EFFECTS OF HEATING CONDITIONS ON HIGH FREQUENCY INDUCTION WELDING BEHAVIOR OF CARBON FIBER REINFORCED THERMOPLASTIC COMPOSITES

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Abstract

This study aims to develop the high frequency induction welding process for continuous carbon fiber reinforced thermoplastics (CFRTP). The materials used for experiment were unidirectional CF/PPS (UD-CF/PPS $[0]_6$ and UD-CF/PPS $[0/90]_3$), woven-CF/PPS and woven-CF/PA66. The induction coil used was pancake type coil.The effects of heating conditions such as the coil height, induction heating power, coil-roller distance were investigated in order to predict the optimum processing conditions. From the some induction heating experiment results, it was found that UD-CF/PPS $[0]_6$ laminate was not suited for induction heating, because the electric circuit was hardly formed in the laminate. On the other hand, UD-CF/PPS $[0/90]_3$ and woven laminates were better heated. From the result of single lap shear strength test, the strength was increased with decreasing the coil – roller distance.

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1. Introduction

Carbon fiber reinforced thermoplastic (CFRTP) has high performance properties such as high productivity, recyclability and impact resistance compared to thermosetting composites (TSC) [1]. Therefore, the CFRTP has a wide range of applications in aerospace, automotive and industrial products. Joining of thermoplastic composites is an important step in the manufacturing of aerospace thermoplastic composite structures. The joining process is necessary to manufacture complex geometry parts and large-scaled structures using CFRTP. The joining methods of thermoplastic composites can be divided into several methods such as mechanical fastening, adhesive bonding and fusion joining or welding [2]. However, 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 method for CFRTP such as ultrasonic welding, resistance welding, induction welding and so on, and these heating principle are completely different [3,4]. The ultrasonic welding method has size restriction of joining parts. The resistance welding method has to insert a metallic heating element between joining faces. Moreover, it is very difficult for these methods to weld continuously between large-scaled CFRTP parts with the high productivity. However, the induction welding method can be carried out fusion joining continuously by moving an induction coil or CFRTP joining parts [5,6]. Moreover, CFRTP can be induction heated directly because the carbon fibers are electrically conductive.

This study aims to reveal the induction welding behavior of CFRTP composites by high-frequency induction heating method. The material used is UD-CF/PPS, woven CF/PPS and woven CF/PA66 laminates. The effects of geometry of coils, coil distance, heating time and the carbon fiber reinforcement on heating behavior of CFRTP composites in induction heating were investigated. The experimental results revealed that the surface temperature of UD-CF/PPS and woven-CF/PPS laminates was increased with increasing the heating time. Moreover, the surface temperature was increased with decreasing the coil distance remarkably.

2. Determination of High Frequency Band

When the CFRTP is heated using the high frequency induction heating, inner carbon fibers of CFRTP laminate is heated preferentially. The inductive current occurs a direction which is at aright angle to the magnetic flux by a induction coil. This inductive current concentrates on surface of the heating object because the current is the high frequency current. This phenomenon is called the skin effect. The result of the skin effect is that most of the heat is concentrated in a specific region on the surface of heating object. This effect is decreased exponentially from the surface of heated object. The eddy current density has also decreased by 1/e. Then, this depth is defined by the penetration depth (δ). The penetration depth is calculated by

$$\delta = 5.03\times10^{5}\sqrt{\frac{\rho}{\mu_r f}} \tag{1}$$

where ρ[Ω・m] is electrical resistivity, μ_r is specific magnetic permeability and f [Hz] is frequency. Figure 1 shows the relationship between frequency and depth of current penetration calculated by Eq.(1). Then, the specific magnetic permeability is μ_r=1. The penetration depth of CFRP is wide renge (ρ=0.2×10^{-5} - 15×10^{-5} [Ωm]) because CFRP has various fiber reinforcement morphology. It can be seen from this figure that proper frequency for CFRP is MHz band.

