ELECTRO FUSION JOINING OF CARBON FIBER REINFORCED THERMOPLASTIC COMPOSITES USING CARBON FIBER HEATING ELEMENT

D. Tanabe[a*], K. Nishiyabu[b] and T. Kurashiki[a]

[a]*Dept. of Management of Industry and technology, Graduate School of Eng., Osaka University, 2-1 Yamadaoka, Suita 565-0871, Osaka, Japan*
[b]*Dept. of Mechanical Engineering, Faculty of Science and Eng., Kinki University, 3-4-1 Kowakae, Higashiosaka 577-8502, Osaka, Japan*
**d-tanabe@mit.eng.osaka-u.ac.jp*

Keywords: CFRTP, Electro Fusion Joining, Spread Carbon Fiber, Heating Element

Abstract
This study aims to develop the electro-fusion joining method for continuous fiber reinforced thermoplastic (cFRTP) composites using spread carbon fiber as resistance heating element. The material for the experiment was woven CF/PPS laminates. The effects of processing conditions such as applied voltage, time and pressure, and also material conditions such as thickness of the inserted PPS films on the fusion behavior of cFRTP composites were investigated to get the optimum condition for electro-fusion joining. The contents for evaluation were surface condition of joint section peeled off after applying current and welding area obtained from those images. The experimental results revealed that electro-fusion behavior was influenced significantly by thickness of PPS films and electric resistivity of cFRTP laminates. As the result of the single lap shear strength (LSS) test, the LSS value was achieved over 27 MPa.

1. Introduction

Continuous fiber reinforced thermoplastic (cFRTP) composites which can be manufactured with press-forming are attracting attention recently in aircraft and automobile applications. However, cFRTP components have rather simple geometry due to the limited deformation allowed for the reinforcing fibers and high viscosity of the resin, and thus require joining as an indispensable step in the manufacturing process of cFRTP. Moreover, the demand of on-site joining without facilities is also expected for a large-scale cFRTP structures.

Conventional joining methods used for thermosetting composites such as mechanically fastening and adhesive bonding are unreasonable of applying for cFRTP components, because those methods have some drawbacks in strength and reliability, such as stress concentration and interlayer delamination. To solve the above-mentioned problems, the joining technologies such as ultrasonic welding, resistance welding and induction welding have been proposed for high performance cFRTP [1]. However, these methods require the fixed equipment for electric power and pressing, and then it is associated with difficulty in utilizing for a large structures and complex shaped components. In case of the resistance welding method, a resistance heating element such as a stainless steel mesh [2, 3 and 4] and Ni-Cr wires is required for fusion joining. However, these heating elements are undesirable materials which has some disadvantages on recyclability, stress concentration and corrosion because the metallic heating elements remains between joining parts. In this study, the electro-fusion welding behavior of woven-CF/PPS laminates jointed using spread carbon fiber sheets as a resistance heating element was investigated.

2. Experimental material and procedure

2.1. Materials

The materials used for the experiment is CF/PPS laminate (TenCate, CETEX®). This laminate has 5H sateen weave construction with a resin content of V_f=45vol.% and a thickness of t=1.2mm (woven-CF/PPS). The PPS resin is semi-crystalline polymer. The result of differential scanning calorimeter (DSC) analysis shown that the glass-transition temperature is T_g=90ºC, and the melting temperature is T_m=290ºC. The result of thermogravimetric analysis (TG) also shown that the decomposition temperature is T_d=410ºC.

2.2. Specimen and welding method

Figure 1 shows the appearance of electro-fusion welding device. The test specimens with W=20mm in width and L=60mm in length were prepared. The welding area is insofar as L_f=20mm from the end of laminates.
A spread carbon fiber sheet (Mitsuya Co., Ltd., t=0.03mm) with W_{CF}=40mm in length was mounted between laminates to work as the heating element. To investigate the effects of thickness of PPS films on electro-fusion behavior, the PPS films (Toray Co., Ltd., TORELINA®, t_{PPS}=0.1mm) with various sheet number were inserted between laminate and heating element. The spread carbon fiber was also inserted in 0° direction as shown in Figure 2(b).
The test specimen was clipped by insulating plates made of ceramics. As the superimposed voltage controlled by an DC power supply (Kikusui electronics Co., Ltd., PWR800L) was applied to carbon fiber heating elements, it made generate a joule heat in the joint interface between laminates, thus made melt PPS resin around the carbon fiber heating elements.

