EFFECTS OF CARBON FIBER HEATING ELEMENT ON RESISTANCE WELDING BEHAVIOR OF WOVEN CF/PPS LAMINATES

D. Tanabe[1], F. Kubohori[2], K. Tamura[2], Y. Yamamoto[2] and K. Nishiyabu[2]

[1] National Institute of Technology,
Wakayama College, 77 Noshima, Nada, Gobo city, Wakayama, 644-0023, Japan
Email: tanabe@wakayama-nct.ac.jp, Web Page: https://researchmap.jp/daikitanabe/
[2]Faculty of Science and Engineering, Kindai University
3-4-1 Kowakae, Higashiosaka City, Osaka 577-8502, Japan
Email: nishiyabu@mech.kindai.ac.jp, Web Page: http://www.kindai.ac.jp/

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Abstract

This study aimes to reveal the effects of various carbon fiber heating elements on resistance welding behavior of woven CF/PPS laminates. The contents for evaluation was electric conducting behavior, pressure fluctuation, surface condition of joint section peeled off after applying current, welding area obtained from those images and single lap shear strength. The material for the experiment was woven CF/PPS laminates as joining welding test specimen. The effects of processing conditions such as applied current, conducting time and pressure, and also material conditions such as aspect ratio of joining area, PPS layer thickness of welding part were investigated to obtain the optimum condition for resistance welding. From the experimental results, it was obvious that the welding area ratio achieved in up to 100% even in wider joining specimens when the woven carbon fiber was used as the heating element. Moreover, the variation of tensile shear strength was reduced in the case of using woven carbon fiber heating elements.

1. Introduction

Carbon fiber reinforced thermoplastic (CFRTP) has high performance properties such as high productivity, recyclability and impact resistance compared to thermosetting composites. Therefore, CFRTP has a wide range of applications in aerospace, automotive and industrial products[1]. The joining process is a necessary step to manufacture complex geometry parts and large-scaled structures using CFRTP[2]. The joining of thermoplastic composites can be divided into several methods such as mechanical fastening, adhesive bonding and fusion joining or welding. The mechanical fastening method has some disadvantages such as stress concentrations, gain of weight and so on. Adhesive bonding method is also difficult to bond chemically between thermoplastic polymers. Therefore, the fusion joining or welding is suitable for CFRTP parts. There are several types of fusion joining methods for CFRTP such as ultrasonic welding, resistance welding, induction welding and so on, and these heating principles are completely different. The resistance welding method has several advantages such as simple joining device, cost-effective and in applicability to large structures compared to other fusion joining methods[3-5]. In this method, heating elements such as stainless steel mesh has been inserted between joint surfaces. However, the heating elements are undesirable materials which has disadvantage on recyclability, low joining strength and corrosion resistance

because the metallic heating elements remains joining parts. Therefore, the materials like carbon fiber are desirable as heating element for resistance welding.
Authors have been proposed the use of carbon fiber heating element to solve these problems. In our previous study[6], the resistance welding method for CFRTP was developed using spread unidirectional carbon fiber as heating element. As the result, the single lap tensile shear strength increased at least three times compared to using metallic heating elements, because the fusion layer was reinforced by carbon fiber heating elements. However, in the case of using spread carbon fiber as heating element, the temperature distribution was uneven frequently, because it was difficult to place uniformly the carbon fibers. Therefore, it is not suitable for welding of large scaled structures. Thus, in order to solve these problems, woven carbon fiber was used as heating element in this study.

2. Experimental procedure and conditions

2.1. Materials

The materials used for the experiment is CF/PPS laminate (TenCate, CETEX®, CF/PPS). This laminate has 5H sateen weave construction with a resin content of V_f=45vol.% and a thickness of t=1.2mm. 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.
Two kinds of carbon fibers were used for the resistance heating element as shown in Fig.1. One is a spread carbon fiber heating element as shown in Fig.1(b). The two sheet of spread carbon fiber were laminated in the identical fiber direction and used as a resistance heating element. The other is plain weave carbon fiber heating element as shown in Fig.1(c).

