Formation behavior of bubbles and its effect on joining strength in dissimilar materials laser spot joining between PET and SUS304

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Abstract

Formation behavior of bubbles and its effect on strength in PET/SUS304 dissimilar materials laser spot lap joint was studied. Surface of SUS304 was irradiated through transparent PET with fiber laser. Static and cyclic contact force was applied at the welding region during the joining process. Strength of the joint was evaluated by conducting tensile shear test. The formation behavior of bubbles inside PET nearby the interface changed with change in condition of contact force. In case of applying lower static contact force, welded area and failure load of the joint increased with increase in contact force. This result might be due to flow of molten PET by applying compressive force. On the other hand, when higher static contact force was applied, welded area and failure load of the joint decreased, because suppress of the flowing for molten and softened PET occurred. The joint joined with applying cyclic contact force showed lower values of welded area and failure load compared to the joint joined with applying the same maximum static contact force. According to fracture surface observation, crack mainly passed through bubbles to failure in all joints. Apparent strength was calculated by failure load and welded area obtained. The strength of the joint decreased with increase in bubbles density, except the joint joined without contact force. In case of joint joined without contact force, large bubbles were formed and decreased strength. Bubble size formed was small when contact force was applied. Density of bubbles affected strength of the joint and changed by applying contact force, particularly that decreased by applying cyclic contact force. It is considered that applying the contact force is an effective way to control formation behavior of bubbles and results in improvement for reliability of the dissimilar material joint between plastic and metallic materials.

Key words : Dissimilar materials joint, PET, Stainless steel, Laser spot joining, Strength of joint

1. Introduction

Dissimilar materials joining has possibility to create new structure and new function in many industrial fields. In generally, mechanical joining or adhesive joining is used for joining between metal and plastic materials. However, in purpose of weight reduction and miniaturization, those joining method have limitation because a part or material is required only for joining. Therefore, direct joining technique between plastic and metallic materials has been investigated. Several joining method for direct joining between plastic and metallic materials were proposed such as laser welding (Seiji Katayama and Yousuke Kawahito, 2008, Yukio Miyashita et al., 2009, Yu Kurakake et al., 2013, P. Amend et al., 2013, Satoshi Arai et al., 2014, Philipp Amend et al., 2014), ultrasonic welding (Sebastian KRUGER et al., 2004) and friction welding (F. Yusof et al., 2012, F. C. Liu et al., 2014). According to previous studies on laser
direct joining between plastic and metallic materials, it was known that bubbles were formed inside plastic nearby the interface when the heat input applied was enough to heat plastic above the decomposition temperature. It was proposed that formation of bubbles can induce strong bonding by pushing molten and softened plastic to metallic surface due to expansion of the bubbles (Seiji Katayama and Yousuke Kawahito, 2008). However, on the other hand, reduction in strength of the joint could be happened due to significant formation of the bubbles to play as defects and thermal degradation of the plastic material (Yukio Miyashita et al., 2009, Philipp Amend et al., 2014). Namely, it can be said that bubbles possibly affect the joining strength, however, that has not been studied yet in detail with viewpoint of mechanics corresponding to the strength of the joint. In this study, laser lap direct joining between polyethylene terephthalate (PET) and SUS304 stainless steel was carried out. Fiber laser was applied from transparent plastic material side. In this study, static and cyclic contact forces were applied to the joining region to aim to change formation behavior of the bubbles. Effect of formation state of the bubbles on the joining strength was studied and appropriate condition for the bubble formation was also discussed.

2. Experimental procedure

In this study, PET and SUS304 plates with thickness of 0.5 mm were used. Size of the specimens was 20×10 mm for the both plates. Physical properties of the materials used are shown in Table 1.

Table 1 Physical property of materials used.