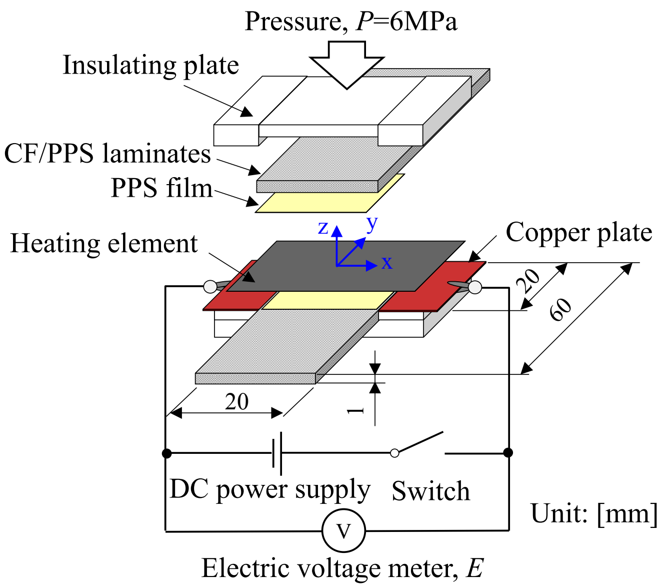
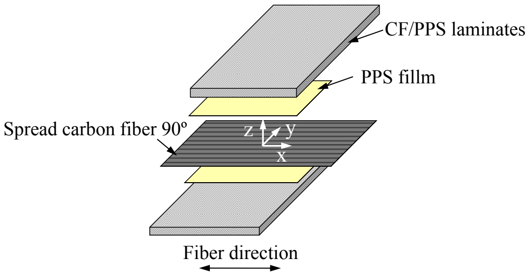
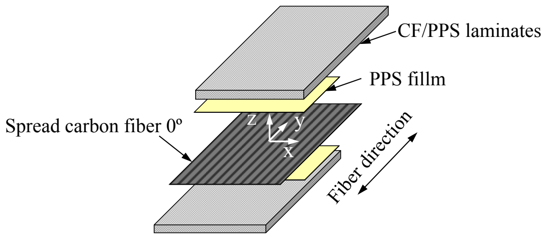


Figure 1. Appearance of electro-fusion welding device.



(a) Spread-CF [90º]



(b) Spread-CF [0º]

Figure 2. Location of PPS film inserted and type of carbon fiber heating elements.

2.3. Evaluation method

The images of joint surfaces peeled off after joining were imported with a scanner device (Epson Co., Ltd., ES-7000H), and the welding area (A_w) was obtained by image analysis. The welding surfaces were also observed with a microscope to investigate the fusion joining interface.
The single lap shear strength test was carried out to evaluate a joint strength by using universal testing machine (SHIMAZU CO., Ltd., AG-50kN XDplus). Figure 3 shows appearance of single lap joining test specimen. Before LSS testing, aluminum tabs were bonded to end of specimens with epoxy adhesive.

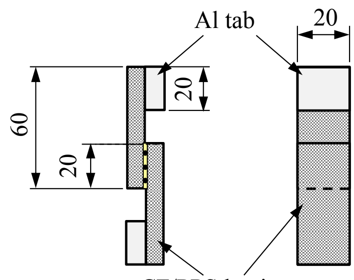


Figure 3. Geometry of single lap joining test specimen.

The cross-head speed was v=1mm/min. The LSS was calculated by using two equations:

$$\tau_{ac} = \frac{P}{A_w} \quad (1)$$

$$\tau_{ap} = \frac{P}{A_L} \quad (2)$$

where τ, lap shear strength [MPa]; A_w, welding area [mm^2]; A_L, overlap area [mm] and P, maximum tensile force [N].

