JOINT EFFICIENCY OF MULTI-POINT SPOT ULTRASONIC WELDING FOR CFRTP

T. Tomioka\textsuperscript{1*}, K. Uzawa\textsuperscript{2}, H. Murayama\textsuperscript{1}, I. Ohsawa\textsuperscript{1} and J. Takahashi\textsuperscript{1}

\textsuperscript{1}Department of Systems Innovation, School of Engineering, The University of Tokyo, Tokyo, Japan
\textsuperscript{2}Graduate Program in Synthesized Engineering, School of Engineering, Kanazawa Institute of Technology, Ishikawa, Japan
* Corresponding author (tomioka@giso.t.u-tokyo.ac.jp)

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1 Introduction

The establishment of lightweight technology and high-efficient recycling technology for vehicles are urgently needed to cope with the global environmental problem. To manufacture lightweight mass-produced automobile by using CFRP (carbon fiber reinforced plastic), we must find solutions for the existing problems of its high cost and low productivity [1].

CFRTP (carbon fiber reinforced thermoplastic) has the potential to achieve cost savings, high-speed moldability, and high recyclability. As the demand for these newly developed CFRTPs increase, so do the requirements for joining [2]. Establishment of the joining technique is critical, especially since thermoplastics generally require facilities with higher forming pressures and temperatures [3]. In order to complete a large vehicle, subassemblies must be integrated by mechanical fastening, adhesive bonding, or welding [4].

Of these, welding is a unique method for CFRTP, utilizing its thermal plasticity. Unlike mechanical fastening or adhesive bonding, it does not require additional products, maintaining less weight [5, 6]. Induction, ultrasonic, and resistance welding are some of the successful welding methods already in practice [7]. We specifically focused on ultrasonic welding due to its many advantages, including the extremely short welding time, ease of automation, and low running cost [8]. Numbers of investigations have been carried out in the past to understand the principles of ultrasonic welding on thermoplastic composites. In most studies, single lap joints were the subject of the experimental and numerical investigations. Many factors affect the welding process, making it difficult to control its welding quality; especially to have the welded interface uniform. In such case, spot welding is useful because it is easier to control smaller welded areas. However, to date only limited research has been conducted on spot welding.

When it comes to assembling metal parts for automobile, spot welding is an effective measure [9]. In many cases, spot welding is processed with two or more spots. Here, we will refer to such spot welding as “multi-point spot”. Multi-point spot welding enables welding of a large area with small, individual weld spots.

Multi-point spot welding on metal is commonly seen in manufacturing process of vehicles, and it would be important to investigate the feasibility of applying multi-point spot ultrasonic welding to joining CFRTP body structures. This is the overall objective discussed in our research, and we have conducted investigations under simplified conditions. As the first step, we looked into the optimal welding conditions required for higher joint strength and adequate sealing by changing certain influential welding parameters. Then we reported the results of the tensile tests conducted on multi-point spot welded CFRTP specimens, along with the C-scan images of the welded area and the microscopic images of the welded area after their failure.

2 Experimental

2.1 Material

Polypropylene (PP) is one of the most commonly used thermoplastic which is low in cost and has a low melting point. In our study, we used CFRTP composed of carbon fiber and polypropylene (CF/PP). It is isotropic, randomly oriented with discontinuous carbon fibers, and has a fiber volume fraction of 20%. This material is hereinafter referred to as carbon fiber mat reinforced thermoplastics.
plate (CMT), and it was provided by Toray Industries, Inc. in a sheet form each with the thickness of either 0.5 mm or 1.1 mm. CMT was stacked, then heated and pressurized concurrently to obtain a plate of thickness of approximately 2 mm. We used the heating and cooling auto press from PEI–France. The curing procedure is as shown in Fig. 1. The material was then cut into the size of 25x100x2 mm each. When welding composite materials ultrasonically, triangular, rectangular, or semi-circular shaped energy directors are often used [8]. Energy directors would have the smallest cross section and the highest strain, causing the heating, melting, and flowing process to initiate from here [10]. However to facilitate the molding procedure, in this research, we did not have any energy directors prepared.

2.2 Welding Conditions

It is identified that joining conditions including (1) weld time, (2) weld pressure, (3) amplitude of vibration, (4) hold time, (5) hold pressure, and (6) joint geometry have a direct effect on joint strength [10]. Among these parameters, we have looked into the weld time and the weld pressure since these two were stated as one of the most influential parameters in previous studies. It is important to find the appropriate weld time and weld pressure where the resin would melt sufficiently and yet not excessively where the joint surface would deform drastically. We varied these two parameters within certain ranges under the limitations of the welder machine, and accordingly to the conditions from a prior research [11].