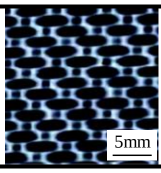
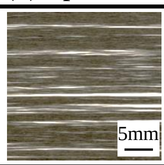
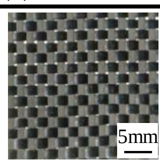
Joining target	Resistance heating element	
(a) Woven-CF/PPS	(b) Spread-CF	(c) Woven-CF
		

Figure 1. Material used for experiments.

2.2. Resistance welding method

Fig.2 shows the appearance of resistance welding method using spread-CF or woven-CF heating element. The resistance heating element was inserted between the two woven CF/PPS laminates for fusion bonding, and the pressure was pressurized with P= 6 MPa through the heat insulating material. The copper electrode was pressed with a constant load on the carbon fiber exposed at both ends of the resistance heating element. 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. Then, joule heat occured in the joint interface between laminates, and thus the PPS polymer was melted around the resistance heating element. In this study, the effects of the width W and length L of the fused part of the woven CF/PPS laminates on the fusion bonding behavior was investigated under the various welding conditions shown in table 1.

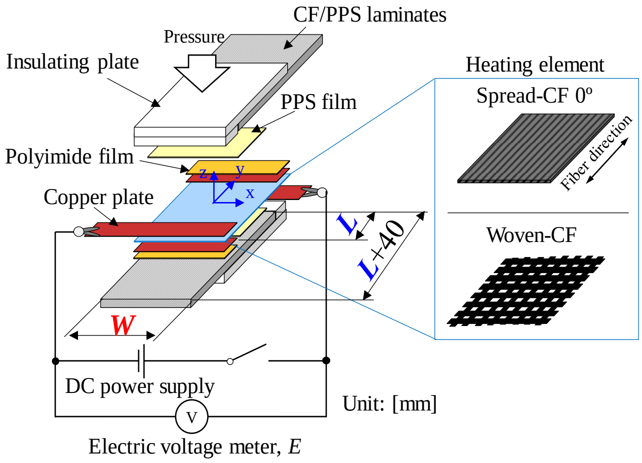


Figure 2. Schematic drawing of resistance welding method using spread-CF or woven-CF heating elements.

Table 1. Experimental conditions of resistance welding.

	(a) Effects of width	(b) Effects of length
Applied current, *I* [A]	0～30	0～15
Conducting time, *t* [s]	300	300
Pressure, *P* [MPa]	8	8
Width, *W* [mm]	20, 50	20
Length, *L* [mm]	20	20, 50

2.3. Evaluation method

In order to evaluate the heating temperature distribution of varied heating elements, an arbitrary current was applied to the resistor heating element using a DC stabilizing power supply as shown in Fig.3. At that time, the heating temperature distribution of the heating elements were investigated by infrared thermograhy (Apiste CO., Ltd., FSV-1200).

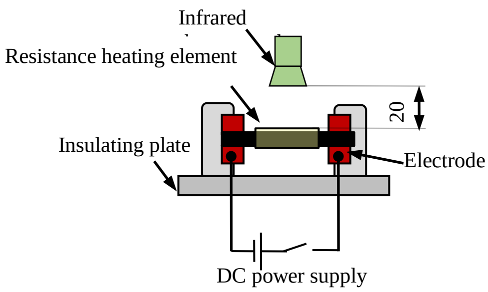


Figure 3. Appearance of observation of temperature distribution.

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 tensile shear strength test was carried out to evaluate a joint strength by using universal testing machine (Shimadzu Co., Ltd., AG-50kN XDplus). Fig.4 shows the appearance of single lap joining test specimen. Before tensile shear strength test, Al tabs were bonded to end of specimens with epoxy adhesive.

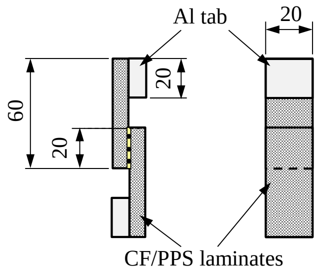


Figure 4. Geometry of single lap joining test specimen.