3. Results and discussion

3.1. Effects of applied voltage

Figure 4 shows the image of welding and laminate surface of specimens processed at t=60s, t_{PPS}=0.4mm, P=6MPa. The welding area was not seen at E=5.0V. The melting of PPS films arose at more than E=5.5V. When the applied voltage was over E=6.0V, the thermal deformation occurred because the joule heat of carbon fiber was generated remarkably.

Figure 5 shows the welding area plotted by the applied voltage. The welding area was increased remarkably in E=5.0 - 6.0V. When the applied voltage was E=7.0V, the welding area achieved A_w=460mm^2. Then, the temperature of melting polymer achieved about thermal degradation temperature (T_d=410ºC) because the melting polymer was changed into black color. From these results, it is revealed that the proper applied voltage is about E=5.7 - 6.5V.

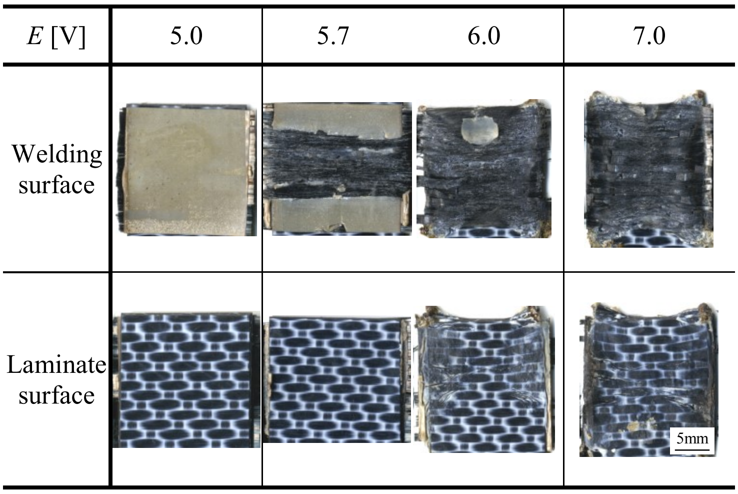


Figure 4. Scan images of welding surface using spread carbon fiber 90º as heating element (t=60s, t_{PPS}=0.4mm).

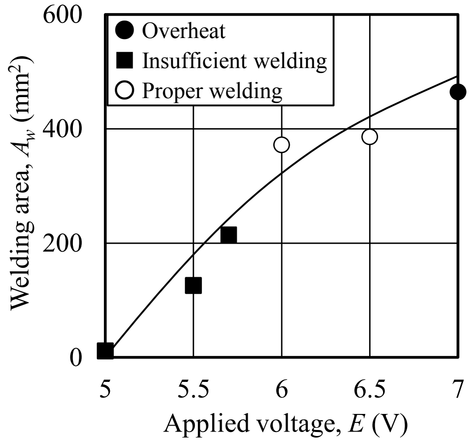


Figure 5. Effects of applied voltage on welding area using spread carbon fiber 90º as heating element (t=60s, t_{PPS}=0.4mm).

3.2. Effects of conducting time

Figure 6 shows the image of welding and laminate surface of specimens processed at E=5.7V, t_{PPS}=0.4mm, P=6MPa. The melting of polymer was seen in central part of laminates at t=60 – 90s. The conducting time was t=120s, the welding area spread through overlap area. However, as for t=150s, remarkable melting of polymer was seen in edge of laminates.

