RESISTANCE WELDING OF CARBON FIBER REINFORCED THERMOPLASTIC COMPOSITES USING SPREAD CARBON FIBER HEATING ELEMENT

D. Tanabe[1], F. Kubohori[2], K. Nishiyabu[3] and T. Kurashiki[4]

[1] Graduate School of Eng., Management of Industry and technology, Osaka university,
2-1 Yamadaoka, Suita 565-0871, Osaka, Japan
Email: d-tanabe@mit.eng.osaka-u.ac.jp,
Web Page: http://www.mapse.eng.osaka-u.ac.jp/w8/indexen.html
[2] Graduate School of Science and Eng. Research, Department of Mechanical Eng., Kindai university,
3-4-1 Kowakae, Higashiosaka, Osaka 577-8502, Japan
Email: kubohori03@gmail.com, Web Page: http://www.kindai.ac.jp
[3] Faculty of Science and Engineering, Department of Mechanical Engineering, Kindai university,
3-4-1 Kowakae, Higashiosaka, Osaka 577-8502, Japan
Email: nishiyabu@mech.kindai.ac.jp, Web Page: http://www.kindai.ac.jp
[4] Graduate School of Eng., Management of Industry and technology, Osaka university,
2-1 Yamadaoka, Suita 565-0871, Osaka, Japan
Email: kurasiki@mit.eng.osaka-u.ac.jp,
Web Page: http://www.mapse.eng.osaka-u.ac.jp/w8/indexen.html

Keywords: CFRTP, Resistance welding, Spread Carbon Fiber, Heating Element, Lap Shear Strength

Abstract

This study aims to develop the resistance welding 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. From the result of the single lap shear strength (LSS) test,it was revealed that the LSS value was achieved over 28 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 [1].

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 [1].

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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 [2]. 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 [3,4] 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 Materials and Procedure

2.1. Materials

Figure 1 shows the surface images of material used. 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=45 vol.% and a thickness of t=1.2mm (woven-CF/PPS). The PPS polymer is semi-crystalline polymer. The result of differential scanning calorimeter (DSC) analysis of PPS polymer shown that the glass-transition temperature is T_g=90 ºC, and the melting temperature is T_m=290 ºC. The result of thermogravimetric analysis (TG) also shown that the decomposition temperature is T_d=410 ºC. A spread carbon fiber sheet (Mitsuya Co., Ltd., t=0.03mm) was used as resistance heating element.

(a) Woven-CF/PPS laminate (b) Spread-CF sheet (resistance heating element)

Figure 1. Surface images of material used.

2.2. Specimen and resistance welding method

Figure 2 shows the appearance of resistance welding device for CFRTP. 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 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 0º 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, and thus it made melt PPS resin around the carbon fiber heating elements.

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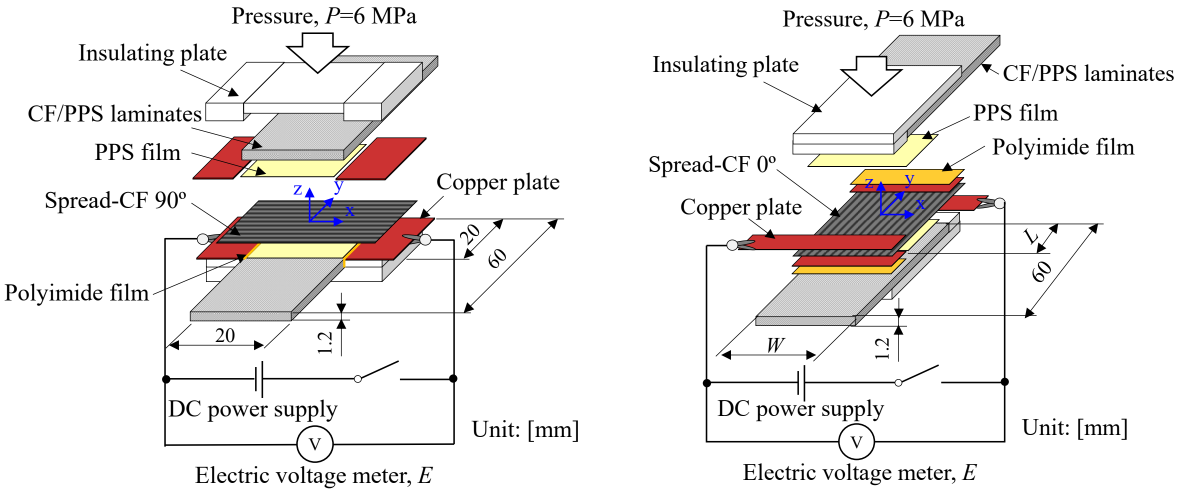

(a) Spread-CF 90º (b) Spread-CF 0º

Figure 2. Appearance of resistance welding device for CFRTP.

