EFFECT OF ELECTRIC FIELD ON ADHESION OF THERMOPLASTIC RESIN AGAINST STEEL PLATE

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ABSTRACT
This work shows controlling adhesion strength of acrylic resin with electric field. Usage of electric field is a new solution to control adhesion of thermoplastic resin in thermoplastic CFRP stamping process. When DC -175 V was imposed on metal specimens, adhesion strength increases to 0.81 MPa which is 57% higher than that of no bias condition. Negative component of surface energy after imposing DC -175 V on metal specimens was 7.6 mJ/m$^2$. This value was 56% smaller than that of no bias condition. When AC electric fields was imposed, adhesion strength decreased from no electric bias condition. Most effective AC bias condition in this research was AC 150 V with 1 MHz, in which case adhesion strength was 0.29 MPa. This value was 44% lower than that of no bias condition.

Keywords: Thermoplastic resin, electric field, adhesion controlling, CFRTP, acrylic resin.

INTRODUCTION
Fuel consumption has being improved in transportation vehicle industries because strong demands for reducing CO$_2$ gas emission is getting bigger and bigger. Vehicle weight reduction is one of the most effective ways to save natural resources. Many Carbon-Fiber-Reinforced Plastic (CFRP) components have been used in aerospace industry because of its lightness as well as high mechanical strength. On the other hand, CFRP parts are not widely used in the automotive industry because cost of conventional CFRP is expensive. Long manufacturing time is one reason of the expensiveness of CFRP. Thermosetting resin, which is the bulk material of conventional CFRP, requires heating time (at least few minutes) from liquid to solid transformation. New material called thermoplastic CFRP has been developed as a productive material [1]. Thermoplastic resin changes its shape easily at high temperature and hardens at low temperature. The material properties match requirement of stamping method. Long Fiber Thermoplastic - Direct (LFT-D) method has been developed for achieving one minute manufacturing of thermoplastic CFRP [2][3]. Procedure of LFT-D method consists of making compound in mixing extruder, heating compound, stamping, cooling and ejecting thermoplastic CFRP from mold [4][5]. One minute stamping is considered to be achieved with LFT-D method because thermoplastic resin and stamping method is used in LFT-D. Although thermoplastic CFRP and LFT-D method have a lot of merits, it is not applied for popular cars. One issue about thermoplastic CFRP is weak bonding between carbon fiber and thermoplastic resin. Thermosetting resin stick to carbon fiber well because viscosity of thermosetting resin is low before hardening. On the other hand, thermoplastic resin is not able to stick to carbon fiber well, because viscosity of molten thermoplastic resin is higher than thermosetting resin. In addition, sizing material covering carbon fiber prevents thermoplastic resin from sticking to carbon fiber. This is the reason why
mechanical strength of thermoplastic CFRP does not satisfy industrial requirements [6][7]. To enhance the adhesion, treating methods have been developed. Chemical substances are widely used for removing sizing material [8]. One demerit of the methods is that chemical substances are very toxic and affect environment. In LFT-D method, because two screws mix carbon fiber and resin in the same chamber at high temperature, they are mixed and adhere well. In addition, sizing material is removed in such high temperature without any specific treatment. Therefore, LFT-D method is considered as not only productive but also an effective method to manufacture the thermoplastic CFRP which has superior mechanical strength. One issue about LFT-D method is that it is not easy to eject thermoplastic CFRP from metal mold. It is attributed to lower thermal expansion and higher viscosity of thermoplastic CFRP than that of conventional thermoplastic resin. One technique to reduce adhesion on metal is to spray mold release agent. The demerit of release agent is such kind of substances contaminate thermoplastic CFRP. The contamination can degrade the mechanical properties of thermoplastic CFRP. From these backgrounds, new method for reducing adhesion between thermoplastic CFRP and metal mold without any release agent is required to be developed. One of the most effective technique to reduce the manufacturing time in stamping as well as LFT-D is to shorten the cooling sequence after pressing. Adhesion at high temperature, especially around glassy-transition temperature of thermoplastic resin, is an important factor when the cooling time is shortened. Some research has reported that adhesion has increased around glassy-transition temperature [9][10]. However, there is no effective method, which can satisfy the demand for reducing adhesion of thermoplastic resin at high temperature. Some methods with electric field have been developed for controlling adhesion or friction because imposing electric field is simple compared to coating methods. Kamiya et al. developed adhesion controlling method for acrylic gam by imposing DC bias to metal surface [11]. He discussed that function group on molecular chains of acrylic rubber moved according to the polarity of electric field. Fujisawa tried controlling Si$_3$N$_4$ friction to mica surface by imposing AC electric field [12]. He observed that specific AC frequency had reduction effect on friction. However, no research has shown availability of electric field to reduction of thermoplastic adhesion. Usage of electric field is clean method compared to release agent. In addition, the method can be used for large mold easily. In this paper, we propose adhesion reduction method for thermoplastic resin with electric bias and verify the availability.