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. Result and Discussion

3.1. Heating temperature distribution of CF resistance heating element

Fig.5 shows the heating temperature distribution of spread-CF and woven-CF resistance heating element. This result shows that the width of fusion joint is (a) *W*=20 mm and (b) *W*=50mm, and the length of fusion joint is *L*=20 mm constant. From the result of this experiment, it was found that the resistance heating element was heated to *T*=150 - 300ºC. At the boundary between the end of heating element and the copper electrode, the temperature was about *T*=100ºC because of the heat dissipation. In the case of spread-CF heting element, it was observed that the temperature distribution was uneven more than 100 ºC in temperature difference because the carbon fiber is not uniformly aligned. On the other hand, in the case of using woven-CF heating element, the temperature distribution was eveness, and it was found that the heating temperature was about *T*=290 ºC overall.

(a) Spread-CF		(b) Woven-CF	
W=20 mm, *L*=20 mm	*W*=50 mm, *L*=20 mm	*W*=20 mm, *L*=20 mm	*W*=50 mm, *L*=20 mm

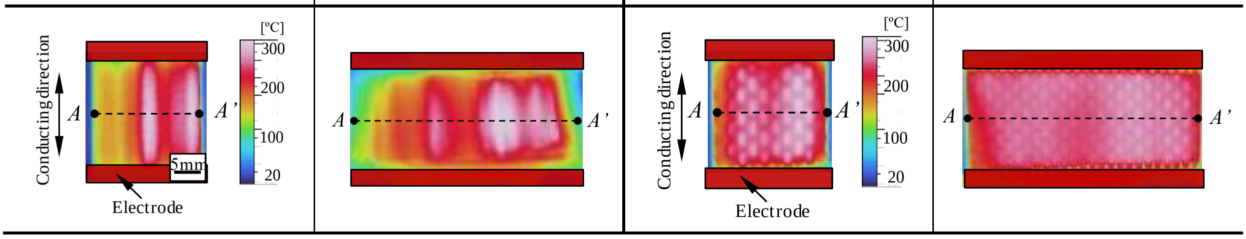
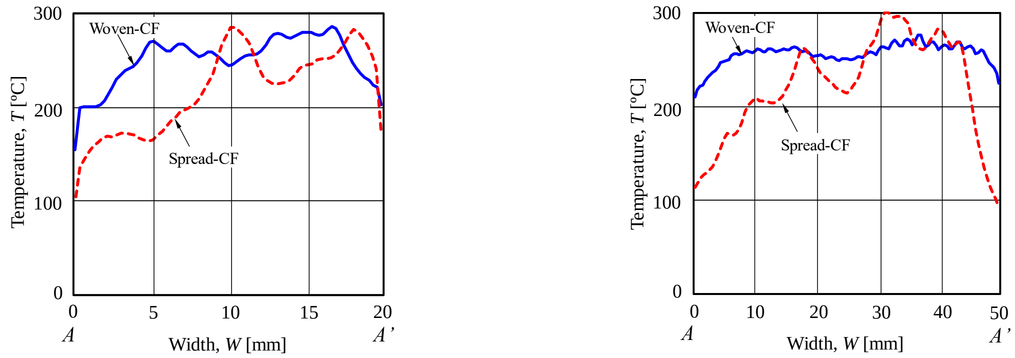


Figure 5. Temperature distribution images of resistance heating elements with varied widths.

Fig. 6 shows the heating temperature profile on the *A* -*A*' line at the time of electric heating of varied resistance heating elements. This *A* -*A*' line corresponds to a line on the thermal image shown in Fig.5. In the case of using spread-CF, it was found that unevenness temperature distribution was occurred significantly. Futhermore, it was found that the end of fusion part showed low temperature because of heat dissipation. In the case of the woven-CF heating element, it was revealed that the even temperature distribution was obtained.
Fig.7 shows the heating temperature distribution of spread-CF and woven-CF resistance heating element. This result shows that the length of fusion joint is (a) *L*=20 mm and (b) *L*=50mm, and the width of fusion joint is *W*=20 mm constant. In the case of the spread-CF heating element, uneven heating temperature distribution was observed.



