Effect of Metal Type and Heating Condition on Joint Strength of Metal and Polymer Prepared by Arc Welding*

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Welding is an important joining technology for dissimilar materials, such as metals and polymers. However, the joint strength of the welded structure and the mechanical behavior of the polymer change significantly owing to the thermal history of the polymer during the welding process. In this study, polyamide 6 (PA6) plates were welded to stainless steel (SUS304) and aluminum (A5052) plates using arc welding at different welding conditions. The effects of the welding conditions and metal type on the joint strength were investigated using the tensile tests. The experimental results demonstrated that the joint strength of the welded structure strongly depended on the thermal history of PA6. When the temperature of the metal plate exceeded the melting temperature of PA6, the joint strength increased. However, the joint strength decreased considerably when the temperature exceeded the thermal decomposition temperature of PA6. The fracture of PA6 was classified into two categories depending on the amount of heat applied to PA6, namely, fracture of interface and fracture of polymer.

Key Words: Arc welding, Dissimilar joint, Polyamide, Digital image correlation, Strain distribution, Polymer, Stainless, Aluminum

1. Introduction

Recently, joining metals and polymers has been considered essential for reducing the weight of transportation equipment, such as automobile and aircraft1~5). Although adhesion and mechanical fastening are usually employed for dissipater joints, these techniques have several disadvantages, such as generating volatile organic compounds (VOC), inducing stress concentration, and increasing weight6). In contrast, welding metals and polymers has the potential to solve these problems.

In metal/polymer welding, a thermoplastic polymer, such as Polyamide (PA), is melted by heating and subsequently bonded to the metal. F. C. Lui7) et al. noted that a covalent bond may be formed between the carbonyl groups of PA6 and a metal element. In this case, the formation of C-O-M bonds (“M” denotes a metal atom) at the welding interface may provide a stronger joint. However, excessive heating of PA6 causes thermal decomposition of the polymer. Furthermore, the mechanical behavior of this polymer is changed significantly by its thermal history8). This consequence indicates that establishing the appropriate welding procedure, e.g., applicable material and heat control, is important for the practical application of welding.

Our research group has been studying the influence of welding conditions on the joint strength of the polymer and metal plate. The results obtained in a previous study9) showed that the amount of heat applied to the polymer in the welding region affected the fracture pattern of the welded structure. In that study, a hot air welding machine was employed for the welding process. However, it was difficult to control the heating area and temperature of the welding process. Therefore, the results varied even for the same heating conditions. Furthermore, the hot air welding machine required a longer time than those of other welding techniques, such as arc welding. Therefore a detailed study on dissimilar welding using various welding methods is required for the practical application of metal/polymer welding.

In this investigation, arc welding was employed as the welding method. The mechanical property of a metal/polymer welded structure was evaluated using the uniaxial tensile test. Stainless steel and aluminum alloy were utilized for the metal plates, and PA6 was utilized as the polymer. Then, the strain distribution of PA6 was evaluated by digital image correlation (DIC), and the effects of metal type and welding conditions on the mechanical properties of the welded structure were investigated.

2. Experimental method

The materials used in this study were plates of PA6, SUS304 and A5052 with dimensions of 100 × 30 × 2 mm. The PA6 plate was made from PA6 pellet (CM1017, TORAY Industries, Inc., Tokyo, Japan) using a heating and cooling compression molding machine (IMC-11D6, Imoto Machinery Co., Ltd, Kyoto Japan). The pellet was directly pressed between two stainless steel plates using a fluororesin sheet to avoid adhesion of PA6 to the mold. All specimens were heated for 5 min at 250 °C and compressed at 40 MPa. Subsequently, the specimens were cooled for 5 min at 10 °C by circulating cooling water while being compressed at 40 MPa.

The PA6 plate was then welded to the SUS304 or A5052 plate.
Arc discharge was employed as the heat source for welding. Fig. 1 shows the setup of the arc welding process. In the welding process, the SUS304 or A5052 plate overlapped with the PA6 plate for 30 mm. The junction region was fixed by a jig, and welding was conducted from the metal plate, as shown in Fig. 1. The discharge time and arc discharge current are listed in Table 1.