MATERIAL AND TEST METHOD

Adhesion test with acrylic resin under several electrical fields were conducted. Fig. 1 shows schematic images of equipment which measured adhesion strength between thermoplastic resin and metal plate at high temperature. The metal holder was connected to the slider which the actuator moved upward or downward. The heater controlled surface temperature on metal specimens. The load cell detected pull-off force on polymer specimens. The polymer holder, whose shape was like a clip, fixed a polymer specimen. In this report, acrylic resin was used as thermoplastic resin specimens. Polymer specimens were cleaned by ultrasonic cleaning in ethanol for one minute. SUS304 was selected as metal specimens. Metal specimens were cleaned by ultrasonic cleaning in ethanol for 15 minutes at first and then were cleaned by ultrasonic cleaning in acetone for 15 minutes.

Metal specimens were heated to 128°C in the first step. Then the actuator moved slider down which pushed a metal specimen to a polymer specimen. When the load cell detected 3 N load, the actuator stopped and kept slider position for 5 seconds. In the next sequence, slider went up. During this sequence, load cell measured adhesion strength. Moving speed of the slider was 0.1 mm/s.
DC bias and AC bias were applied to the metal specimen holder. In DC bias case, bias intensity was varied from -175 V to 175 V. The polymer specimen holder was connected to ground. In AC bias case, AC bias was imposed between the metal and polymer specimen holder. Three types of bias intensity, -175 V to 175 V, -100 V to 100V and -50 V to 50 V, were used in this paper. In each bias intensity, AC bias frequency was varied from 100 Hz to 1 MHz. Electric bias was imposed before polymer specimens attached to metal specimens till polymer specimens detached from metal specimens.

![Fig. 1 - Schematic images of adhesion test equipment](image)
(a) Equipment setting with DC power supply. (b) Equipment setting with AC power supply.

**ADHESION IN DIRECT CURRENT BIAS**

Figure 2 shows the adhesion strength results in several DC bias conditions. When DC -175 V is imposed to metal specimens, adhesion strength is 0.81 MPa which is 57% higher than that of no bias condition. When DC -100 V and DC -50 V is imposed, adhesion strength shows 0.61 MPa and 0.53 MPa, respectively. When positive bias is imposed, the maximum adhesion strength is 0.59 MPa in DC 175 V condition. The adhesion strength is 15% higher than that of no bias condition. On the other hand, adhesion strength in positive bias condition shows lower value than that of negative bias condition.

From these results, it is clarified that the adhesion strength increases proportionally as bias intensity increases. In addition, negative bias affects adhesion strength between acrylic resin and metal more than positive bias.

**ADHESION IN ALTERNATING CURRENT BIAS**

Figure 3 shows the adhesion strength results in several AC bias conditions. Each point of AC 50 V and 150 V is shifted by 20% for visibility of the graph. Dotted horizontal lines drawn in Fig. 3 indicate adhesion strength in DC bias conditions shown in Fig. 2. The lowest adhesion strength in AC bias conditions is 0.29 MPa in AC 150 V, 1 MHz condition. The value is 44%
lower than that of no bias condition. The minimum adhesion strength in AC 50 V conditions is 0.36 MPa in AC 50 V, 1 MHz condition. The value is 30% lower than that of no bias condition. Even the strongest adhesion strength in these tests shows lower adhesion strength than that of no bias condition. Other feature of Fig. 3 is that adhesion strength decreases as electrical frequency increases. As the result, the minimum adhesion strength is observed in 1 MHz frequency in three AC bias conditions.
EFFECT OF DC BIAS ON ADHESION STRENGTH

The results shown in Fig. 2 indicates that DC bias affects adhesion strength of acrylic resin on metal steel surface. Molecular chains of acrylic resin have carbonyl groups on its side. Carbonyl groups and neighbor carbon atoms charge positive and negative, respectively. There are electric charge deviations even whole molecular is neutral in electrically. [-O-CH$_3$] groups also bond to carbon atoms which has positive electrical charge. When bias is not imposed, negative charged oxygen atoms and [-O-CH$_3$] groups contact metal surface. When negative electric field is imposed on metal specimens, carbonyl groups which have negative charge go inside of polymer. In addition, carbon atoms which have positive charge is go surface of polymer because negative bias attracts positive charge. [-O-CH$_3$] groups also go surface of polymer because the oxygen atoms and [-O-CH$_3$] groups locate opposite side of the carbon atoms. It is considered that increase of Van der Waals force between [-O-CH$_3$] groups and metal surface generates stronger adhesion strength. On the other hand, when negative charge is imposed to metal specimens, function groups do not move because positive charged atoms already exist on surface in initial condition. In this case, electric field generates Coulomb force between polymer surface and metal specimens. It is considered as the mechanism that adhesion strength increases when positive bias is imposed.