To investigate the effects of aspect ratio of heating element on fusion behavior in the case of the spread-CF 0º, the width and the longer dimension of the laminate and the heating element was changed as shown in Teble 1.

Table 1. Dimensions of joint area

	Width derection, *W* [mm]	Longitudinal direction, *L* [mm]
(a)	20	20, 30, 40, 50
(b)	20, 30, 40, 50	20

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 single lap shear strength test was carried out to evaluate a joint strength by using universal testing machine (Shimadzu Co., Ltd., AG-50kN XDplus). Figure 3 shows the appearance of single lap joining test specimen. Before LSS testing, Al tabs were bonded to end of specimens with epoxy adhesive.

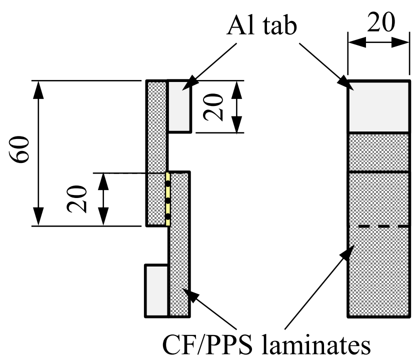

Figure 3. Geometry of single lap joining test specimen.

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

$$\tau_{ap} = \frac{P}{A_L} \tag{1}$$

where τ, lap shear strength [MPa]; 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 spread-CF 90º specimens processed at t=60s and t_{PPS}=0.4mm. The PPS films did not melt below the applied voltage of E=5.0V. When the applied voltage was over E=6.0V, the thermal deformation of woven-CF/PPS laminate occurred because the joule heat of carbon fiber generated remarkably.

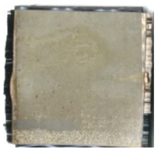
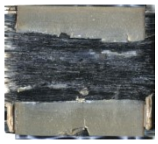
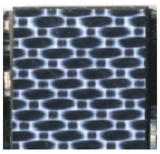
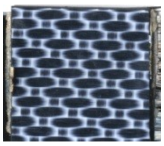
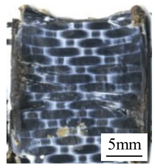
E [V]	5.0	5.7	6.0	7.0
Peeled face				
External face				

Figure 4. Scan images of welding surface of spread-CF 90º specimens (t=60s, t_{PPS}=0.4mm).

Figure 5 shows the welding area of spread-CF 90º specimens plotted by the applied voltage. The welding area was increased remarkably in the range of E=5.0 - 6.0V. When the applied voltage was E=7.0V, the welding area achieved to A_w=460mm^2. The temperature of melting polymer achieved over the thermal degradation temperature (T_d=410ºC), thus the melting polymer was changed into black color. From these results, it is revealed that the proper applied voltage is about E=6.0 - 6.5V.

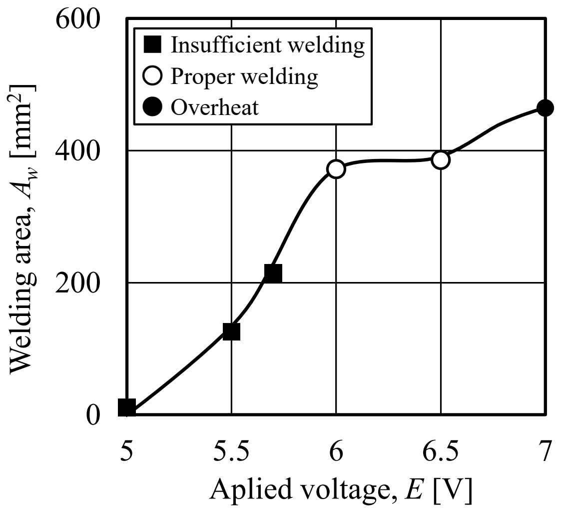


Figure 5. Effects of applied voltage on welding area of spread-CF 90º specimens (t=60s, t_{PPS}=0.4mm).

