Joining of CFRTP and aluminum alloy thin plates using ultrasonic vibrations

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Abstract
In order to realize light weight structure with multi-materials, this research applied ultrasonic joining method for dissimilar joining. As the joining members, aluminum alloy and CFRTP, CFRP using thermoplastic as base resin are selected because of their specific strength. By using ultrasonic joining system which generates maximum stress amplitude on joining plane, this stress fluctuation by ultrasonic application promote plastic flow in aluminum alloy. As a result, the plastic flow at interface remove resin of the CFRTP matrix, and the exposed carbon fibers are embedded in the Al alloy. Those mechanical interlocking at the interface enabled this dissimilar joining. Focusing on those effects caused by ultrasonic, we examined conditions that show high joining strength. By preparing specimens under various conditions, discuss relationship between joining conditions and joining strength by a series of cross tensile strength test. Moreover, the series of experiments with changing ultrasonic application time revealed that this joining method has the most suitable processing time, 0.8 s, and excess processing decrease its joining strength. Finally mechanism of this joining method has been discussed with the results of joining interface observation. And it was confirmed that carbon fibers embedded into Al alloy by plastic deformation form mechanical interlocking between carbon fiber and Al alloy.

Keywords: Ultrasonic vibrations, Joining, Plastic deformation, CFRTP, Aluminum alloy, Multimaterialization

1. Introduction

As new materials with high specific strength such as aluminum alloy and CFRP are used practically, structures need to be designed with using the right material for right place (Cui, et al, 2008)(Sakundarini, et al., 2013). In order to realize this trend of multimaterialization, it is necessary to prepare suitable joining methods for using various material combinations. For that purpose, development of dissimilar material joining is currently underway (André, et al., 2016) (Jung, et al., 2013)(Lambiase, Ko, 2016)(Mitschang, et al., 2013).We chose Al alloy and CFRTP as joining members. CFRTP, CFRP using a thermoplastic resin as a base matrix, attracts attention as a new lightweight material due to its high processability compared with conventional CFRP. On the other hand, it is known to have low adhesive property. Furthermore, mechanical joining methods involving mechanical processing such as drilling, cause degradations, fiber breakage and delamination (Abrão, et al., 2007)(Davim, Reis, 2003)(Feito, et al.,2014).

One of joining methods between dissimilar metals is the ultrasonic joining method. This is a solid-phase metallurgical joining method using plastic deformation assisted by ultrasonic vibrations (Siddig, Ghassemieh, 2008)(Siddiq, Tamer, 2011)(Zhou, et al., 2018), and this method can join in a short time (Haddadi, Tsivoulas, 2016) and keep joining tool life longer. In liquid metallurgical processes, IMC generation (Bouché, et al, 1998) is a large problem which leads degradation of joining strength. However, same as other solid-phase joining (Watanabe, et al., 2006) this ultrasonic joining is also able to reduce IMC generation relatively (Haddadi, 2015)(Macwan, et al.,2017). In this research, this ultrasonic joining method is applied to CFRTP/Al alloy joining.
2 Joining apparatus

Fig. 1 shows the schematic drawing of the joining apparatus. A die and a stripper fix joining members. And a punch apply ultrasonic vibrations with static load. The tip diameter of this tool is 3.0 mm. In this equipment, static loads are applied to make base materials closely and to decrease the propagation of ultrasonic vibrations. Although higher load obtain better contact, it would increase joining member’s deformation and degrade strength of base materials. Also, this apparatus includes a vibration system that are designed to generate the node of vibration and the maximum stress amplitude on the joining interface. Ultrasonic vibrations are generated by an ultrasonic transducer attached to the upper end of the vibration system, and applied to the joining members with the resonance of this vibration system. At this time, the frequency of ultrasonic vibrations is controlled to maximize its amplitude automatically within a set range of 1.4 kHz or it is kept at a given value. Following the change of frequency and amplitude, input energy also varies throughout the joining process. Then statuses of ultrasonic vibration are output as analog signals and recorded with history of press load.