First, we prepared single lap joints with a lap length of 12.5 mm. Ultrasonic welder machine from Nippon Future Co., Ltd., shown in Fig. 2, was used to weld the specimens. We welded them by using two different types of horns as shown in Fig. 3. The expected welded area is also depicted here. To distinguish the two, the ones welded with the rectangular horns will be called “face welded” and the ones with the circular horns will be called “spot welded”. Although our main focus of the study is spot welding, we have also looked at the basic single lap joint for comparison.

Typically, ultrasonic spot welding refers to a welding method where the horn tip penetrates the upper specimen. However, here in our research, we evaluated the welding conditions where the substrate quality would not be affected. We did so because spot welds without deteriorated externals have the potential of versatile applications. We used the circular horn with the diameter of 10 mm. With a smaller diameter, the substrate could not withstand the concentrated pressure from the horn tip to maintain its original form. The specimens were supported from all four sides during the welding process as shown in Fig. 4, to avoid specimens from sliding in horizontal directions.

The weld time and the weld pressure were varied. The welder machine was fixed at a nominal operating frequency of 20 kHz. The amplitude of both horn vibrations was fixed at 27 µm. Hold time was kept constant at 1.0 s to provide sufficient time for the interface temperature to cool.

After welding, the performance of the ultrasonically welded joints was determined by conducting tensile tests. We used the universal testing machine of Shimadzu Corporation shown in Fig. 5, and measured the load the joint bore and the displacement of the crosshead. We referred to the testing conditions of adhesive bonds in FRPs [12]. The speed of the crosshead was 1 mm/min. Aluminum tabs were attached to the specimen ends.

2.3 Multi-Point Spot Welding

After determining the optimal values of the weld time and the weld pressure, we investigated how the load will be distributed when the number of spots is increased. The spot configuration is as shown in Fig. 6.

An ultrasonic flaw detector from Physical Acoustics Corporation was used to identify the well-welded areas. After conducting tensile tests on these joints, the microscopic images of the welded area were viewed with a VHX-1000 digital microscope from Keyence Corporation. Number of samples was 5.

3 Results and Discussions

3.1 Welding Conditions

Here are the results from the initial part of the research. Figure 7 shows the shear strength of the face welded joints with weld time varying from 0.5 s to 1.5 s, and weld pressure as 1.5 MPa or 3.0 MPa.
The average shear strength is calculated by the equation below:

$$\bar{T} = \frac{F}{LB}$$  (1)

Where $\bar{T}$ is the average shear strength, $F$ is the maximum load, $L$ is the nominal lap length and $B$ is the nominal breadth of the test specimen.

From this, the optimal weld time for face welded CMT was determined as 1.0 s. It can also be assumed that as long as the weld time is the optimal, the welding pressure 1.5 MPa or 3.0 MPa does not have a large impact on the shear strength.

Figure 8 shows the equivalent graph for spot welded joints. Spot welded joints with weld time varying from 0.5 s to 2.5 s, and weld pressure as 6.0 MPa or 12.0 MPa were tested. The weld pressure was set 4 times higher than the pressure for face welded joints. This is simply because the applied load was kept the same but the spot welded area was approximately 1/4 compared to the face welded area.

Here, the maximum load/nominal welded area was calculated. The nominal welded area per spot is defined as the area of the circle with a diameter of 10 mm.

Optimal welding time was difficult to draw from the test results since the maximum load kept rising at 6.0 MPa. When pressure is doubled, the maximum load peaked at welding time 1.0 s. However, as the picture of a welded joint with the higher pressure provided in Fig. 9 indicates, 12.0 MPa appeared to be too high of a pressure, causing drastic carving on the upper surface of the specimen with resins flowing out from the sides. This could lead to degradation in the quality of the joint, which is not preferable. Table 1 organizes the quality for each condition of spot welded joints. Taking this into account, we have chosen weld time 1.0 s and weld pressure 6.0 MPa as the standard condition for latter part of the experiments for spot welded joints.

### 3.2 Multi-Point Spot Welding

Reflecting the results obtained from the above, from hereon we fixed the weld time and the weld pressure for spot welded joints as 1.0 s and 6.0 MPa.

Figure 10 shows the C-scan images of the welded cross sections of single-row, double-row, and triple-row spot welded joints. The red areas indicate separation of the specimens, namely the non-welded areas. The bluer or the whiter spots suggest the sealed areas.

From this, it can be said that each welded spot is sufficiently welded from the center towards the rim of the circle. This again proves that the welding time and welding pressure set here is adequate.

Also, the four sides of the overlap area seem to be welded. This could be explained by the intensive friction triggered at these sides, where the relatively sharp edges of the specimen are rubbed against one another.

The spots are welded from the row on the right side of the image. Strictly speaking, the vibrating conditions should be different each time depending on whether the specimens are already welded or not. However, from these C-scan images, no notable difference could be seen among the first, second, and third-row spots. This suggests that processing multi-point spot welding all at the same time, and processing it one spot by one, could have the same effect, promising flexible welding measures.