After preparing the welded specimen, a uniaxial tensile test was conducted at a tensile displacement rate of 1 mm/min using a tensile tester (LSC-1/30-2, Tokyo Koki Testing Machine Co. Ltd, Tokyo, Japan). During the tensile test, the strain distribution on the PA6 surface was measured by DIC. A schematic diagram of the tensile test is shown in Fig. 2. As shown in the figure, the strain measurement area was the surface of the PA6 plate that included both the welded and unwelded regions. A random pattern was assigned to the PA6 plate surface using a black spray, and the surface of the PA6 plate in the tensile test process was captured using a single lens reflex camera (body: D5200, lens: AF-S DX Micro NIKKOR 40 mm f/2.8G, Nikon Corporation, Tokyo, Japan) for 30 s, and the inhomogeneity strain occurring in the PA6 plate was evaluated using netDIC(10). Furthermore, the temperature change of the metal plate during and after arc discharge at the positions shown in Fig. 3 were measured by thermocouples.

### Table 1  Welding conditions

| Discharge time [s] | 2, 2.5, 3, 4, 5 |
|-------------------|-----------------|
| Arc discharge current [A] | 25, 50 |
| Arc length | 6 mm |
| Electrode | W-2%CeO2 |
| Electrode diameter | 4.0 mm |
| Electrode tip angle | Angle of 30° |
| Shielding gas | Argon gas |
| Gas flow rate | 25 l/min |
| Metal type | SUS304, A5052 |

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### 3. Results and discussion

#### 3.1 Welding of PA6 and A5052

The results obtained by performing the tensile tests on the A5052/PA6 welded specimens are explained in this section. The relationships between tensile force and displacement for the A5052/PA6 specimens are shown in Fig. 4. Three tensile tests were performed for each welding condition. As the discharge time increased, the elongation and the joint strength increased for both the 25 A and 50 A cases. The elongation and the joint strength for the 50 A case were significantly larger than those of the 25 A case. As the discharge time and arc discharge current increased, the amount of heat applied to the PA6 increased. This heat caused an enlargement of the melting area of PA6 and an increase in the elongation and the joint strength of the welded specimen.

We found that the fracture patterns of the welded specimens can be classified according to two fracture modes. Representative results for both cases are shown in Fig. 5. Fig. 5(a) shows the fracture of interface. In this case, the PA6 plate was peeled off the aluminum plate; thus, PA6 did not remain on the aluminum plate. This fracture mode was observed when the arc discharge current was 25 A. Fig. 5(b) shows the fracture of polymer. In this case, the shear force applied to the welding area exceeded the tensile strength of PA6. This fracture mode was observed when the arc discharge current was 50 A.

Fig. 6 shows the relationship between temperature and time for different positions. The temperature rapidly increased during arc-discharge and then gradually decreased. The maximum temperature increased with increasing magnitude of the current.
Although the temperature during arc-discharge varied with measurement location, after arc-discharge, the temperature was similar at different locations. This behavior enlarged the welding area and improved the values for strength and elongation, as determined by tensile tests. However, the area exceeding the melting temperature of PA6 (represented in the Fig. 6 by a dashed line) was limited in the experimental conditions (25A and 3s) in Fig. 6(a). This results indicated that the welding area for these conditions was smaller than those of the other conditions. It generated high shear stress, which induced interface fracture, as shown in Fig. 5(a). In contrast, the temperatures at measurement locations far from the welding point exceeded the melting temperature of PA6. In this case, the shear stress of the welding area was moderate, and the total shearing force applied to the welding area exceeded the tensile strength of PA6.

3.2 Welding of PA6 and SUS304
The relationships between tensile force and displacement for the SUS304/PA6 specimens are shown in Fig. 7. The axes for displacement and force are magnified because the elongation and force of these specimens were significantly less than those of the A5052 specimens. As the discharge time increased, the elongation and the joining strength decreased for both the 25 A and 50 A cases. In these tests, all the specimens exhibited interface fracture. A representative fractured specimen is shown in Fig. 8. A discolored area that may have been generated by carbonization of the polymer was observed near the welding area of the fracture surface of the PA6 plate. Furthermore, a large indentation formed at the center of the welding area. PA6 experiences thermal decomposition at approximately 400 °C, so the existence of a discolored area and indentation on the PA6 surface indicated that thermal decomposition may have occurred because of the large amount of heat applied to PA6. This amount of heat resulted in shear fracture at the boundary between areas affected and unaffected by heat.

Fig. 9 shows the relationship between temperature and time for different positions. Similar to the temperature of the A5052 plates, the temperature of SUS304 increased during arc-discharge and then gradually decreased. The important difference from A5052 case is that the maximum temperature at the center was close to 1000 °C, a value that significantly exceeded the thermal decomposition temperature of PA6. On the other hand, the temperatures at locations far from the welding point were much lower than those at the central point of arc welding. In addition, the temperature at 3.25 mm also exceeded the decomposition temperature. This area approximately corresponds to the size of the indentation on PA6. Welding at this much higher temperature caused the thermal decomposition of PA6 at the central point of arc welding. This decomposition resulted in significant deterioration of the joint strength between PA6 and SUS304.