In case of metal-metal joining by this equipment, the maximum stress amplitude causes stirring due to plastic flow at the interface between base metal plates and forms the metallurgical bonds. Fig. 2 shows the schematic image of the metal-metal joining mechanisms of this method. Initially, oxide layers existing on the surface of the base metals prevent formation of metallurgical bonds between base metals. They are destroyed by stress and displacement amplitude due to application of ultrasonic vibrations, and it is dispersed into the base materials(Juan, et al., 2017). At the same time, the interface is stirred and deforms with plastic flow(Allamech, 2005)(Bai, Yang, 2016)(Bakavos, Prangnell, 2010)(Mizushima, et al., 2011). As this deformation progresses, newly formed surfaces appear and recrystallization leads generation of new crystal grain boundaries(Haddadi, Tsivoulas, 2016)(Magan, Balle, 2014). As a result, metallurgical bonds are formed. In this study, apply this joining method for dissimilar materials between CFRTP and Al alloy. The joining members and those details are shown in Fig. 3 and Table 1. Plain fabric carbon fiber sheets are used in CFRTP. Specimens are made by laying over those members cross, and joining at the center spot (see Fig. 4).
Table 1  Joining members

<table>
<thead>
<tr>
<th>Material</th>
<th>Al alloy</th>
<th>CFRTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size [mm²]</td>
<td>A5052</td>
<td>PMMA/CF</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>0.5</td>
<td>0.34</td>
</tr>
</tbody>
</table>

3. Consideration about effect of ultrasonic condition on joining process and strength

As important parameters for ultrasonic joining, there are frequency and amplitude of ultrasonic vibrations and the static load. The resonance frequency and ultrasonic amplitude of this joining change according static load. In order to discover the joining conditions that enables to apply the maximum stress amplitude stably, verify the state of ultrasonic vibrations and the joining strength with changing the frequency and the load.

Fig. 5 shows applied ultrasonic vibrations history, and Table 2 shows the cross tensile strength of each joint. Both frequency and amplitude are measured at ultrasonic transducer, and the values of amplitude are relative ones for maximum output amplitude, 1.4 μm. Ultrasonic vibrations were applied for 2.5 s and two samples were prepared for every condition, and two results under same conditions are identified in solid and broken line. In Fig. 5(a), frequency controlled in the range of 24.8 to 26.2 kHz under static loads of 5, 7.5, and 10 kN. In the joining process, frequency changes to maximize amplitude and input power also change following transitions of frequency and amplitude. Stable resonance can be obtained near 24.8 kHz under all static load conditions. It has been shown that higher load applying leads larger amplitude propagation in the comparison of same frequency. Fig. 5(b), similarly, ultrasonic vibrations were applied in the range of 25.8 to 27.2 kHz, for each static loads of 5, 7.5, and 10 kN. Although case of (a) had similar frequencies under all conditions, in this range the final frequencies were separated into two values, 26.5 and 27.2 kHz. However, the cases with 26.5 kHz, since the value of the amplitude is 0, resonance is not maintained and it shows failure of resonance. Three cases of 27.2 kHz that could maintain resonance were on the high load side, 7.5 and 10 kN, indicating that ultrasonic transmission to be stabilized by high static load. On the other hand, resonance is maintained even at the one case of 7.5 kN, and the other one are not maintained. That suggest the existence of factor influencing the vibration system in addition to the static load.

Joining strength was evaluated by cross tensile strength with the joints made in this verification. Those strengths were taken as the maximum value of the load measured up to destruction. The results are shown in Table 2. No joining was formed in any cases which ultrasonic vibrations were applied with 5 kN. For each joints of both frequency range, those strengths with 7.5 kN were higher than one’s of 10 kN. This result suggest that application of higher load does not always reinforce the joint, and it would lead a large deformation of base materials and a decrease in strength. In addition, the joining at higher frequency range, 25.8 to 27.2 kHz showed higher strength when compared with the same static loading joint in another range. This difference of strength is caused by difference of applied amplitude. So those results show that value of the static load need to be given not to degrade base materials, and frequency should be given to make amplitude larger to make joint stronger.
Among the results obtained in the previous section, non-negligible differences in the applied amplitude and joining strength were found, even static load and frequency range were the same. Although some effects of ultrasonic conditions on CFRTP/Al joining were suggested, they should be regarded as just tendencies. Therefore, in this joining method, it suggests existence of another factor influencing the ultrasonic vibration system. There is one factor that have not considered, that is the geometrical difference attributed to the texture of carbon fiber fabric in the CFRTP plate.

CFRTP used in this study is made of a plain-woven carbon fiber fabric sheet and PMMA, base resin. And Fig. 6 shows a shape of its fabric. The warp and weft are composed of a bundle of carbon fibers, and its width is about 3 mm. Since this width is close to the diameter of the circle shape joining area (3.0 mm), there is a difference in the density of the carbon fibers included joining area, depending on the position of the weave at the joining surface. As a result, and it is considered that the vibration system becomes slightly different, and the resonance frequency and the propagated amplitude also change due to the joining position. In order to take this influence of this joining position into account, classification was carried out after joining, according to the position of the joining surface on the weave. Fig. 6(b) to (e) shows the classification of each joining positions, they are “Corner”, “Edge” and “Face”. This classification is based on the bundle of carbon fibers in joining area. The case that two bundles of both warp and weft are joining area is “Corner”, and that one bundle of both warp and weft are in the area is “Face”. And the case two bundles of either warp or weft and one bundle of the other are in the area is “Edge”.

