of the ABS, resulting in diminished bonding strength.

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