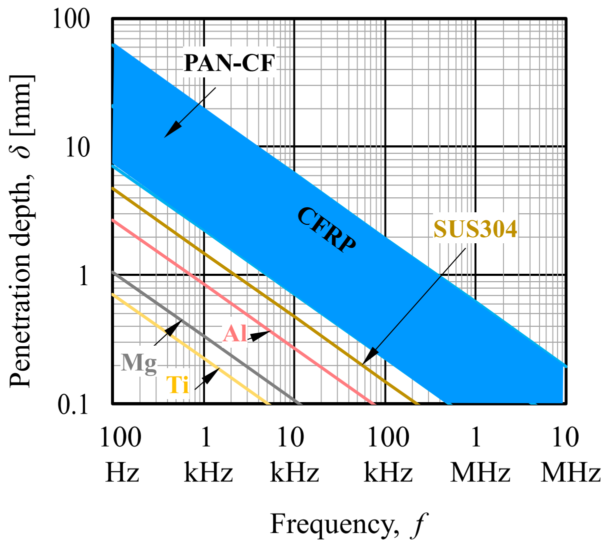

Figure 1. Relationship between frequency and depth of current penetration.

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3. Experimental Materials and Procedure

3.1. Induction Heating Experiment

3.1.1. Materials

The materials used for the induction heating experiment is unidirectional CF/PPS laminate (TenCate, CETEX® TC910, V_f=58 vol.%, UD-CF/PPS $[0]_6$ and UD-CF/PPS $[0/90]_6$) and 5H- sateen weave CF/PPS laminate (TenCate, CETEX®, V_f=45 vol.%, woven-CF/PPS). The thickness of these laminate is t=1.2 mm.

3.1.2. Induction Heating Method and Evaluation Method

Figure 2 shows the appearance of induction heating equipment for CFRTP. The purpose of this experiment is to reveal the effects of carbon fiber reinforcrment morphology and the fiber orientation angle on the high frequency induction heating of CFRTP. The heating device used is the high frerquency induction heating device (YS Denshi Co., Ltd., IH-012MH3, AC200V, f=2 MHz, P=1 kW) The laminate surface was observed by the infrared thermography (Apiste Co., Ltd., FSV-1200, Emissivity ε=0.85). Then, the distance between the induction coil and laminates (z_c) was variously changed.

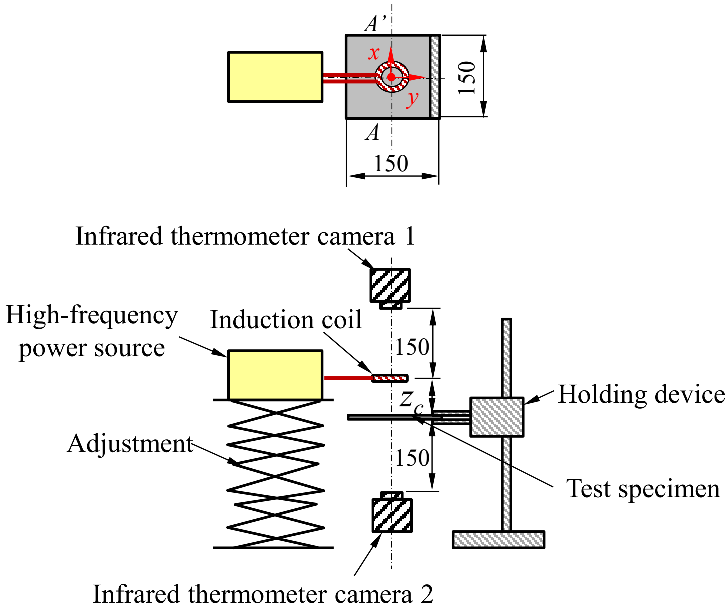

Figure 2. Appearance of induction heating equipment for CFRTP.

The induction coil used was pancake coil with 30 mm in diameter as shown in Figure 3. The surface of coil was covered by highly heat resistant glass tape.

(a) Appearance (b) Schematic drawing

Figure 3. Appearance of pancake type coil.

3.2. Induction Welding Experiment

3.2.1. Materials

The material used for the induction welding is woven CF/PA66 laminate (BondLaminates, Twill, V_f=45 vol%, woven-CF/PA66). The thickness of this laminate is t=0.75 mm. The PA66 resin is semi-crystalline polymer. The result of differential scanning calorimeter (DSC) analysis shown that the glass-transition temperature is T_g=50ºC, and the melting temperature is T_m=255ºC. It is also shown from the result of thermogravimetric analysis that the thermal decomposition temperature is T_d=350ºC.