![Graph](image)

**Table 2** Results of cross tensile strength test

<table>
<thead>
<tr>
<th>Load [N]</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [kHz]</td>
<td>24.8-26.2</td>
<td>29.6</td>
<td>38.0</td>
</tr>
<tr>
<td></td>
<td>25.8-27.2</td>
<td>Not joined</td>
<td>60.9</td>
</tr>
</tbody>
</table>

Fig. 5 Ultrasonic frequency and amplitude at ultrasonic transducer for each condition

Fig. 6 Shape of the fabric and its classification.
4. Investigation on effect of processing time

To investigate about the progress of joining process against ultrasonic application time, a series of experiments are performed with changing the processing time of the ultrasonic joining and cross tensile strength measured for every joint. All of those joints were made under 7.5 kN of static load and at “Corner” of carbon fiber fabric. And joining position is set at the “Corner” position. Fig. 7 is a plot of the vibration time and joining strength (CTS). Fig. 7 (a) shows the results of all the specimens, and (b) shows the results until 3.0 s with enlarged view. The change in strength due to the processing time can be divided into three stages. Up to 0.8 s, the first stage, improvement in strength can be confirmed as ultrasonic vibration continues. Thereafter, it reaches the second stage until 2.0 s, and the strength gradually decreases. Eventually, after 5 s, the change of strength stopped, and strength stay in 20 to 40 N. It corresponds to the third stage.

![Fig. 6  Classification of joining position](image)

![Fig. 7  Comparison of cross tensile strength with processing time](image)
5. Joining interface observation and discussion on joining mechanisms

In order to verify the joining mechanism by comparing the interface state of joints at each ultrasonic application time, joining interfaces were observed. Details of the specimen used for observation are shown in Fig. 8. Strengths and processing time of observed joints were shown in Fig. 8 (a). Observations were held about specimen A and B, the one that strength was maximized and the most decreased one. This comparison enables us to verify the progress of joining due to the continuation of ultrasonic vibrations and the decrease in strength. Observations were carried out with secondary electron images and reflected electron images of Al alloy fracture surfaces (see Fig. 8 (b) and (c)) and its cross section. Reinforcement, resin embedding, cutting, mechanical polishing and ion milling are applied to Al plate to prepare a specimen shown in Fig. 8 (d) for cross-sectional observation.

Observation results of Specimen A are shown in Fig. 9. (a), (b) and (c) show the fracture surface. The fact that Al alloy was exposed in almost all fractured surfaces indicates that fracture mainly occurs at the CFRTP/Al alloy interface. A black fragment, a part of CFRTP remains on the Al alloy surface, and some of carbon fibers are exposed from base resin in enlarged view, Fig. 9 (b). Marks like carbon fiber pressed onto Al alloy surface were observed in Fig. 9 (b), (c). The length of those marks, a few hundred μm, suggests that carbon fibers had contacts with Al alloy over a long area. Fig. 9 (d) and (e) show the cross sectional image of joining area. Upper side of this observation area filled with embedding resin and distinction between this resin and CFRTP base resin could not confirmed. A cross section of the radius from the center to the end of the joined portion, Fig. 9 (d), indicate that this fracture mainly occurs at the CFRTP/Al alloy interface. And in the enlarged view Fig. 9 (e), marks of carbon fiber could be confirmed under the remaining CFRTP, like observed in the Al fracture surface in Fig. 9 (b), (c). This result suggests that some carbon fibers embedded into Al alloy once, and formed mechanical interlocking between carbon fibers and Al alloy. And it would be a main bond of this joining method.