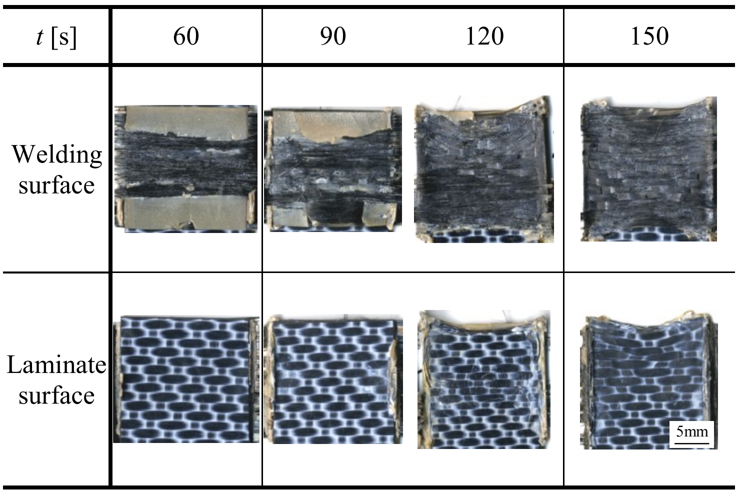


Figure 6. Scan images of welding surface using spread carbon fiber 90º as heating element (E=5.7V, t_{PPS}=0.4mm).

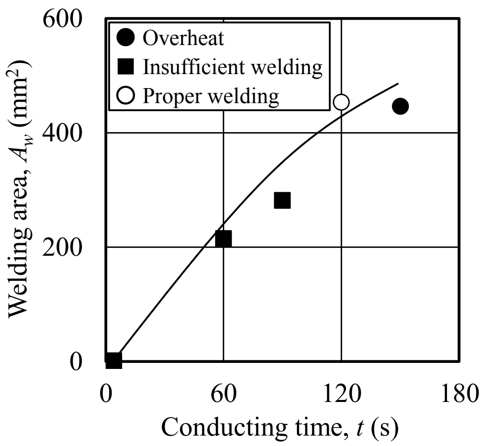


Figure 7. Effects of conducting time on welding area using spread carbon fiber 90º as heating element (E=5.7V, t_{PPS}=0.4mm).

Figure 7 shows the welding area plotted by the conducting time. The welding area was increased with increasing the conducting time at t=0 - 120s. The welding area achieved A_w=454 mm^2 at t=120s. From these results, it is considered that the proper conducting time is about t=120s.

3.4. Effects of fiber orientation angle of heating element

In order to investigate the effects of fiber orientation angle of the spread carbon fiber heating element on the welding behavior, the heating element was set 0º direction as shown in Figure 2(b). Figure 8 shows the scan images of welding and laminate surface of specimens processed at t=60s, t_{PPS}=0.4mm and P=6MPa. When the applied voltage was E=5.5V, the unmelted PPS film remained in the joining surface. On the other hand, the PPS film was melted completely as E=6.0V.

Figure 9 shows the welding area plotted by the applied voltage about spread-CF [0º] and [90º]. The welding area of spread-CF [0º] specimens was increased with increasing the applied voltage as with spread-CF [90º]. These experimental facts, it was revealed that the welding behavior showed the same tendency compared to 90º directions.

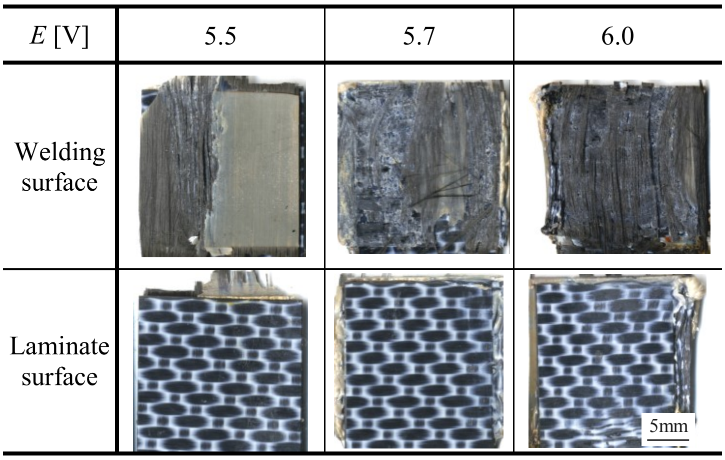


Figure 8. Scan images of welding surface using spread-CF [0º] as heating element (t=60s, t_{PPS}=0.4mm).