Aluminum has a larger thermal conductivity than stainless steel. This higher thermal conductivity enabled a wide area to heat with a temperature above the melting temperature of PA6. On the other hand, excessive heat was applied to only a narrow area of SUS304.
that resulted in the thermal decomposition of PA6. Consequently, arc welding using aluminum alloy plate was determined as the better option.

3.3 Digital image correlation (DIC)

Stress concentration around the welding spot is an important consideration in the practical application of the welding. From sections 3.1 and 3.2, a strong joint was achieved between the polymer and the metal when the temperature of the metal plate was in a range from the melting temperature to the thermal decomposition temperature. In this study, discharge current of 50 A was applied to A5052, so the joint strength was large and fracture occurred at the PA6 near the welding area. Fig. 10 shows the strain distribution on the specimen surface per tensile displacement in the tensile test as evaluated by DIC. Strain was greatly concentrated in the PA6 above the center point of arc welding. This strain distribution may have been caused by not only tensile load but also thermal deterioration of the heat affected zone of PA6. The effect of thermal deterioration will be investigated in a future study.

4. Conclusion

PA6 was welded to stainless steel and aluminum alloy plates by arc welding, and the joint strength was evaluated using a uniaxial tensile test. The results obtained in this study are as follows:

(1) When welding PA6 and A5052, as the discharge time and arc discharge current increased, the amount of heat applied to PA6 increased. This heat enlarged the melting area of PA6 and increased the elongation and joint strength.

(2) The fracture patterns of the A5052/PA6 welded specimen could be divided into two fracture modes, namely, fracture of interface and fracture of polymer, depending on the total heat applied to PA6.

(3) Welding PA6 and SUS304 caused a discolored area and large indentation on the PA6 surface. These effects indicated that thermal decomposition may have occurred because of the large amount of heat applied to PA6, inducing shear fracture at the boundary between heat affected and unaffected areas.

(4) Because aluminum has a higher thermal conductivity than stainless steel, this higher thermal conductivity enabled a wide area to heat with a temperature above the melting temperature of PA6. In contrast, excessive heat was applied to only a narrow area of SUS304, resulting in the thermal decomposition of PA6.

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Reference

1) A. B. Abibe, S. T. Amenico – Filho, J. F. Dos Santos and E. Jr. Hage: Development and analysis of a new joining method for polymer metal hybrid structures, J. Thermoplast. Compos. Mater., 24 (2004), 233.
2) H. E. Friedrich: Challenges of materials technology for low consumption vehicle concepts, Adv. Eng. Mater., 5 (2003), 105-112.
3) C. E. Bakis, L. C. Bank, V. L. Brown, E. Cosenza, J. F. Davalos, J. J. Lesko, A. Machida, S. H. Rizkalla and T. C. Trantafillou: Fiber-reinforced polymer composites for construction – state-of-the-art review, J. Compos. Constr., 6 (2003), 73-87.
4) F. Balle, G. Wanger and D. Eifke: Ultrasonic metal welding of aluminum sheets to carbon fiber reinforced thermoplastic composites, Adv. Eng. Mater., 11 (2009), 1-2.
5) W. S. Kim, I. I. Yun, J. J. Lee and H. T. Jung: Evaluation of mechanical interlock effect on adhesion strength of polymer-metal interfaces using micro-patterned surface topography, Int. J. Adhes. Adhes., 30 (2010), 408-417.
6) A. Filho, and S. T. Dos Santos: Joining of polymers and polymer-metal hybrid structures: Recent developments and trends, Polym. Eng. Sci., 49 (2009), 1461-1476.
7) F. C. Liu, P. Dong, W. Lu, K. Sun: On formation of Al-O-C bonds at aluminum/polyamide joint interface, Appl. Surf. Sci., 466 (2019), 202-209.
8) M. Uchida, Y. Shinno, H. Asano and Y. Kaneko: Effect of thermal history on the microstructure and inelastic deformation behavior of polypropylene films, Proceedings of the Conference on Fracture and Strength 2016, (2016), 441-442.
9) H. Kobayashi, M. Uchida, H. Kitano, Y. Kaneko: Effect of heating condition on bonding strength of hot-air welding of stainless steel and PA plates, J. Soc. Mater Sci., 68 (2019), 833-838.
10) M. Uchida and N. Tada: Sequential evaluation of continuous deformation fields of semi-crystalline polymers during tensile deformation accompanied by neck propagation, Int. J. Plast., 27 (2011), 2085-2102.