Observation results of Specimen B are shown in Fig. 10 (a), the wide area observation confirmed more CFRTP fragments remaining on the Al alloy surface than specimen A. As shown in the enlarged view Fig. 10 (b), it was also confirmed that some carbon fibers were broken away from base resin and remained on Al alloy surface. On the other hand, observed carbon fibers were shorter than A, and it suggests that the carbon fibers were destroyed by excess application of ultrasonic vibration. In addition, not only carbon fiber but also base resin were degraded in this case. As can be seen in the image of Fig. 10 (b) and (c), the base resin remaining on the surface of B shows crushed structure compared with theirs in specimen A, uniform and smooth case. From these results, it is clear that excess application of ultrasonic vibrations for a long time degrades both base resin and carbon fiber of CFRTP. This phenomenon is a cause of strength lowering that is once increased by the continuation of the ultrasonic application from a certain time. Also from the cross sectional observation in Fig. 10(d), it shows that the joint breakage occurs mainly inside the CFRTP, and deterioration of CFRTP greatly affects the decrease in joint strength. From the enlarged view, Fig. 10 (e), it is indicated that the carbon fibers are broken and that their directions are changed from the original fiber orientation. Those broken carbon fibers were moved by deformation of surrounding base resin. It suggests that ultrasonic vibration assisted plastic flow not only in Al alloy, also in base resin with the effect of temperature elevation. In this image, CFRTP base resin could be made distinction from embedding resin because of stirring with carbon fiber. And it is observed in Fig. 10 (e) that some carbon fibers are embedded into Al alloy. Then it shows that this joining was formed by mechanical interlocking of carbon fiber. It was also observed that the shorter carbon fiber stuck into Al alloy. This result shows that the carbon fiber pushed into Al alloy by static load and ultrasonic vibrations as the driving force. And there are difference of orientation with specimen A. Orientation of B became random from A and it considered to be occurred following vertical deformation of joining members. But on this paper, we discussed about only cross tensile strength, vertical loading. Then we considered that difference of longitudinal carbon fibers have no influence on cross tensile strength.

From these results, the mechanism of this joining method is summarized in Fig. 11. The initial state before joining is shown in Fig. 11 (a). Primary, static load assists close contact between joining members, and following application of ultrasonic vibrations, deformation of the joining member’s interface with plastic flow (Allamech, 2005) (Bai, Yang, 2016)(Bakavos, Prangnell, 2010) (Mizushima, et al., 2011) and elimination of oxide layer on the Al surface occurs. As the deformation of the base material progresses, parts of carbon fibers in CFRTP contact and be embedded into the Al alloy with plastic deformation of Al alloy (see Fig. 11 (b)). As a result, a mechanical bond between the CFRTP and the Al alloy is formed mediated by carbon fibers. Furthermore, if the application of ultrasonic vibration is continued, destruction of the carbon fibers and deterioration of the base resin occur in Fig. 11 (c), which causes deterioration of bonding and strength. This is the main bonding mechanism between CFRTP and Al alloy using ultrasonic vibrations.
Fig. 8  Details of specimen for observation

(a) Strength and processing time of each specimen   (d) Prepared specimen for cross sectional observation

Fig. 9 SEM observation results of specimen A, maximum CT strength joint

(a) Fracture overview       (b) Remained CFRTP

(c) Enlarged fracture

(d) Cross sectional overview at radius of joining area

(c) Carbon fiber marks

Fig. 10 SEM observation results of specimen B, most decreased CT strength joint

(a) Fracture overview       (b) Broken carbon fiber

(c) Degraded base resin

(d) Cross sectional overview at radius of joining area

(e) Embedded carbon fiber
6. Conclusion

By applying the ultrasonic vibration and its maximum stress amplitude to the interface of joining members, CFRTP-Al thin plate joining succeed. Static load and ultrasonic frequency are set as joining conditions, the static load has an optimum value to suppress the deformation of base materials and assist transmitting the ultrasonic vibration. And higher ultrasonic amplitude brought by high frequency leads strength improvement. In addition, it was confirmed that the joining strength varies depending on the duration of ultrasonic application, and the optimum processing time maximizing the strength was clarified. On the other hand, it was confirmed that the strength was decreased by excessive ultrasonic vibrations. Al alloy’s fracture surface and cross sectional observation results revealed that excess ultrasonic application breaks carbon fiber and degrades base resin, and this phenomena causes strength decreasing. Joining mechanisms also verified with this observation. Some carbon fibers were observed to be embedded into Al alloy like it mediates Al alloy and base resin. Then this joining can be described as mechanical interlocking between carbon fiber and Al alloy.

From these results, it is summarized that this joining phenomenon proceeds as follows: at the beginning, joining is advanced on the joining member’s interface by application of ultrasonic vibrations, and accordingly joining strength gradually improves. After the interface bonding is completely formed, breakage of the bonding occurs due to excess application of ultrasonic vibrations and decreases the joining strength. The decreased strength rises again after 2.0 s, and it shows the same value after 5.0 s. It is considered that in this range, vertical deformation of base materials proceeds and its side face contacts. Then bonding formed on side interface, and strength rises again. After this, more proceeding of vertical deformation breaks side interface bonding until 5 s. Finally, this joining become similar to the mechanical clinch by deformation of the base materials, and the joining state of interface no longer changes.

Acknowledgement

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