EFFECT OF DC BIAS ON SURFACE ENERGY

Previous chapter discusses the mechanism of adhesion strength increase in DC bias. In this chapter, surface energy is discussed for confirming the mechanism. Surface energy was calculated by measuring contact drop angle on acrylic resin surface. Surface energy measuring was conducted following sequences. At first, temperature of a metal specimen to which DC bias was imposed was increased to $128^\circ$C. Then a polymer specimen was contacted to the metal specimen. After that, the temperature at the metal specimen was decreased to room temperature. Electric field was imposed during these sequences. After the temperature decreased to room temperature, the polymer specimen detached from the metal specimen. In

![Surface energy of acrylic resin after imposing DC bias](image)
the next step, surface energy of polymer specimens was measured by sessile drop technique. In this research, total surface energy, dispersive component, positive polar component and negative polar component of surface energy was calculated by using water, formamide and diiodo-methane [13-14].

Figure 4 shows surface energy on acrylic resin specimens after imposing several DC bias. It is seen that negative polar component of surface energy decreases when negative electric field is imposed. DC -175 V decreases the component of surface energy more than DC -100 V. This result indicates that the more DC bias intensity increases, the more negative polar component decreases. Dispersive component of surface energy also increases when negative bias is imposed. On the other hand, dispersive component does not change when positive bias is imposed compared to no bias condition.

**EFFECT OF AC ELECTRIC FIELD ON DIELECTRIC CONSTANT**

From the results shown in Fig. 3, it is clarified that adhesion strength decreases as AC bias frequency increases. In addition, higher bias intensity decreases adhesion strength more than that of lower bias intensity. When electrical bias is imposed, carbonyl groups and charged carbon atoms move to surface or inside of resin. In the case of AC bias, electrical field shifts continuously. If there are some conditions in which adhesion strength is strong or weak, measured adhesion strength equals weak one. This is because conditions shifts continuously during detaching process. Increase of phase lag between electrical field and polarization in acrylic resin may lead decreasing of adhesion strength.

Dielectric constant measurement in 128°C was conducted to confirm these discussion. Figure 5 shows real and imaginary term of dielectric constant. Then dielectric tangent is calculated from dielectric constant. It is clarified that dielectric tangent increases as electrical frequency increases. Increase of dielectric tangent indicates that phase lag between electrical field and polarization in dielectric substance increases. Figure 6 shows the schematic of relation between electric field and polarization in acrylic resin. During one cycle of AC bias, there are four type of conditions. Polarization between electrical field and dielectric substance equal in 2nd and 4th conditions. Thus, adhesion characteristic in DC bias is observed in 2nd and

![Fig. 5 - Dielectric constant of acrylic resin in several frequency at 128°C](image-url)
4th conditions. On the other hand, opposite polarization should be observed in 1st and 3rd conditions. It is clarified that surface energy of negative component decreases and increases from resin surface when negative and positive bias is imposed, respectively. Then AC polarization change to opposite polarity, resin surface polarization repels from metal surface in 1st and 3rd condition. AC field shifts continuously through 1st to 4th conditions shown in Fig. 6. When resin specimens detaches from metal surface, surface condition should be what the smallest adhesion strength occurred. This is the mechanism which AC field decreases adhesion strength. It is considered that large phase lag causes large repel force between resin surface and metal surface. Adhesion strength decreases as AC frequency increases because dielectric tangent increase as AC frequency increases.

CONCLUSIONS
In this research, adhesion reduction method of acrylic resin to metal surface is investigated. In addition, the mechanism is discussed. Main results is shown in following;

1. When DC -175 V is imposed on metal specimens, adhesion strength is 0.81 MPa which is 57% higher than that of no bias condition. When DC 175 V is imposed, adhesion strength is 0.59 MPa. It is clarified that imposing DC bias increases adhesion strength as well as negative bias has large effect on it.

2. When AC 150 V, 1 MHz is imposed, adhesion strength is 0.29 MPa which is 44% lower than that of no bias condition. Adhesion strength decreases as electrical frequency increases.

3. From the results about sessile drop technique, when negative bias is imposed on metal surface, negative and dispersive component of surface energy on resin surface decreases and increases, respectively. This results means that negative bias attracts positive charged carbon atoms as well as [-O-CH₃] groups. Finally, it is considered that increase of Van der Waals force increases adhesion strength in the case of negative DC bias. On the other
hand, imposing positive bias increases negative component of surface energy. Thus, Coulomb force increases adhesion strength in positive DC bias case.

4. Dielectric tangent in acrylic resin increases as frequency increases at 128°C. This result means that phase lag between polarization of resin and electric field increases as frequency increases. When phase lag increases, it is considered that resin surface repels from metal surface. This is considered as the reason that adhesion strength decreases as frequency increases.

REFERENCES