3.2.2. Continuous Induction Welding Method and Evaluation Method

Figure 4 shows the appearance of continuous induction welding equipment. Two superposed woven-CF/PA66 laminates was fed by pressure roller at v=14 mm/s. Then, the laminates is induction heated rapidly by the induction coil. The heating behavior of fusion joining face was measured by fine wire thermocouples using a temperature measuring instrument (Graphtech Co., Ltd., midi LOGGER GL220). The temperature profile of B – B' line was measured by the infrared thermography (Apiste Co., Ltd., FSV-1200, Emissivity ε=0.85). The images of joint surfaces peeled off after joining were imported with a scanner device (Epson Co., Ltd., ES-7000H). The welding surfaces were also observed with a microscope to investigate the state of fusion bonding. The single lap tensile shear strength (LSS) test was carried out to evaluate a joint strength by using universal testing machine (Shimadzu Co., Ltd., AG-50kN XDplus).

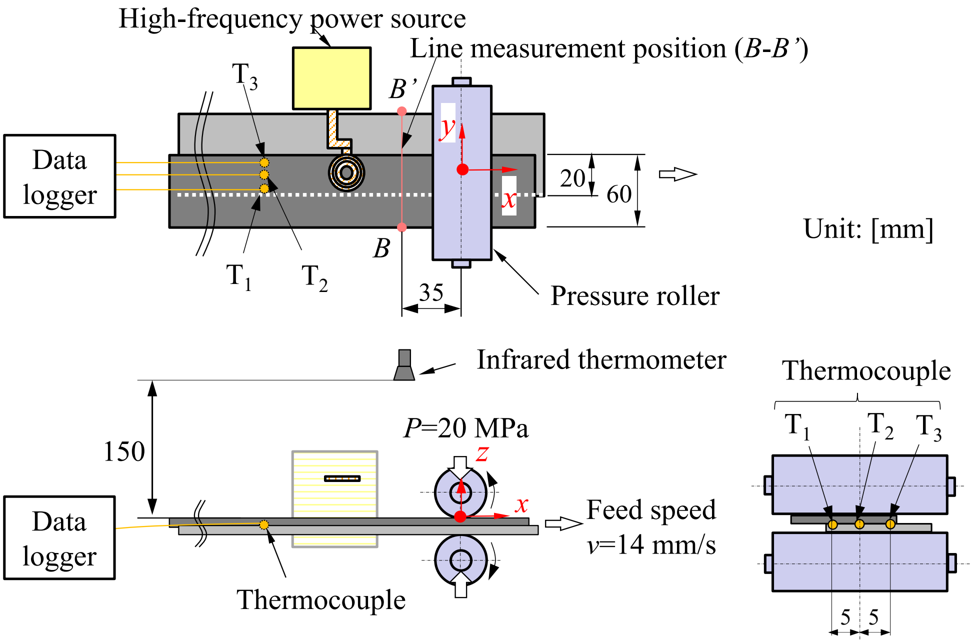

Figure 4. Appearance of continuous induction welding equipment.

Figure 5 shows the appearance of single lap joining (SLJ) test specimen. Before SLJ testing, aluminum tabs were bonded to end of specimens with epoxy adhesive. The cross-head speed was v=0.5mm/min. The lap shear strength (LSS) was calculated by using the below 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].

