DEVELOPMENT OF HIGH CYCLE RIVET FASTENING PROCESS BY SERVO PRESS MACHINE USING UNIDIRECTIONAL CFRTP RIVET

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ABSTRACT

This study aims to develop unidirectional carbon fiber reinforced thermoplastic (UD-CFRTP) rivet fastening process using a servo press machine and infrared or another heating method. To realized compact and lightweight portable UD-CFRTP rivet fastening system using servo press machine. The materials used for experiment were unidirectional carbon fiber reinforced polyamide6 (UD-CF/PA6) rod for rivet fastener. The effects of heating method, forming load and holding time on fastening process were investigated. The contents for evaluation are heating distribution of UD-CFRTP rivet, pressure loading behavior, cross-sectional observation after joining, tensile shear strength test and pull through strength test. The tensile shear strength and the pull through strength were compared by CFRTP rivet, aluminum rivet and epoxy adhesive. The tensile shear strength of the UD-CFRTP rivet was 200MPa, which was higher than the other joints. In the case of UD-CFRTP rivet specimen, the strength was increased significantly compared to other fastening and bonding because unidirectional carbon fiber was located continuously within the matrix polymer. The structure where the rivet head and body are united with continuous fibers showed sufficient strength. The high availability of UD-CFRTP rivet as mechanical fastener was shown from these results.

1. INTRODUCTION

A light-weighting of materials re most effective at saving energy in the automotive and aerospace industries. However, this must be achieved at a feasible cost. In recent years, carbon fiber reinforced plastic (CFRP) has been widely used, but it is not easy to reduce materials and production costs, and it is difficult to increase productivity while maintaining high quality.Therefore, a multi-material combining the advanced composite materials and conventional metals is focusing from point of view of the high cost effective lightweight performance [1]. Therefore, multi-materials combining advanced composite materials and conventional metals are attracting attention from the viewpoint of cost-effective and lightweight performance. On the other hand, metal materials are extremely low-cost, and large-scale and complex shapes can be mass-produced in a short time by press molding, and they have low environmental

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impact and excellent recyclability from the viewpoint of life cycle assessment (LCA). Material. Therefore, multi-materials that combine high-performance composite materials with conventional metals are attracting attention from the viewpoint of cost-effectiveness and lightness.

In general, continuous carbon fiber reinforced plastics (CFRPs) have insufficient deformability, and press molding due to plastic deformation at room temperature like metals cannot be applied. Thus, it can be softened with heating and press forming, however more wrinkles occur due to the large anisotropy peculiar to the woven fabric structure [2]. In order to manufacture a large structural material having a complicated shape, it is necessary to joining and fastening. In general, for joining of thermosetting CFRP, mechanical bonding with metallic rivets, bolts or adhesive bonding using epoxy adhesive is used, but weight increase and corrosion of metal fasteners are problematic [3]. The cause of galvanic corrosion, the difference in electrochemical potentials between carbon fiber and the standard metals used in rivets, for example, chromium steels and so on [4]. Adhesive bonding with a thermosetting resin is useful, it is not suitable for joining of thermoplastic CFRP (CFRTP) because chemical bonding with thermoplastic resin is insufficient. For this reason, it is desirable for mechanical joints such as rivets made of thermoplastic CFRP are used for fusion bonding of multi-material including thermoplastic CFRP [5-7].