3.2. Monitoring of current value and electricity value

Figure 6 shows the change of current value and electric power of the spread carbon fiber and spread-CF 0º and 90º specimens. In the case of only spread carbon fiber, the current value was shown I=5.5 A, which did not change with conducting time. On the other hand, the similar tendency of 0º and 90º specimens was shown. The current and electricity value were increased with increasing the conducting time. As soon as turned on the power, the current value and electric power kept constant value (I=6.0 – 8.0 A, P=40 – 45 W) during t=0 - 70s. Subsequently, the current value was increased from I=6.0 A to 18 A when the conducting time was t=70 - 120s, because the conducting occurs from spread carbon fiber to the carbon fiber bundles of laminates. Then, it is considered that the welding area was increased remarlably.

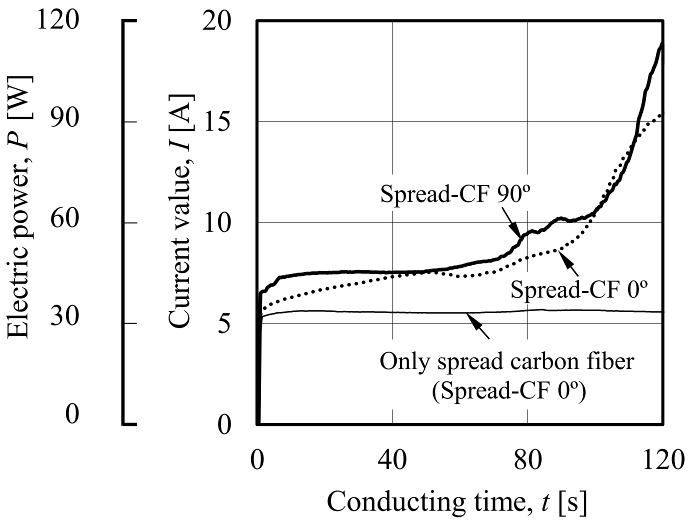


Figure 6. Effects of conducting time on current value and electricity (E=5.7 V, t=60 s, t_{PPS}=0.4 mm).

3.3. Effects of applied current

According to Figure 6, in order to prevent the overheating in the welding surface, it was considered that the proper current value was I=5.0 A - 8.5 A. Figure 7 shows scan images of peeled and external face of spread-CF 90º specimens processed at t=300 s and t_{PPS}=0.4 mm. The PPS polymer was remained in welding surface at I=6.5 - 7.5 A. On the other hand, when the applied current was over I=8.0 A, the polymer was melted completely. The thermal deformation and thermal degladation of laminate was not seen compared to in the case of applied voltage control.

E [V]	5.0	5.7	6.0	7.0
Peeled face				
External face				

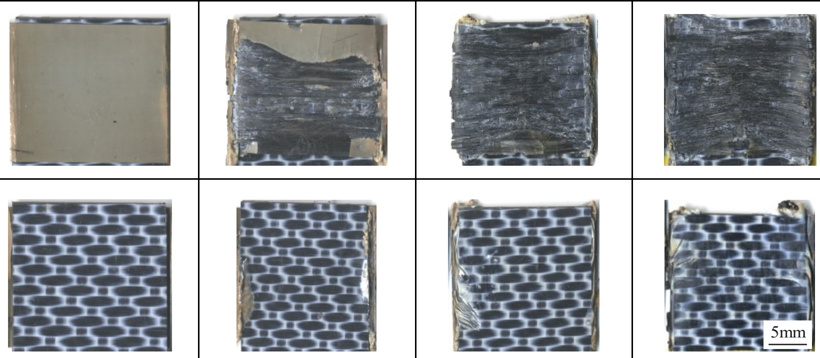


Figure 7. Scan images of peeled and external face of spread-CF 90º specimens (t=300 s, t_{PPS}=0.4 mm).

Figure 8 shows the effects of applied current on welding area of spread-CF 90º and 0º specimens precessed at t=300s and t_{PPS}=0.4mm. When the applied current is from I=5.0 A to 7.0 A, the welding area was increased with increasing the applied current in both specimens. While the applied current was from I=7.5 A to 8.5 A, the welding area was attained constant because the wole area of joint surface was welded. From these results, it was revealed that the proper applied current was I=7.5 - 8.5 A.

