CONTINUOUS TAPE LAYUP MOLDING OF CFRTP USING NEAR-INFRARED HEATING AND HIGH FREQUENCY INDUCTION ROLLER HEATING

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Abstract
This study focused on the heating behavior, thermal distribution and interlaminar shear strength in a laying process of unidirectional carbon fiber reinforced thermoplastic tape to predict the optimum processing condition for carbon fiber prepreg tape laying. The material used for the experiment was unidirectional CF/PA6 prepreg tape. The source of heat was used near infrared heating and high frequency induction roller heating. The effects of processing conditions such as the position of infrared heaters, feed speed of prepreg tape and temperature of compaction roller on the laying behavior of prepreg tape and their bonding strength were investigated. From the experimental results, it was found that the near infrared heating was required for removing the moisture contained in prepreg tape.

1. Introduction

Automated thermoplastic tape laying (ATL) and automated fiber placement (AFP) are high-potential manufacturing methods for continuous fiber reinforced thermoplastic (cFRTP) composites which can ensure operational safety even in highly loaded components such as aircraft wing skins and fuselages or construction large scaled structures [1-5]. These methods often use computer-controlled robotics to lay one or several layers of carbon fiber thermoplastic tape or tows onto a mold, and should be optimized some processing parameters such as heating, pressing and feed speed and so on. The cFRTP tape are commonly heated up to the melting temperature by various heating sources hot gas torch and high powder diode laser before pressing by consolidation roller [1-5]. However, these type of heaters have some problems that is high facility cost and the limited heating area. Though the final aim of this study is to manufacture composite laminates made from tapes pre-impregnated with unidirectional carbon fiber and thermoplastic matrix, this study focuses on thermal distribution and bonding strength

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in a laying process of unidirectional carbon fiber reinforced thermoplastic tape. The tape is commonly heated up to the melting temperature by various heating sources including heated roller, hot gas torch, near-infrared light lamp, induction coil and high powder diode laser and so on. A near-infrared heater has some advantages such as rapid start-up heating for carbon fiber. However, the heating characteristic is deeply influenced by position of the heater and feed rate of prepreg tape, thus it is necessary to optimize those heating parameters. On the other hand, the crystallinity of thermoplastic polymers is directly affected by cooling rate, and the bonding strength between prepreg tapes is depended on the degree of crystallization. Therefore, it is important for the thermoplastic prepreg tape laying process to investigate the cooling and consolidation behavior.

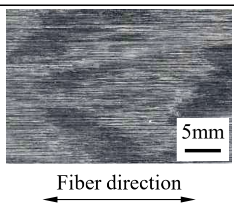
This study aimed to predict the optimum processing condition for thermoplastic tape laying. The material used for the experiment was unidirectional carbon fiber reinforced polyamide 6 prepreg tape. The effects of processing conditions such as number and position of infrared heaters, feed speed of tape, temperature and pressure of compaction roller on the laying behavior of prepreg tape were investigated. The temperature distribution on the prepreg tape obtained by infrared thermometer and thermocouple measurement and the interlaminar shear strength of tapes are correlated as concluding remarks of this study.

2. Experimental Materials and Procedure

2.1. Materials

The materials used for the experiment is unidirectional CF/PA6 prepreg tape (TenCate, CETEX® TC910) as shown in Table 1. This prepreg tape has unidirectional construction with a resin content of V_f=58vol.% and a thickness of t=0.16mm. The PA6 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=225ºC. It is also shown from the result of thermogravimetric analysis that the thermal decomposition temperature is T_d=300ºC.

Table 1. The thermal characteristics of unidirectional CF/PA6 prepreg tape

Fiber content, V_f [vol%]	58
Grass transition temperature, T_g [ºC]	50
Melting temperature, T_m [ºC]	220
Thermal decomposition temperature, T_d [ºC]	300
Surface image	

2.2. Lamination process

Figure 1 shows appearance of the tape laying machine which has been manufactured for the basic experiments originally by authors. The near-infrared heater (Heraues, ZKB600/80G) was used as source of heating. The heater which has two tungsten filament as heating source is suitable as the heater of CFRTP prepreg tape because the absorbed fraction is high into black body as carbon fiber. The consolidation rollers are heated rapidly to any temperature by an induction heating equipment (Hidec Co., Ltd.). This tape laying process is divided into the three steps. Firstly, the prepreg sheets are heated by near infrared heater. Then, the matrix polymer of prepreg sheets is melted rapidly. Secondly, two prepreg tapes are welded by pressing using consolidation rollers. Finally, the laminated tape is cooled down.