Figure 11 shows the results obtained from the tensile tests of single-row, double-row, and triple-row spot welded joints. The average value of the maximum load/welded area did not differ substantially among the three. This means that load was distributed equally to each spot. The difference between the maximum value and the minimum value attained were approximately 45% of the average value, most likely because of the dispersions in the actual welded area for each specimen.

Figure 12 shows the interface images of single-row, double-row, and triple-row spot welded joints after failure. Each image corresponds with the images from Fig. 10. First thing to notice is that other than the intended welded areas, resins can be seen around the edges of the overlap areas. Another thing is that the shape of each spot is nonidentical. This can be attributed to the minute slippage during the welding process, and also possibly to the uneven texture of the specimen surface. All joints failed by cohesive failure, where resins could be seen on both specimen sides of the interface. As expected from the previous C-scan images, the surface of each spot and the rims of the overlap areas are white, due to the resins that have melted from the concentrated heat. However, although the spot welded area and the edges of the overlapped area appear to be alike by visual inspection, we have found that these two are distinctively different from the following enlarged views.
Figure 13 shows the microscopic view of the interface image of the center of a single-row spot joint. It can be said that the resin has melted sufficiently in these intended areas. Resins are filling up the spaces in between fibers.

Figure 14 shows the microscopic view of the interface image of the edge of the overlap area of a single-row spot joint. Resin rich area can be seen prominently around these edges. The edges produce higher friction compared to the other parts of the overlap area and therefore resins have melted in this area. Since there is no pressure applied here, the resins here have depth, some parts resembling whipped cream with strong peaks. Because of this significant difference, we have not considered these areas as “welded”, but just as areas with some resin surfacing locally.

What appeared to be the same by the naked eye is actually different. This is why we have adopted “nominal welded area” as simply the area of the spot circles.

Figure 15 shows the microscopic view of the interface image of a triple-row spot joint in between the first and second row, and Fig. 16 shows the equivalent in between the second and third row. Notice how the periphery edges of the first row and the second row is smeared in resin, whereas those of the second and third row have a distinctive mark around the periphery. Earlier, we mentioned that no difference could be seen among the first, second, and third spots. However, from the comparison between these two images, we could make the following assumption. For the first spot, even though all four sides of the specimens were supported by the metal fixture (as shown in Fig. 4), it still allows minute horizontal slippage during the welding process. We suppose this accounted for the wavy resin boundary between the welded area and the non-welded area. As for the second and third spot, since the first and second spot is already welded by then, it causes less slippage. As a result, it left a more explicit boundary mark.

4 Conclusions
An experimental investigation concerning the joint efficiency of multi-point spot ultrasonic welding for CF/PP material was carried out in this paper. The adequate welding time and welding pressure for welding this material was first searched. Then specimens were welded at multiple spots to find out how load transfer will occur. We also took a close look at how the specimens were welded at the interface.

From the first part of the research, we were able to set an adequate weld time of 1.0 s and weld pressure of 6.0 MPa for spot welding, in which the substrate quality was maintained. Noticeable result from the latter part was that when there are multiple spots, each spot were subjected to an equal amount of load. Also, two types of resin melted areas were seen: the welded part, and the part where the resin is simply surfacing.

We were able to verify that welding a large area with small separate spots is a valid measure. As a conclusion, we would like to emphasize the efficiency and the potential of quality control by adopting multi-point spot welding.

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Fig. 2. Ultrasonic welder machine

Fig. 3. Schematic of the horn shape and the welded area (top: rectangular, bottom: circular)

Fig. 4. Schematic of the welding fixture

Fig. 5. Universal testing machine
Fig. 6. Spot configuration (top: single-row, middle: double-row, bottom: triple-row; unit: mm)

Fig. 7. Shear strength of face weld joints

Fig. 8. Maximum load/welded area of spot weld joints

Fig. 9. Enlarged view of the welded joint with 12.0 MPa pressure provided

Table 1. Quality of the spot welded joints

<table>
<thead>
<tr>
<th>Pressure</th>
<th>0.5 sec</th>
<th>1.0 sec</th>
<th>1.5 sec</th>
<th>2.0 sec</th>
<th>2.5 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MPa</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>12 MPa</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
<td>Poor</td>
<td>(NA)</td>
</tr>
</tbody>
</table>
Fig. 10. C-scan images of multi-point spot welding

Fig. 11. Maximum load/welded area of multi-point spot welding

Single-row

Double-row

Triple-row

Fig. 12. Interface images of multi-point spot welding
Fig. 13. Microscopic image of the center of a single-row spot joint

Fig. 14. Microscopic image of the edge of the overlap area of a single-row spot joint

Fig. 15. Microscopic image of a triple-row spot joint in between the first and second row

Fig. 16. Microscopic image of a triple-row spot joint in between the second and third row

References