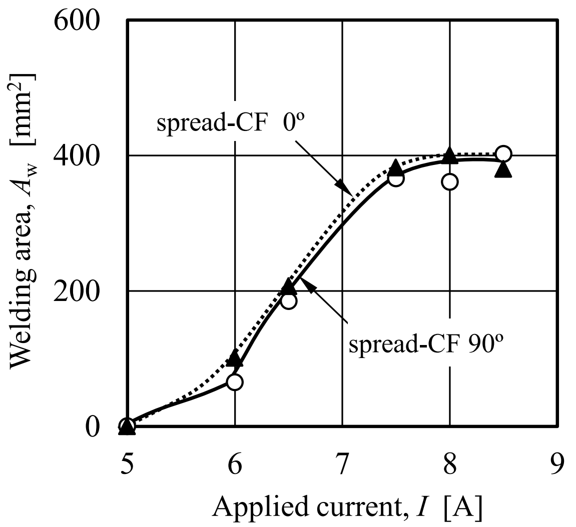


Figure 8. Effects of applied current on welding area (t=300 s, t_{PPS}=0.4mm, spread-CF 0º and 90º).

3.4. Effects of aspect ratio of the laminate

Figure 9 shows the change of the electric power with conducting time at I=8.0 A. In the case (a) of changing the width direction of joining part, the electric power was decrease with increasing the width of joint (W). In the case (b) of changing the longitudinal direction of join part, the electric power was increased with increasing the length of joint (L). This phenomenon can be explained by the equation of resistance and electric power. The resistance of heating element can be calculated by

$$R = \rho \frac{l}{A} \tag{2}$$

where R, resistance value [Ω]; l, length of the heating element [m]; ρ, specific resistance of the material [U]; A, cross-sectional area of heating element [m^2]. The thickness of the heating element is assumed to be constant.

The electric power can be calculated by

$$P = I^2 R \tag{3}$$

where P, electric power [W]; I, current [A]; R, resistance [Ω].

In the case of changing the width direction, the resistance value of heating element was decreased because the cross-sectional area of conducting was increased with increasing the width of joint (W) by the resistance equation. Therefore, the electric power (P) was decreased with increasing the width of joint (W). In the case of changing the longitudinal direction, the resistance value of heating element was increased because the conducting length (l) was increased with increasing the length of joint (L) by the resistance equation. Therefore, the electric power (P) was increased with increasing the length of joint (L).

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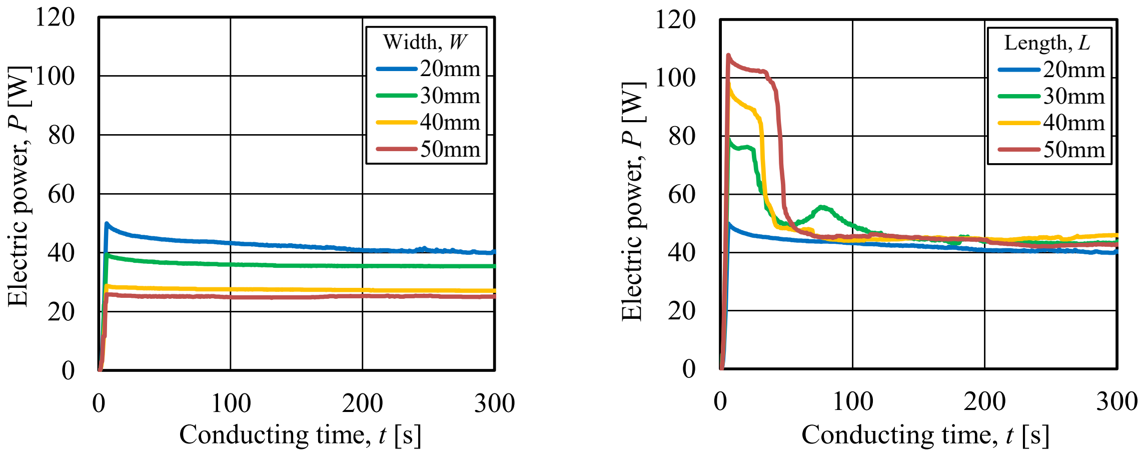

(a) Change in width direction (b) Change in longitudinal direction

Figure 9. Effects of the joint size on electric power (I=8.0A, spread-CF 0º).

3.5. Single lap shear strength

Figure 10 shows the single lap shear strength (τ_{ap}) and maximum load of spread-CF 0º and 90º specimens plotted by the applied current. The single lap shear strength and maximum load were increased exponentially with increasing the applied current up to I=7.5 A. In the case of spread-CF 0º specimens, the lap shear strength was increased significantly. The reason why the lap shear strength improved is the fiber direction of spread carbon fibers was arranged in the load direction. Therefore, the strength was achieved over τ_{ap}=28.2 MPa at I=8.5 A.