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Two fine thermocouple (ANBE SMT Co., Ltd., KSG-40-100-100, type K) were bonded on the surface of prepreg tape to investigate the fusion bonding behavior. Two prepreg tapes with 50mm in width were inserted to consolidation roller at an angle of θ_{CF}=60º. The fiber direction of two prepreg tapes and the feed direction is same direction. The angle of the near-infrared heater was fixed at θ_H=30º, and the feed speed was changed from v=14mm/s from to v=28mm/s.

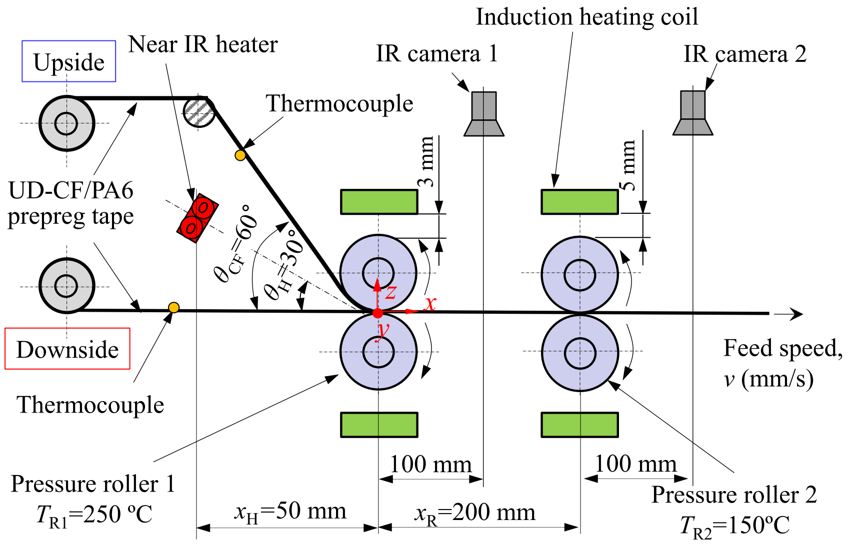


Figure 1. Appearance of CFRTP continuous laminate molding machine using double rollers.

2.3. Evaluation method

The heating behavior of the surface of prepreg tape was measured by fine wire thermocouples using a temperature measuring instrument (Graphtech Co., Ltd., midi LOGGER GL200A). 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 2 shows the appearance of single lap joining (SLJ) test specimen. Before SLJ testing, aluminum tabs were bonded to the 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:

$$\tau_{ap} = \frac{P}{A_L} \qquad (1)$$

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

The weight of before heating prepreg tape and after heating prepreg tape were measured by an electric balance to investigate the weight decrease ratio of prepreg tapes.

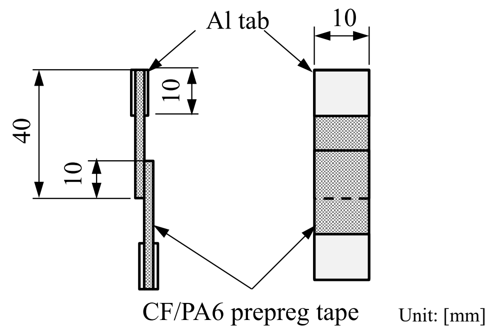


Figure 2. Geometry of single lap joining test specimen.

3. Results and discussion

3.1 Effects of feed speed

Figure 3 shows temperature distribution of the prepreg tape at P_H=70%. Generally, the surface temperature of prepreg tapes was decreased with increasing the feed speed. In the case of the v=14 - 28mm/s, the surface temperature of prepreg tape was achieved over melting temperature of PA6 polymer. The surface temperature was also cooled quickly by heat dissipation to achive the pressure roller 2. It was considered that the surface temperature was decreased with decresing the feed speed. In the case of v>42 mm/s, the temperature of the prepreg tape was not achieved the melting temperature of PA6 polymer because the feed speed was faster. From these results, it was revealed that the surface temperature was affected remarkably by the feed speed.