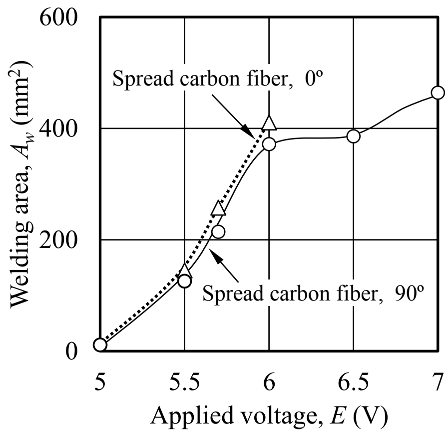


Figure 9. Effects of applied voltage on welding area using spread-CF [0º] as heating element (t=60s, t_{PPS}=0.4mm).

3.5. Single lap shear strength

In order to investigate the influence which a kind of heating elements and the fiber orientation angle on joint strength, the singe lap shear strength (LSS) test was carried out as shown in Figure 3. Table 1 shows electro fusion conditions of single lap tensile test specimens. The heating elements used were Ni-Cr wires with 0.2mm in diameter, carbon fiber bundle and spread carbon fiber. These conditions were proper values obtained by experiments. Figure 10 shows load displacement curve obtained by the LSS test. As for the test specimen used spread carbon fiber as heating element, the breaking force was increased remarkably. In case of spread carbon fiber 0º, the breaking force achieved up to P=11kN.

Figure 11 shows comparison of the singe lap shear strength using various heating elements. In case of using spread carbon fiber heating element, the τ_{ap} value was increased remarkably compared to other specimens because the welding area was increased to entire area. When the spread carbon fiber 0º was used as heating element, the LSS value was improved significantly because the joining layer was reinforced with carbon fiber to the load direction. Therefore, the LSS value achieved over 27MPa.

Figure 12 shows microscopic observation images of breaking surface of spread-CF [90º] and spread-CF [0º] specimens. In case of spread-CF [90º], the unmelted PPS film remained in edge of breaking surface as shown in Figure 12(a). The spread carbon fiber was also little seen in fracture surface, and a discoloration of PPS polymer was occurred locally. Therefore the single lap shear strength was not able to improve notably compared to Ni-Cr wires and carbon fiber bundles. When the spread carbon fiber 0º was used as the heating element, the fiber was remained on fracture surface remarkably as shown in Figure 12(b). The PPS polymer was also adhered uniformly.

Heating element	Ni-Cr wire	3K-CF	Spread-CF
Applied voltage, E [V]	4.5	6.0	5.7
Conducting time t [s]	60	120	120
Number of heating element n	3	3	-
Distance of heating element L_H [mm]	4	5	-
Thickness of PPS resin t_{PPS} [mm]	0.4	0.2	0.4

Table 1. Electro fusion conditions of single lap tensile test specimens.

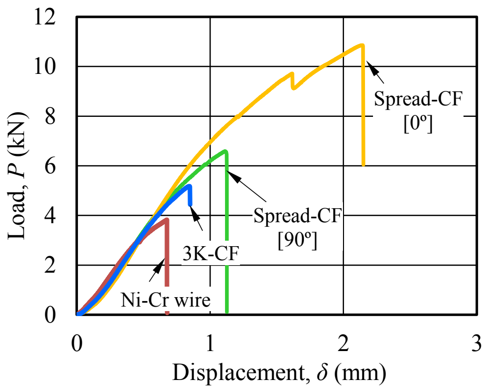


Figure 10. *P*-*δ* curve.