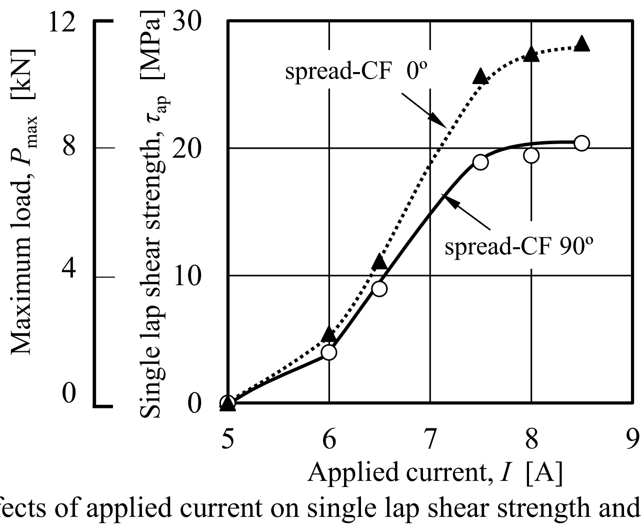

Figure 10. Effects of applied current on single lap shear strength and maximum load (t=300s, t_{PPS}=0.4 mm).

The influence of heating elements and the fiber orientation angle on joint strength was investigated. The heating elements used were three Ni-Cr wires with 0.2mm in diameter, three carbon fiber bundles and spread carbon fiber sheets. From the singe lap shear strength test carried out under the proper conditions, load versus displacement curves was obtained as shown in Figure 11. As for the test specimens joined using spread carbon fiber as heating element, the maximum load was increased remarkably compared to the other specimens. Especially in the case of spread-CF, the maximum load of 0º specimen is much higher than that of 90º one. This result suggests that the carbon fiber direction affects significantly on the interlaminar shear strength.

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Figure 12 shows the comparison of the singe lap shear strength of specimens using various heating elements. In the case of specimens joined using spread carbon fiber as a heating element, the τ_{ap} value was increased remarkably compared to the 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 28MPa.

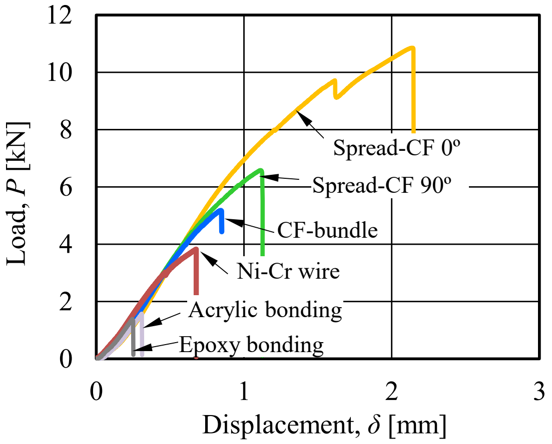

Figure 11. *P*-δ curve.

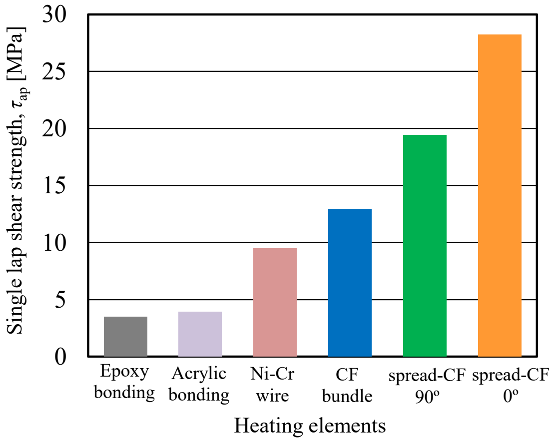

Figure 12. Comparison of single lap shear strength.

4. Conclusion

In this study, the electro-fusion joining method using spread carbon fiber sheet as a resistance heating element was developed. The electro-fusion mechanism was revealed by investigating the electro-fusion condition such as applied voltage, conducting time, current 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. It is necessary to carry out the electro fusion with a constant current value in order to improve the fusion qualities. From the result of singe lap tensile strength test of specimens joined using spread carbon fiber sheets as resistance heating element, the *LSS* value (τ_{ap}) was increased over 42% compared to using Ni-Cr wires or carbon fiber bundles. In particular, when the spread carbon fiber 0º was used as resistance heating element, the *LSS* value (τ_{ap}) was achieved over 28MPa because the joining layer was reinforced with carbon fiber to the load direction.

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