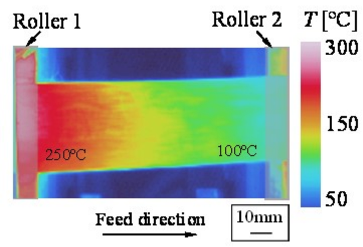
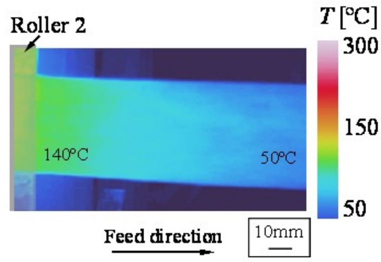
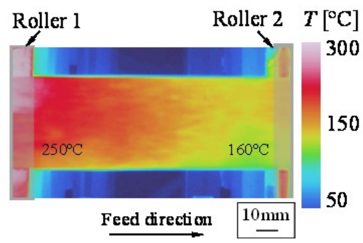
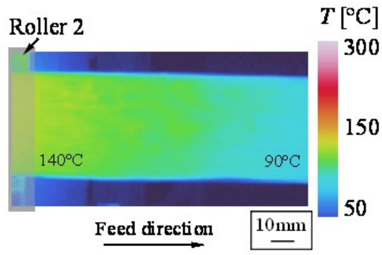
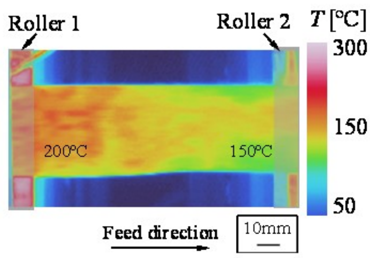
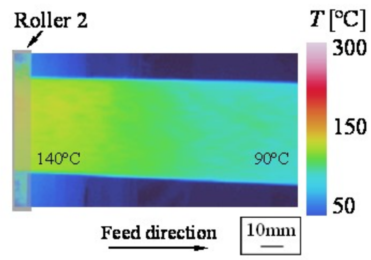
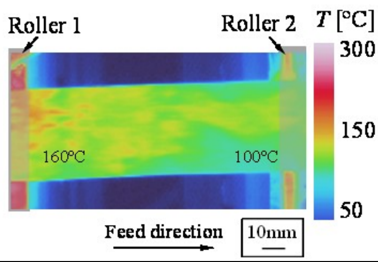
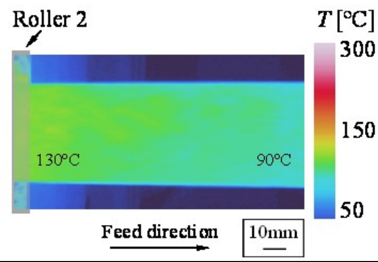
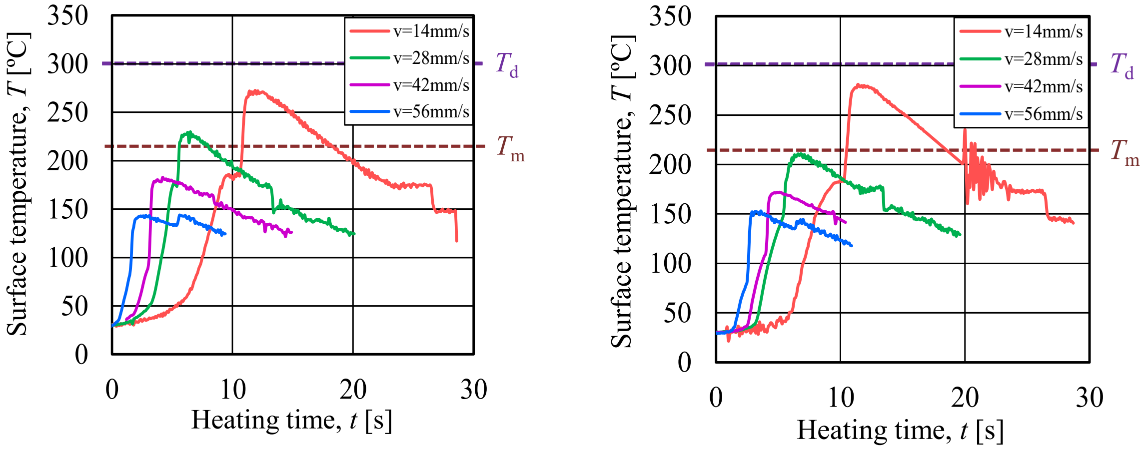
v [mm/s]	IR camera 1 (x=100 mm)	IR camera 2 (x=300 mm)
14		
28		
42		
56		