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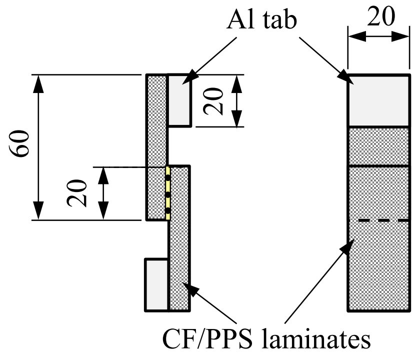
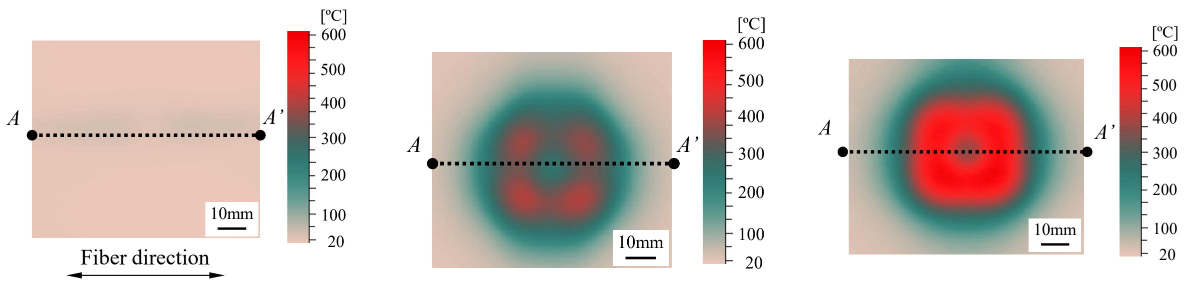


Figure 5. Geometry of single lap joining test specimen.

4. Results and Discussion

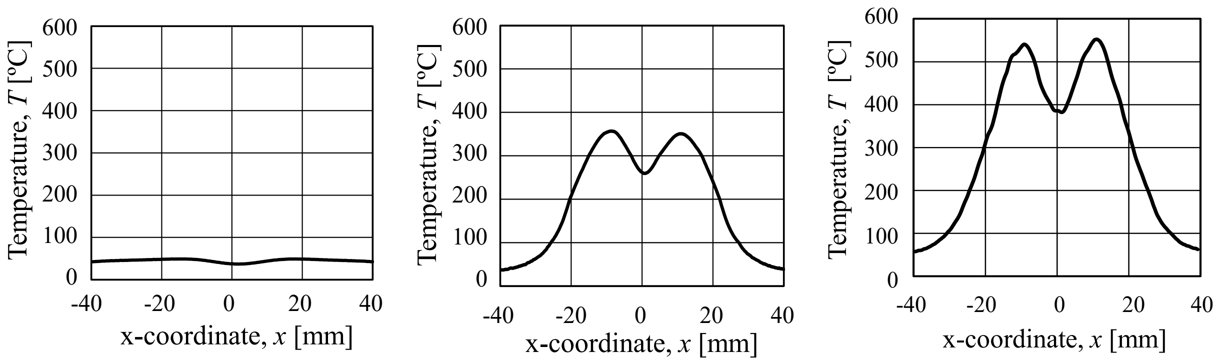
4.1 Effects of Fiber Reinforcement Morphology

Figure 6 shows the temperature distribution of various laminates at P=100%, z_c=5 mm and t=20 s, and the temperature profiles of laminates was also shown in Figure 7. In the case of the UD-CF/PPS $[0]_6$, the heating temperature was very low (T≦50 ºC). On the other hand, the temperature of UD-CF/PPS $[0/90]_3$ and woven-CF/PPS was higher than that of UD-CF/PPS $[0]_6$. Especially, the temperature was highest around just under the induction coil. Figure 7 shows that the temperature reached a minimum at the center of the induction coil, and two peaks were predicted just below the induction coil. From these result, it was found that the UD-CF/PPS $[0]_6$ was not suited for induction heating because the electric circuit were hardly formed in laminate. On the other hand, it was found that the UD-CF/PPS $[0/90]_3$ and woven-CF/PPS were better suited for induction welding.



(a) UD-CF/PPS $[0]_6$ (b) UD-CF/PPS $[0/90]_3$ (c) Woven-CF/PPS

Figure 6. Temperature distribution of UD-CF/PPS $[0]_6$, UD-CF/PPS $[0/90]_6$ and Woven-CF/PPS (back side).



(a) UD-CF/PPS $[0]_6$ (b) UD-CF/PPS $[0/90]_3$ (c) Woven-CF/PPS

Figure 7. Temperature profiles of UD-CF/PPS $[0]_6$, UD-CF/PPS $[0/90]_6$ and Woven-CF/PPS (back side).