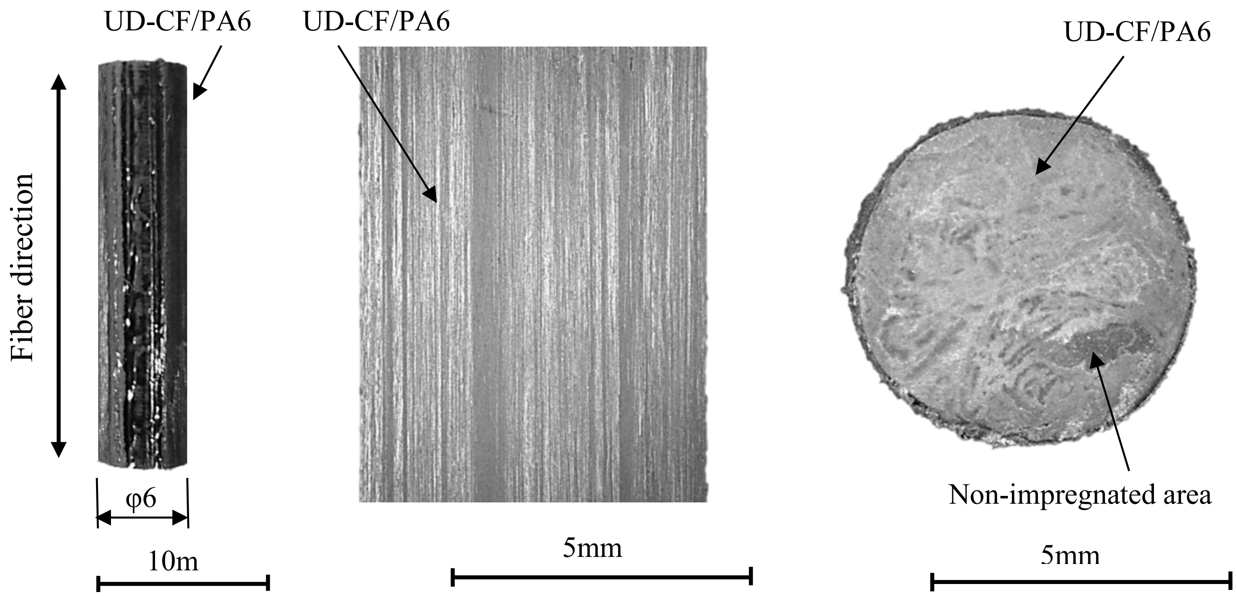
This study aims to evaluate the rivet fastening process of unidirectional carbon fiber reinforced thermoplastics (UD-CFRTP) using an ultra-compact servo press machine with near-infrared heating developed by the authors. In this compact and lightweight portable machine, the precise control of UD-CFRTP rivet fastening was realized. This paper introduces infrared heat press molding of thermoplastic CFRP rivets using a servo press unit. The materials used for experiment are unidirectional carbon fiber reinforced polyamide 6 (UD-CF/PA6) round-rod with 6mm in outer-diameter for rivet fastener. The round rods were fabricated by pultrusion process. In this study, the effects of heating method, forming load and heating temperature on fastening behavior were investigated. The contents for evaluation are heating distribution of UD-CFRTP rivet, pressure loading behavior, cross-sectional observation after joining, tensile shear strength test and pull-through strength test. The tensile shear strength and the pull-through strength were compared by CFRTP rivet, aluminum rivet and epoxy adhesive.

2. EXPERIMENTAL PROCEDURE AND EVALUATION METHODS

2.1 Materials

The materials used for the rivet are unidirectional carbon fiber reinforced polyamide 6 rod. This rod has unidirectional reinforced fiber with a fiber content of V_f>40vol.% and a diameter of D=6mm. UD-CF/PA6 of the materials were pultrusion round rod. The carbon fibers in the pultrusion round bar were continuously oriented straight. Shear loading and tensile loading is applied to rivet carbon fiber. The continuous carbon fibers in the rivet structure favor load of the axial direction. It is considered that the uniformly dispersed carbon fibers also exhibit strength in the shear direction. The PA6 polymer is crystalline polymer, and the glass-transition temperature is T_g=50ºC and the melting temperature is T_m=225ºC. The result of thermogravimetric analysis (TG) also shows that the decomposition temperature is T_d=400ºC.

The results of cross-sectional observation are shown in Figure.1. Figure.1 (a), (b) and (c) show the CFRTP rod appearance, axial-sectional, and cross-section. Figure.1 (a) shows appearance of the UD-CF/PA6 pultrusion rod. A gloss part is seen due to the resin exudation out on the rod surface. This is probably because the molding pressure during the pultrusion of the round bar was low.The rods were cut off, ribet length 24mm. Fine stripe pattern consists of carbon fiber and polymer inside the UD-CF/PA6 rod can be observed from Figure.1 (b) and (c) of the microscope image, Figure.1 (b) shows unidirectional carbon fiber of axial direction. In Figure.1 (b), the dense part of black colored line in fine stripe pattern were portion where a large amount of carbon fiber is present.In the (c)cross section of the microscope image, an unimpregnated area can be confirmed.



(a) Appearance (b) Axial-sectional observation (c) Cross-sectional observation

Figure.1 Appearance and axial-sectional, cross-sectional observation of CFRTP round-rod.

2.2 Molding and Fastening Process of CFRTP Rivet

CFRTP can be produced in a very short period of time by repeating high-speed melting and solidifying by cooling due to the inherent properties of thermoplastic matrices polymer. It can be also easily secondaly deformed by re-heating and welded by heating like metal. CFRTP reinforced with continuous fiber, which has been attracting attention in recent years, has high mechanical properties at low cost. Because of the advantages of the material properties of CFRTP, when CFRTP is used as an alternative to metal fasteners for fastening CFRP and multi-material structures, it is lightweight, high-strength, rustproof, and productive. It can be expected to be excellent. For these reasons, in this study, in oder to use UD-CFRTP rivet instead of conventional metal fasteners, a innovative process for forming and fastening for CFRTP rivets was developed by using a compact electric servo press unit. The features of this process are rapid heating of CFRTP round bar using an omega type near infrared heater and quality control by precise load-displacement control on CFRTP rivets during press forming.