Figure 3. Heating distribution images of CF/PA6 prepreg tapes at various feed speeds.

Figure 4 shows the change of surface temperature of CF/PA6 prepreg tape at various feed speed obtained by thermocouples measurement. At that time, the near infrared power was P_H=70%. The maximum temperature was increased with decreaseing the feed speed because the heating time was long. In the case of v=14 - 28mm/s, it was revealed that the temperature was achived over melting temperature of PA6 polymer. On the other hand, in the case of v=42 and 56 mm/s, the prepreg tapes was separated because the temperature was not increased to melting temperature. Therefore, it was found that the optimum feed speed was ranged from around v=28 mm/s.



(a) Top surface (b) Lower surface

Figure 4. Change of surface temperature of CF/PA6 prepreg tape at various feed speed.

Figure 5 shows the effects of feed speed on maximum temperature of top and lower surface of prepreg tapes. While the temperature difference of between top and lower prepreg tape was not significant, when the feed speed was changed. This result shows the usefulness of heating the pressure rollers. If the feed speed is decreased under v=14mm/s, the temperature is increased remeakably. From these result, it was considered that the proper feed speed of CF/PA6 prepreg tape was v=14 – 28 mm/s.

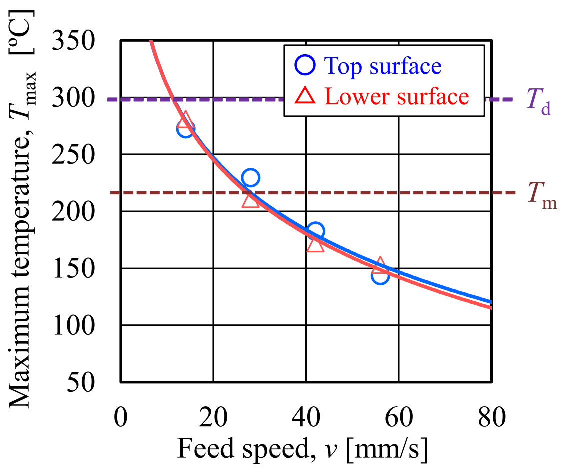


Figure 5. Effects of feed speed on maximum temperature.

3.2. Single lap shear strength

Figure 6 shows the effects of feed speed on single lap shear strength at various near infrared heater powers. Generally, the single lap shear strength was decreased with increasing the feed speed because the heating temperature was not achived the melting temperature of PA6 polymer. In the case of P_H=100%, the single lap shear strength was decreased compared to P_H=50 and 70% because the high temperature area was locally on the prepreg surface. When the heater power was P_H=70%, the single lap shear strength was increased remarkably at v=14 and 28 mm/s because the prepreg tape was heated sufficiently by near infrared heater and induction heating roller. On the other hand, in the case of P_H=0%, the strength was decreased significantly because the prepreg tape was not heated completely. In addition to this, it is a reason that the moisture contained in PA6 polymer was not able to remove

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fully. From these result, higher feed speed conditions was not proper for laying because the matrix polymer was not melted sufficiently, and the proper conditions of feed speed was v=28 mm/s.