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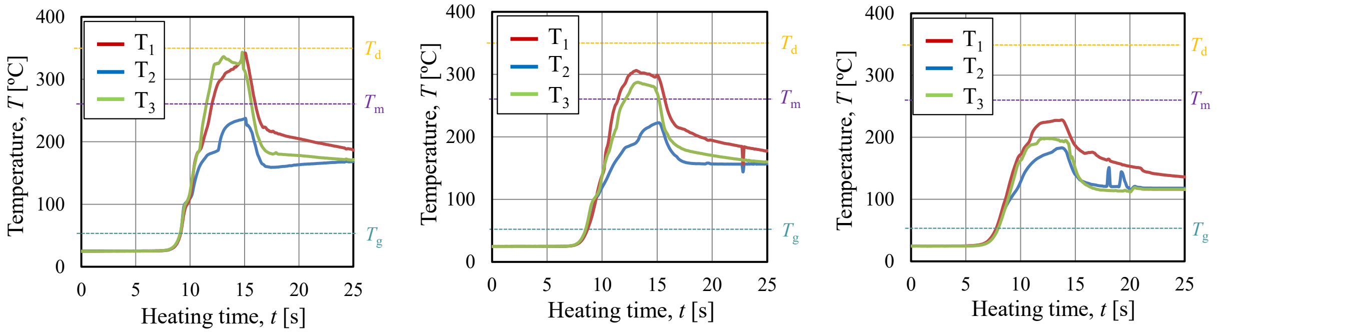
4.2 Effects of Coil Height

Figure 8 shows the change of temperature on joining surface obtained by thermocouples using the continuous induction welding equipment as shown in Figure 4. From the measurement results, it was found that the maximum temperature of laminate was increased with decreasing the coil height. Moreover, the termocouples of T_1 and T_3 were found to be showed higher temperature compared to T_2 thermocouple, bacause the temperature of center in the induction coil is lower than the edge of coil. When the heating time was t=15s, the surface of laminates was cooled down quickly, because the laminate contacted to the pressure roller.



(a) z_c=3 mm (b) z_c=4 mm (c) z_c=5 mm

Figure 8. Change of temperature on joining surface measured by thermocouples.

4.3 Single Lap Shear Strength

Figure 9 shows the effects of coil - roller distance on single lap shear strength. The coil height was z_c=5 mm. The tensile shear failure occurred at the all coil –roller distance conditions. The single lap shear strength was decreased with increasing the coil – roller distance because the laminate was cooled down by the heat dissipation into the air. When the coil – roller distance was x_c=40 - 60 mm, the single lap shear strength was τ_{ap}=5 - 5.5 MPa. On the other hand, in the case of the x_c=80 – 100 mm, the single lap shear strength was decreased significantly because the fusion joining surface was not welded completely. From this result, it was found that the proper coil – pressure roller distance was x_c=40 mm.

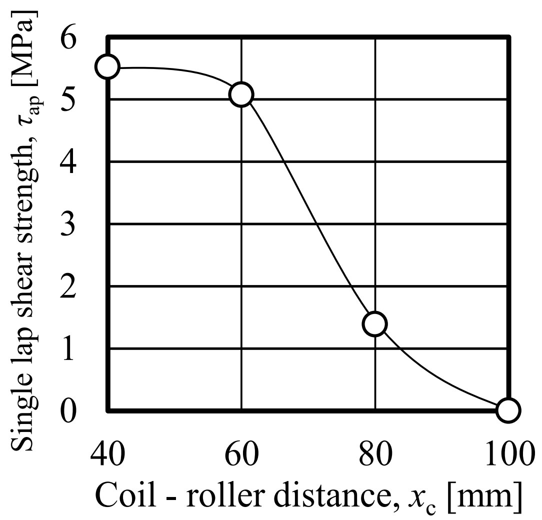


Figure 9. Effects of coil - roller distance on single lap shear strength.

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5. Conclusion

This study aims to develop the high frequency induction welding process for continuous carbon fiber reinforced thermoplastics. The result of induction heating and welding experiment using the high frequency induction welding device (f=2 MHz) and pancake type coil, it was found that UD-CF/PPS $[0]_6$ laminate was not suited for induction heating, because the electric circuit was hardly formed in the laminate. However, UD-CF/PPS $[0/90]_3$ and woven laminates were better heated. From the result of single lap joining test, the single lap shear strength was increased with decreasing the coil – roller distance. To develpe the higher efficient induction welding device for CFRTP is the future subject in this study.

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