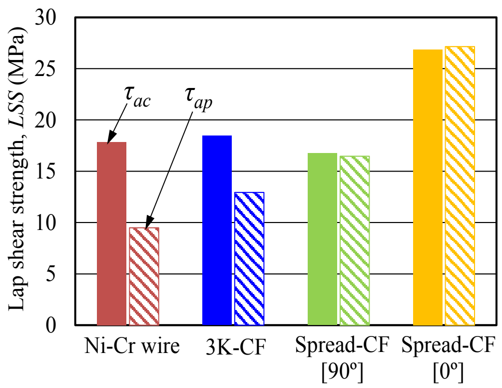
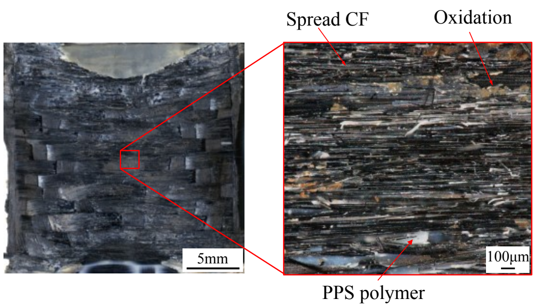
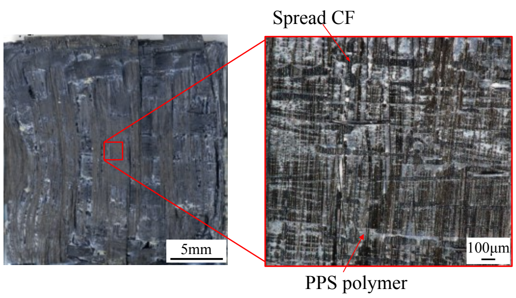


Figure 11. Comparison of the lap shear strength.



(a) spread-CF [90º].



(b) spread-CF [0º].

Figure 12. Microscopic observation images of spread-CF [90º] and spread-CF [0º].

3.6. Monitoring of current value

Figure 13 shows the effects of conducting time on current value in case of using spread carbon fiber heating elements. The conducting time was increased with increasing the current value and the specimens of spread-CF [0º] and spread-CF [90º] were shown the same tendency. After conducting to the heating elements, the current value was nearly constant value (I=6 - 7A) as t=0 - 60s. Subsequently, the current value was increased from I=6A to 18A when the conducting time was t=60 - 120s, because the conducting occurs from heating elements to the spread carbon fiber sheet of laminates.

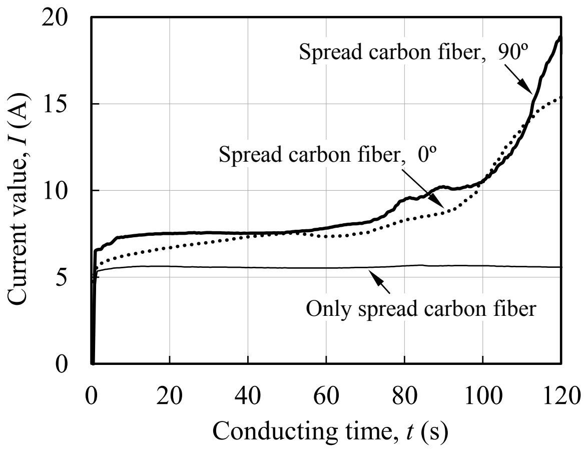


Figure 13. Effects of conducting time on current value of various carbon fiber heating elements.

3.7. Effects of current value

The results of the monitoring of current value, the current value was changed from 5A to I=8.5A in order to prevent the overheating in the welding surface. Figure 14 shows the scan images of welding and laminate surface of spread-CF [90º] specimens processed at t=300s, t_{PPS}=0.4mm and P=6MPa. The PPS polymer was remained in welding surface at I=6.5 - 7.5A. On the other hand, when the applied current was over I=8.0A, the polymer was melted completely. Figure 15 shows the effects of applied current on welding area at t=300s and t_{PPS}=0.4mm. The welding area was increased with increasing the applied current. The behavior of welding area was also shown the same tendency as I=8.0 - 8.5V. From these results, it was revealed that the proper applied current was I=8.0 - 8.5V.

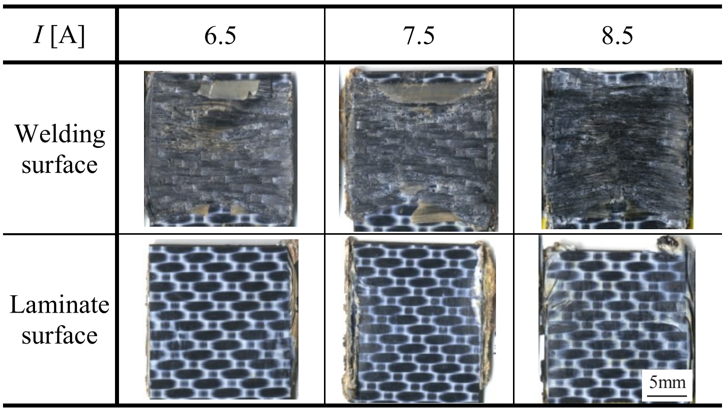


Figure 14. Scan images of welding surface using spread-CF [0º] as heating element (t=300s, t_{PPS}=0.4mm).