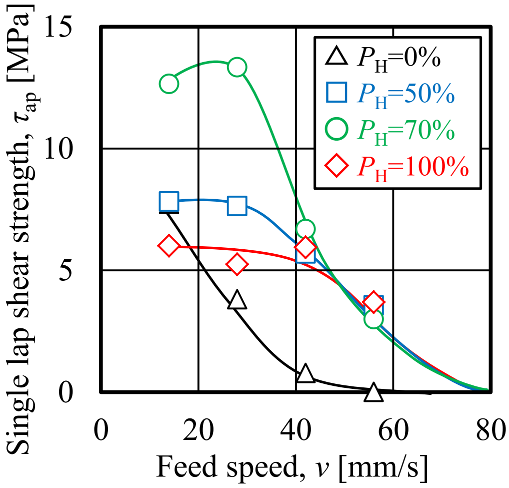

Figure 6. Effects of feed speed on single lap shear strength at various near infrared heater powers.

Figure 7 shows SEM images of fracture face after single lap joining test. In the case of v=14 and 28 mm/s, PA6 polymer was seen around the carbon fiber. On the other hand, in the case of over 42 mm/s, the polymer rich layer was seen wholly. Higher feed speed conditions were not proper for tape laying because the matrix polymer was not melted sufficiently.

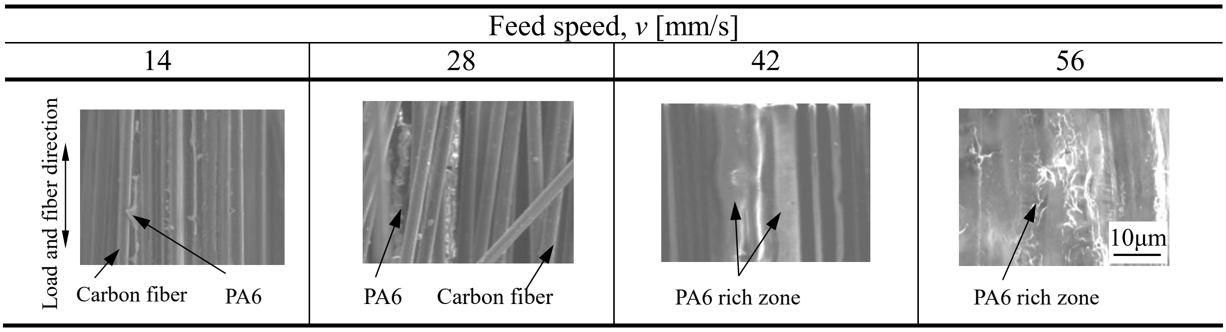

Figure 7. SEM images of fracture face at various fed speeds.

3.3. Weight decrease ratio of prepreg tape

Figure 8 shows the effects of feed speed on weight decrease ratio of prepreg tape at various near infrared heater power. The dashed line (ΔW=1.6 wt%) shows complete drying of the CF/PA6 prepreg tape. Generally, the weight decrease ratio of prepreg tape was decreased exponentially with increasing the feed speed. Moreover, this weight decrease ratio was increased with increasing the infrared heater power. When the feed speed and the heater power were v=14 mm/s and P_H=100%, the weight decrease ratio achived over 1.8 wt%. In this conditions, it was considered that the gasification of PA6 polymer arose slightly. From these result, it is important to remove the moisture in CF/PA6 prepreg tape by using infrared heater for the tape laying process.

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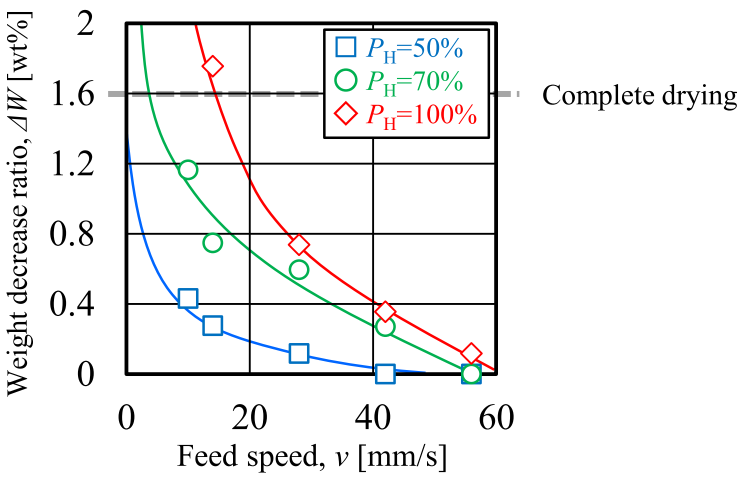

Figure 8. Effects of feed speed on weight decrease ratio of prepreg tape at various near infrared heater power.