Figure.2 shows CFRTP rivet fastening process using servo press machine. This process is divided into two steps: (a) Molding process of rivet head and (b) Fastening process by rivet.

(a)-1 A CFRTP round rod is inserted into the hole of lower mold, and the upper end part of the rod is rapidly heated by the near infrared heater to a temperature equal to or higher than the melting temperature of the matrix polymer.
(a)-2 The rivet head is formed by the upper mold attached to the servo press unit. At that time, the pressing load and moving distance of the upper mold are controlled appropriately by the servo press. The formed rivet head is cooled while maintaining the load and then demolded from the upper mold.

(b)-1 The CFRTP rivet is inserted into the hole opened in the plates to be joined and only the upper end of the rivet is rapidly heated by the near-infrared heater as in the case of rivet head molding process.
(b)-2 The rivet is fastened by the upper mold attached to the servo press unit. The pressing load and travel distance of the upper mold are controlled appropriately by the servo press similarly.
(b)-3 The rivet is released from the upper mold after cooling down to the glass transition tempeerature of the matrix plymer while maintaining the load. Then, the rivet fastening process is completed.

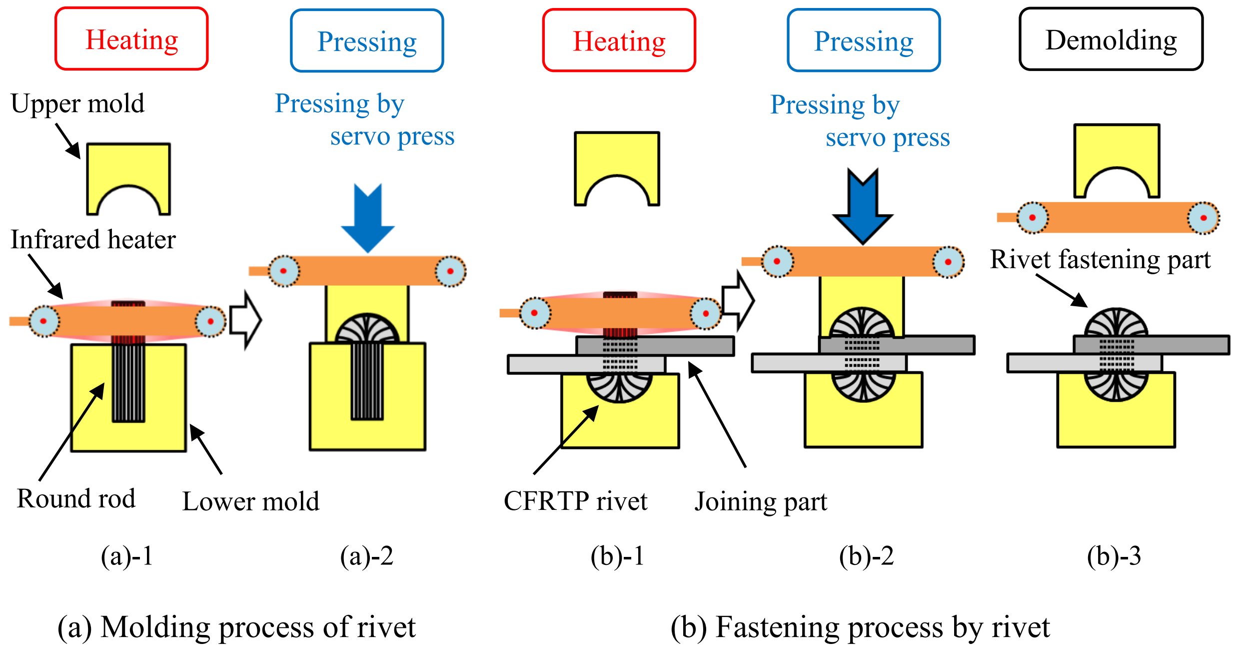


Figure.2 Molding and fastening process of CFRTP rivet using servo press machine.

2.3 Fastening Unit for CFRTP Rivet by Servo Press

Figure.3 shows appearance of CFRTP rivet fastening device using servo press unit and heating unit. This device consists of the servo press unit (Dai-ichi Dentsu Ltd., DSP-3000) for press forming of CFRTP rivet head, infrared heating device (Heraeus, OMEGA250/23-G, 250W/115V) for heating of CFRTP, and the radiation thermometer (KEYENCE, FT-H20) for temperature monitoring. Thermal transmittance of Infrared heater was affected by wave lengths, but this infrared heater is low cost and compact, then it is very useful for manufacturing of CFRTP. In this study, infrared heaters with different irradiation angle were used for comparison.