<table>
<thead>
<tr>
<th></th>
<th>PET</th>
<th>SUS304</th>
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<tbody>
<tr>
<td>Density, g/cm$^3$</td>
<td>1.45</td>
<td>7.93</td>
</tr>
<tr>
<td>Glass transition temperature, °C</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Melting temperature, °C</td>
<td>200-255</td>
<td>1126-1181</td>
</tr>
<tr>
<td>Specific heat capacity, J/kg°C</td>
<td>1000</td>
<td>500</td>
</tr>
<tr>
<td>Thermal conductivity, W/(cm°C)</td>
<td>0.24</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Figure 1 shows schematic illustration of the joining experiment. Laser spot joining was carried out in lap welding configuration. Fiber laser (IPG Photonics, YLR-150/1500-QCW-MM-AC-Y11) with wavelength of 1070 nm was used in this study. In order to avoid getting damage on optical system by reflection of laser beam, the laser head was inclined with 10° from a vertical axis to the specimen surface. Heat input was fixed as 5.6 J/P (Joule/Pulse) with applying laser power of 280 W and pulse duration of 20 ms. Formation of bubbles was confirmed with that laser irradiation condition according to results of trial experiments carried out in advance. Specimen surfaces were cleaned before conducting the joining experiment. A PET plate was placed on a SUS304 plate and then fixed by a fixing plate with screws to a jig. Focal position of laser was set to the interface between PET and SUS304. Transparent PET was used in this experiment, therefore applied laser could pass through PET and heated surface of SUS304 at the interface as shown in Fig.1. Laser spot diameter at the interface was 0.075 mm. Static and cyclic contact forces were applied by using a piezoelectric actuator and a screw through a backing plate made by SUS304 to bottom of the SUS304 plate during the joining in order to change formation behavior of the bubbles. The contact force was measured by strain gage attached at surface of piezoelectric actuator. The applied static contact forces were varied from 0 to 500 N. Where, contact force of
0N means making contact between bottom surface of the specimen and a backing plate without additional contact force. Cyclic contact force was applied by using a piezoelectric actuator as shown in Fig.1. Cyclic loading conditions applied were the maximum force of 100 N and load range of 30 N (i.e. the mean load; 85 N, the minimum load; 70 N) with frequency of 0.1, 1, and 10 kHz.

Strength of the joint was evaluated by conducting tensile shear test with crosshead speed of 0.5 mm/min. Schematic illustration of tensile shear test is shown in Fig.2. Sizes of welded area and bubbles were measured on the fracture surface after the tensile shear test. Size of a bubble was observed as its projected area in the fracture surface. Density of bubbles was defined as number of bubble in unit length of 1 mm in bubbles formed area. Observations of bubbles are shown later in Fig. 3, 4 and 6.

3. Result and discussion

Welded area was observed through PET as shown in Fig.3. Bubbles were formed inside PET nearby the interface in all joints welded in the present experiment regardless condition of applied contact force. Bubbles were also observed in cross section of welded area as shown in Fig.4. Bubbles might be formed due to thermal decomposition of PET (Seiji Katayama and Yousuke Kawahito, 2008). Therefore, bubbles were observed significantly at the center region of the welded area because higher temperature was generated at the center by irradiation of laser. Figure 5 shows failure load and welded area obtained in the joints. In the figure, load is indicated instead of stress (strength) because load carrying capacity of the joint is important for practical application of spot joint in industries. Apparent strength values of the joints are shown in Fig.8.
In case of applying static contact force, joints joined with applied contact force from 0 to 200 N, failure load and welded area increase with increase in applied contact force. On the other hand, joints joined with applied static contact force from 300 to 500 N, failure load and welded area decrease with increase in applied static contact force. In case of applying cyclic contact force, failure load and welded area show lower value compared to those of a joint joined with the same maximum static contact force of 100 N. Moreover, failure load and welded area slightly decrease with increase in frequency of the applied cyclic contact force.

Fig. 4 Observations of bubbles formed in cross section of welded area in the joint joined with different contact force conditions. Bubbles are observed in welded region regardless of condition of applied contact force.

Fig. 5 Effect of applied static and cyclic contact forces at the joining area on failure load and welded area of the joint. Failure load and welded area increases with increase in applied contact force within static contact force range from 0 to 200 N. In case of joints joined with applied static contact force range from 300 to 500 N, failure load and welded area decreases with increase in applied static contact force. Failure load and welded area of joint joined with applied cyclic contact force shows lower value compared to those of a joint joined with the same maximum static contact force of 100 N.
Figure 6 shows an example of fracture surface observation. Stick of PET was observed at some areas in fracture surface of SUS304 side. That area agreed with potion of bubbles formed in PET side. Therefore, it is speculated that crack might propagate through the bubbles as coalescence of bubbles to the fracture.

Distribution of bubble size is shown in Fig.7. According to the figure, relatively large bubble was formed in the joint joined without contact force (contact force of 0N). On the other hand, relatively small bubbles were formed in the joint when static or cyclic contact force was applied. Apparent tensile shear strength of the joint was calculated with the failure load divided by the welded area. Relationship between the strength and density of bubbles are shown in Fig.8. Where, density of bubbles was defined as number of bubbles in unit length of 1mm. According to Fig.8, density of

Fig.6 An example of fracture surface observation in SUS304 side for the joint joined with applied static contact force of 200N. (a) overview, (b) magnified view of a square in (a) and (c) EDS analysis of Carbon. Crack might propagate through bubbles.

Fig.7 Distribution of bubble size. Small bubbles were formed in the joint when static or cyclic contact force was applied.
bubbles for the joint joined with applying static or cyclic contact force is higher than that for the joint joined without applying contact force. Moreover, in case of joints joined with applying cyclic contact force, density of bubbles decreased with increase in frequency. On the other hand, in case of applying static contact force, density of bubbles increased with increase in the contact force. Results shown in Fig. 8 could be summarized that strength of joints decrease with increase in density of bubbles, except the joint joined without contact force.