(a) *W*=20mm, *L*=20 mm (b) *W*=50 mm, *L*=20 mm

Figure 6. Temperature profiles (*A-A'*) of resistance heating element.

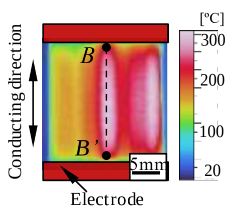
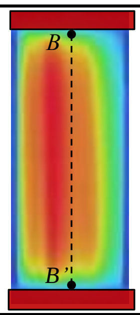
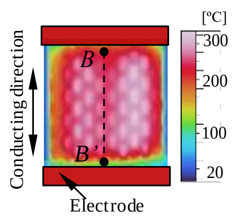
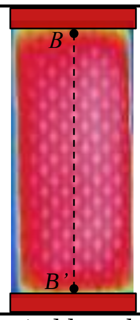
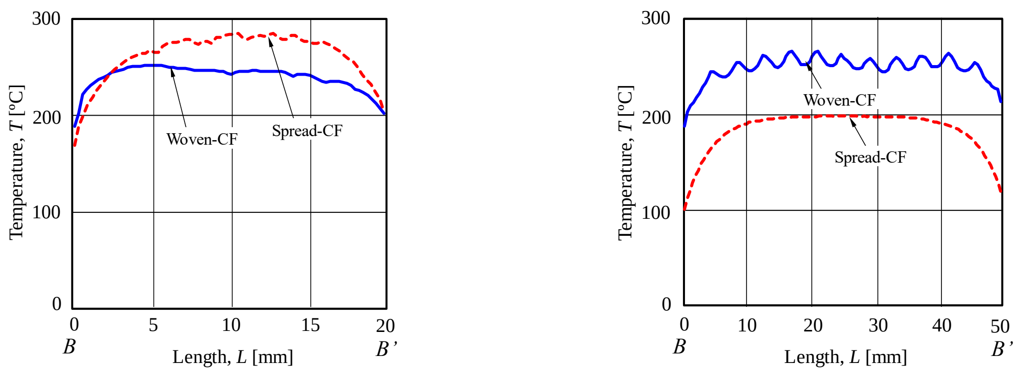
(a) Spread-CF		(b) Woven-CF	
W=20 mm, *L*=20 mm	*W*=20 mm, *L*=50 mm	*W*=20 mm, *L*=20 mm	*W*=20 mm, *L*=50 mm
			

Figure 7. Temperature distribution images of resistance heating elements with varied lengths

Fig.8 shows the heating temperature distribution of various resistance heating elements. This *B-B*' line corresponds to a line on the thermal image shown in Fig.7. Especially, in the case of the spread-CF specimens, the current was easy to conduct because the conducting direction and carbon fiber direction was identical direction. In the case of using woven-CF heating element, it was found that the the high temperature distribution area was obsereved around intersections of carbon fiber bundles. It was considered that the contact resistance increased at the intersection of warp and weft bundles. From thease experimental facts, in the case of using spread-CF heating element, it was revealed that spread carbon fiber needs to be uniformly arranged to heat stably. In the case of using woven-CF heating elements, it was found that the temperature distribution was almost uniform because the carbon fiber was arranged uniformly.



(a) *W*=20mm, *L*=20 mm (b) *W*=50 mm, *L*=20 mm

Figure 8. Temperature profiles (*B-B*') of resistance heating element.

3.2. Effects on welding area ratio

Fig.9 shows the scan images of peeled face of specimens welded by changing applied current. The test specimen has W=50 mm width and L= 20 mm in length. In the case of using the spread-CF heating element (Fig.9(a)), it was found that the PPS polymer was not melted completely even if the current value was increased. The heating temperature of fusion part was unevenness because there were uneven part of carbon fiber in resistance heating elements. On the other hand, in the case of using the woven-CF heating element (Fig.9(b)), there was a wide range of unmelted part of PPS film at I=22 A. In the above I=28 A, it was found that the melting area was increased significantly. As for these reasons, the woven-CF heating element is easy to heat up because the electric resistance increases in the woven structure and the carbon fiber bundles are aligned evenly.