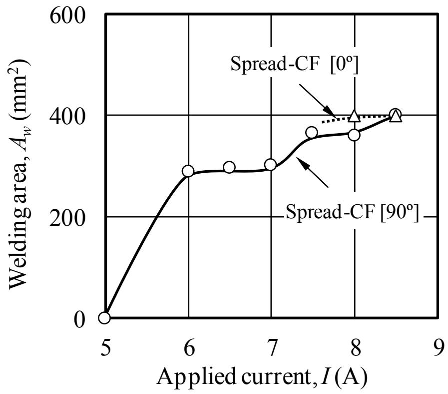


Figure 15. Effects of applied current on welding area (t=300s, t_{PPS}=0.4mm).

Figure 16 shows the single lap shear strength (τ_{ap}) plotted by the applied current about spread-CF [0º] and [90º] specimens. The lap shear strength was increased exponentially with increased applied current. In case of spread-CF [0º] specimens, the lap shear strength was higher than spread-CF [90º] specimens. This is because the fiber direction of spread carbon fibers was arranged in a load direction. Therefore, the strength was over τ_{ap}=27MPa at I=8A.

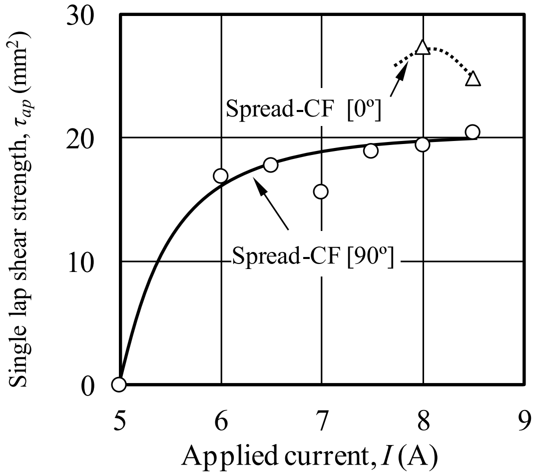


Figure 16. Effects of applied current on single lap shear strength (t=300s, t_{PPS}=0.4mm).

Conclusion

In this study, the electro-fusion joining method using spread carbon fiber sheet as a heating element was developed. The electro-fusion mechanism was revealed by investigating the electro-fusion condition such as applied voltage, conducting time and thickness of PPS films. The welding area was increased with increasing the applied voltage, current and the conducting time. It was revealed that there were optimum welding conditions in order to prevent the thermal deformation and thermal degradation of laminates. It was also revealed that the uniform welding area was obtained by inserting the PPS film with the optimum thickness. The result of singe lap tensile strength test, when the spread carbon fiber 0º was used as heating element, the *LSS* value was achieved over 27MPa because the joining layer was reinforced with carbon fiber to the load direction.

References

[1] T.J. Ahmed, D. Stavrov, H.E.N. Bersee and A. Beukers, "Induction welding of thermoplastic composites–an overview", Composites: Part A, 37, pp.1638-1651 (2006)..

[2] M. Dube´, P. Hubert, A. Yousefpour and J. Denault, "Resistance welding of thermoplastic composites skin / stringer joints", Composites: Part A, 38, pp.2541–2552 (2007)..

[3] D. Stavrov and H.E.N. Bersee, "Resistance welding of thermoplastic composites-an overview", Composites: Part A, 36, pp.39–54 (2005).

[4] Meng Hou, Mingbo Yang, Andrew Beehag, Yiu-Wing Mai and Lin Ye, "Resistance welding of carbon fibre reinforced thermoplastic", Composite Structures, 47 , pp.667-67 (1999).