Figure 9 shows schematic illustration of the welding process. In case of a joint joined without contact force, bubble might be easily expanded to large size due to high pressure induced by generation and rapid expansion of bubbles (Seiji Katayama and Yousuke Kawahito, 2008) as shown in Fig.9 (a) then that large bubble plays as a large defect and decreases the strength significantly. On the other hand, in case of a joint joined with the contact force, expansion of bubble might be suppressed by compressive force and results in that small bubbles are formed. Additionally, in case of applied static contact force below 200 N, welded area also increased by spreading of softened and molten PET as shown in Fig.9 (b). However, in case of static applying contact force above 300 N, contact between PET and SUS304 became too strong then softened and molten PET could not be spread due to suppression of flowing of the softened and molten PET as shown in Fig.9(c) and results in decrease in welded area. Heat transfer from PET to SUS304 due to the strong contact could also affect flow behavior of softened and molten PET. The bubble might be able to move actively with flow and convection of molten PET induced by applying cyclic contact force as shown in Fig.9 (d), therefore, density of bubbles becomes lower. Welded area observed in the joint joined with applied cyclic contact force with the maximum force of 100 N was smaller than that in the joint joined with applied static contact force.

![Fig.8 Relationship between tensile shear strength and density of bubbles. Strength of joints decrease with increase in density of bubbles except the joint joined without contact force. Density of bubbles decreased with increase in frequency when cyclic contact force was applied.](image)

![Fig.9 Schematic illustrations for the welding process.](image)
force of 100 N. This may be due to lower average contact force in the cyclic contact force compared to the static contact force of 100 N and also due to the effect of viscous elastic in PET, however, study on the detail is required as a future work.

Strength decreased with increase in density of bubbles for the joint joined with static or cyclic contact force, as shown in Fig.8. Therefore, effect of bubbles density was investigated based on fracture mechanics by assuming 2-dimensional model of periodic cracks as shown in Fig.10. The stress intensity factor can be calculated with equation (1) and (2) (Yukitaka Murakami ed., 1986).

\[
\begin{align*}
K_1 &= F_I \alpha \sqrt{\pi a} \\
F_I &= \frac{d}{\sqrt{\pi a}} \tan \left( \frac{\pi a}{d} \right)
\end{align*}
\]

According to Fig.7, in case of joints joined with applying contact force, bubble with size below 500 µm was the most significantly observed then constant crack size of 2a=25 µm was assumed. Distance between cracks, d was calculated from the bubble size assumed and density of bubbles. Shear force was applied apparently in the present experiment, however, in the model, it was assumed that tensile stress (corresponding to crack opening mode, Mode I) acting normal to the interface was dominant on the fracture. The same trend was observed in numerical study on strength of dissimilar materials joint between PET and aluminum alloy (Yu Kurakake et al., 2013). The result indicated that delamination force acting normal to the interface was predominant on the fracture behavior.

Correction factor \( F_I \) in equation (1) was calculated for the joints obtained. Relationship between \( F_I \) and strength of the joint is shown in Fig.11. According to the figure, the strength is well arranged by \( F_I \). Size of bubbles were relatively small in the joint joined with applying contact force as mentioned in above, however, when applying contact force was...
too high, increase in welded area did not occur, then resulted in increasing in density of bubbles. In case of applying cyclic contact force, bubble moves and distributes by occurrence of significant flow and convection of softened and molten PET, then results in that density of bubbles decreases. Strength of a joint with higher density of bubbles is lower because that coalescence of the bubbles easily occurs. Therefore, difference in strength of the joints with applying contact force observed in the present study was mainly due to difference in density of bubbles changed with condition of applying contact force. It is considered that applying contact force is an effective way to improve strength of dissimilar materials joint between plastic and metallic materials through control of formation behavior of bubbles.

Strength of joint depends on not only density but also size, shape and position of bubbles. Additionally, change in mechanical property of PET in the welded area by heating and residual stress at the interface could also affect the strength. Many factors would influence the strength and the fracture behavior of the joint in actually. In this study, a simple model was used to explain strength of the joint based on difference in density of bubbles. Another model including other influence factors will be proposed in a future work to understand strength and fracture behavior of the joint in detail.

4. Conclusion

Dissimilar materials spot joining between PET and SUS304 was carried out by using fiber laser. Formation behavior of bubbles formed inside PET nearby the interface changed by changing condition of applying contact force. Size and density of bubbles affected strength of the joint. In particular, density of bubbles decreased by applying cyclic contact force. Therefore, it is considered that the applying contact force is an effective way to control formation behavior of bubbles and improve strength of a dissimilar materials joint between plastic and metallic materials.

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