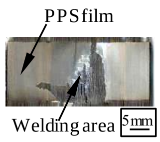
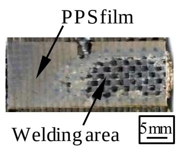
(a) Spread-CF			(b) Woven-CF		
I=14 A	I=17 A	I=19 A	I=22 A	I=28 A	I=29 A
					

Figure 9. Scan images of peeled face of resistance weled specimens with varied widths.

Fig.10 shows the welding area ratio of specimen with varied heating elenemts and widths. The test specimen has W=20 mm width and L=50 mm in length. The welding area ration was increased with increasing the applied current. In the case of the W=20 mm specimens, the welding are ratio was increased with a low current compared with the case of W = 50 mm specimens, because the welding area was small. In both cases of spread-CF and woven-CF heating element, the welding area ration was over ΔA_w=100 %, because the PPS polymer of fusion part was leaked out of the welding surface, and the reticulation of woven CF/PPS laminates was deformated significantly. In the case of the W=50 mm, the welding area of test specimens using spread-CF heating element was low compared to woven-CF specimens. From these experimental results, it was found that the width dimension of joining part has a large effect on the welding area ratio.

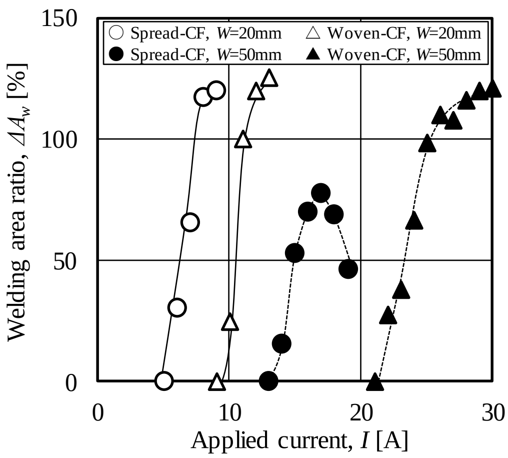


Figure 10. Welding area ratio of specimen with varied heating elenemts and widths (L=20 mm).

Fig.11 shows the scan images of peeled and external surface of resistance welding specimens. The applied current was changed variously. The test specimen has W=20 mm width and L=50 mm in length. The welding area was not changed even if the applied current was increased, and it was found that the melt of PPS polymer was occurred significantly around the near the copper electrode. This is electrical phenomenon called the edge effect [7-9]. It was considerd that the current leakage occurred in woven CF/PPS laminates because the length of the energization was long. In order to prevent this edge effect, it was suggested that the resistance heating element and woven CF/PPS laminates should be insulated.

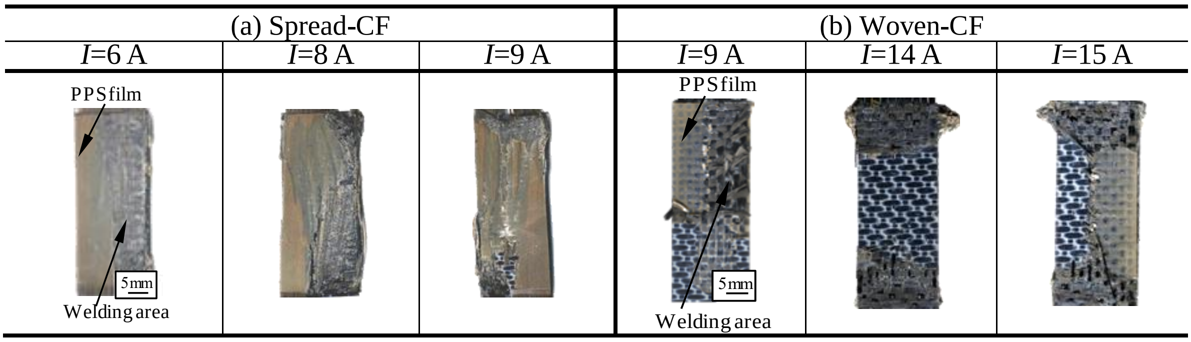


Figure 11. Scan images of peeled face .