3.4. Mechanism of Continuous Tape Laying

Figure 9 shows the tape laying mechanism and SEM images of the laminated prepreg tape. This tape laying mechanism was devided into the four steps. (i) Firstly, before pre heating by near infrared heater, the PA6 polymer was visible on the carbon fiber wholly. (ii) Secondly, after the prepreg tape was pre-heated by near infrared heater, the moisture was outgassed, and the polymer was melted. (iii) Thirdly, two prepreg tape was pressed by first heated roller.After passing the first roller, the tapes was cooled down slowly. (iv) Finally, the tape was consolidated by second rollers. Then, the tape layup is compleated.

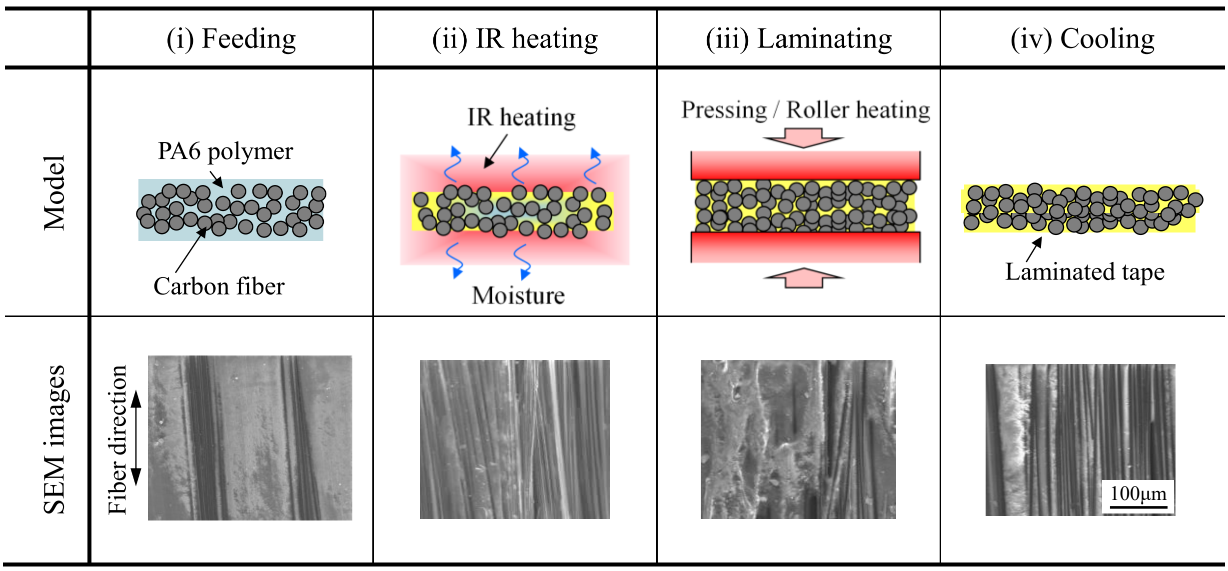

Figure 9. Mechanism diagram of continuous laminating process (with near infrared heater).

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4. Conclusion

This study aimed to predict the optimum processing condition for thermoplastic tape laying. The material used for the experiment was unidirectional CF/PA6 prepreg tape. The effects of processing conditions such as feed speed of prepreg tape and infrared heater power on the laying behavior of prepreg tape were investigated. As a result of investigation of a relationship between feed speed, infrared heater power and single lap shear strength, the single lap shear strength was increased remarkably at v=28 mm/s when the heater power was P_H=70%. From the experimental results, it was found that the near infrared heating was required for removing the moisture contained in prepreg tape.
Moreover,CFRTP tape laying mechanism using the near infrared heating and the induction roller heating was revealed in this study.

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