Fig.12 shows the effects of applied current on welding area ratio. In this case, the specimen of the length was *L*=20 and 50 mm. In the both resistance heating elements, the welding area ratio was about ΔA_w=70%. The welding area ration was decreased with increasing the applied current at *L*=50 mm specimens. In this reason, it was considered that the amount of the joule heat was higher around the electrode, and the current was preferentially flowed in the woven CF/PPS laminates. From thease results, it is difficult to realize uniform heating temperature distribution because of the edge effect when the joining part is increased by increasing the length of joining part. Threfore, it is desirable to increase the welding area by increasing the widh of joining part.

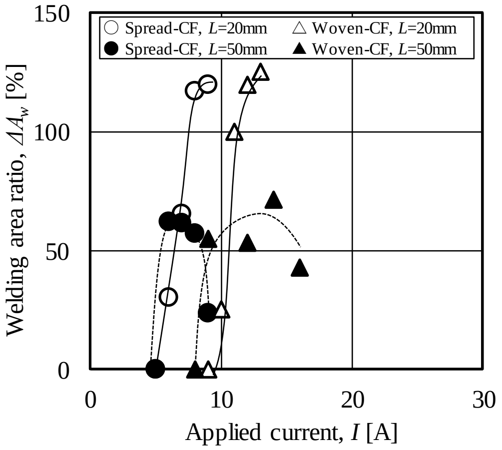
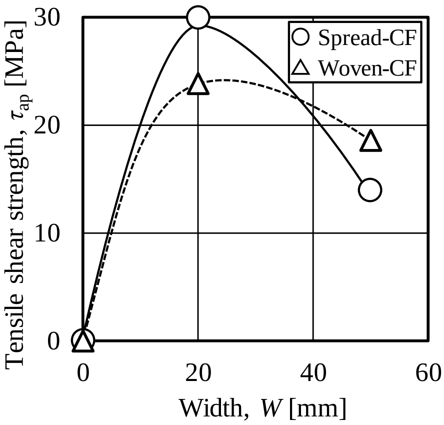


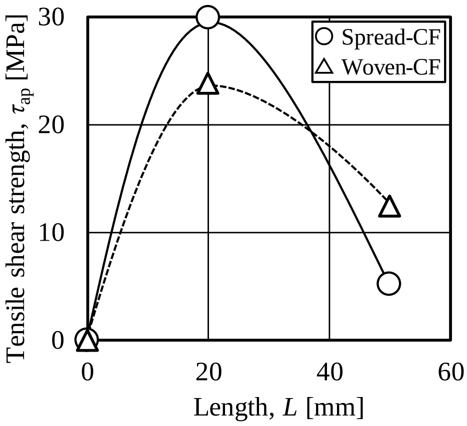
Figure 12. Welding area ratio of specimen with varied heating elenemts and lengths (*W*=20 mm).

3.3. Tensile shear strength

Fig.13 shows the relationship between dimensions of joining part and single lap shear strength. The applied current was the appropriate value obtained by experiments that the welding area ration was the maximum. In the case of *W*=*L*=20 mm, the tensile shear strength showed the maximum value. When the joining width and the joining length were increased, the joining strength decreased because the welding area ratio was small, and the woven CF/PPS laminates was thermally deformed. It is necessary to prevent thermal deformation of laminates and improve the welding area ratio.



(a) Effects of joining width



(b) Effects of joining length

Figure 13. Effects of dimensions of joining part on tensile shear strength.

4. Conclusions

This study was investigated the effects of various carbon fiber heating elements on resistance welding behavior of woven CF/PPS laminates. From the experimental results, in the case of using spread-CF heating element, it was revealed that the spread carbon fiber heating element needs to be uniformly arranged in order to heat stably. In the case of using woven-CF heating elements, it was found that the temperature distribution was almost uniform because the carbon fiber was arranged uniformly. Moreover, the woven-CF heating element is easy to heat up because the electric resistance increases in the woven structure, and the carbon fiber bundles are aligned evenly. From various experimental results, when the joining part is enlarged by increasing the length of joining part, it is difficult to realize uniform heating temperature distribution because of the edge effect. Threfore, it is desirable to increase the welding area by increasing the widh of joining part.

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