Firstly, a heating device (Near infrared heating) moves vertically to the heating position. After the slide reaches the heating position, the heat operation starts. Immediately, rivet is heated to the specified temperature. The heating temperature of tip CFRTP rivets is measured by the radiation thermometer. The CFRTP rod is heated to temperature less than the thermal degradation temperature of matrix polymer.

Secondly, rivet head shape is molded by mold attached to the servo press unit. Then, the load and moving distance of press mold are controlled appropriately by servo press. This electric servo press is capable of high-precision press load and the slide position control, and fully digital operation allows faster (1ms or less) load value sampling, so realizing a ±0.01mm repeated position accuracy. By using digital servo motor, full control of the press speed and position is possible. Using at system servo press slide stroke is 50mm, and the maximum press load is 10kN. After the mold attached to the servo press reaches to the specified position, it moves with the position control. After it reaches to the specified position, searching for tip of CFRTP rod starts, and the slide moves down according to the detected press load to match the desired press load. In the load control, the press load reaches to the specified load and is kept.

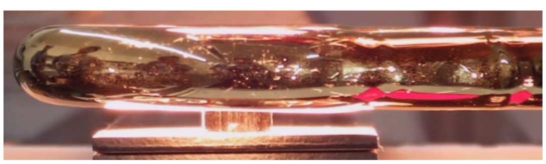
Finally, cooling and load holding is performed by a mold set at room temperature or an arbitrary temperature, and the mold is released at a temperature lower than the glass transition temperature of the rivet.

Servo press unit
(Dai-ichi Dentsu Ltd., DSP-3000)

Press load, F	0-10kN
Press speed, v	0-222mm/s
Pressing time, t_p	0-999s
Stroke, S	0-50mm
Sampling time	1ms
Position accuracy	±0.01mm

Short-wavelength infrared heater:
(Heraeus, OMEGA)

Voltage, V	115V
Wavelength, λ	1.2-1.7 μm
Heater output, P	0-0.25kW



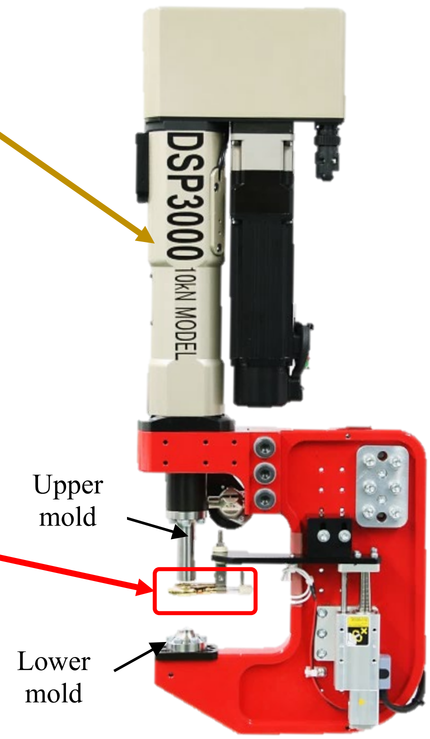


Figure.3 Appearance of CFRTP rivet fastening device using servo press unit and the infrared heater.

2.4 Evaluation Method

In order to evaluate the tensile shear strength and the tension strength of UD-CF/PA6 rivet, the single lap shear strength test specimens and pull through strength test specimens (NASM 1312-8) were performed. Figure.4 shows configuration of the single lap shear strength test specimens and Figure.5 configuration of the pull through strength test specimens and fixtures of pull through strength test respectively. Specimen of Figure.4, a hole was drilled using 6mm drill and the S30400 were fastening using the CFRTP rivet to form single lap shear strength test specimens . Before the tensile shear strength test, tabs of S30400 were bonded to end of the specimens with epoxy adhesive. Aluminum rivet and epoxy adhesive shear strength test specimen were also prepared.

The pull through strength test fixtures are shown disassembled in Figure.5 along with their corresponding test specimens. That each test specimen consists of two plates fastened together at their centers, with one plate rotated 45° in relation to the other so that all eight corners are exposed. The individual plates that make up the specimen are 38mm square. The specimen is composed of UD-CF/PEEK laminate. When the specimen is installed in its fixture, the four corners of the upper plate rest on the four posts that protrude from the fixture base. Then the top portion of the fixture is placed in position, its four posts resting on the four corners of the lower plate. Guide pins ensure proper relative positioning of the two halves of the fixture. As a downward force is applied to the top of the fixture assembly, the two plates are pushed apart, inducing a tension force in the fastener [8]. The crosshead speed was tested at 0.5mm/min.

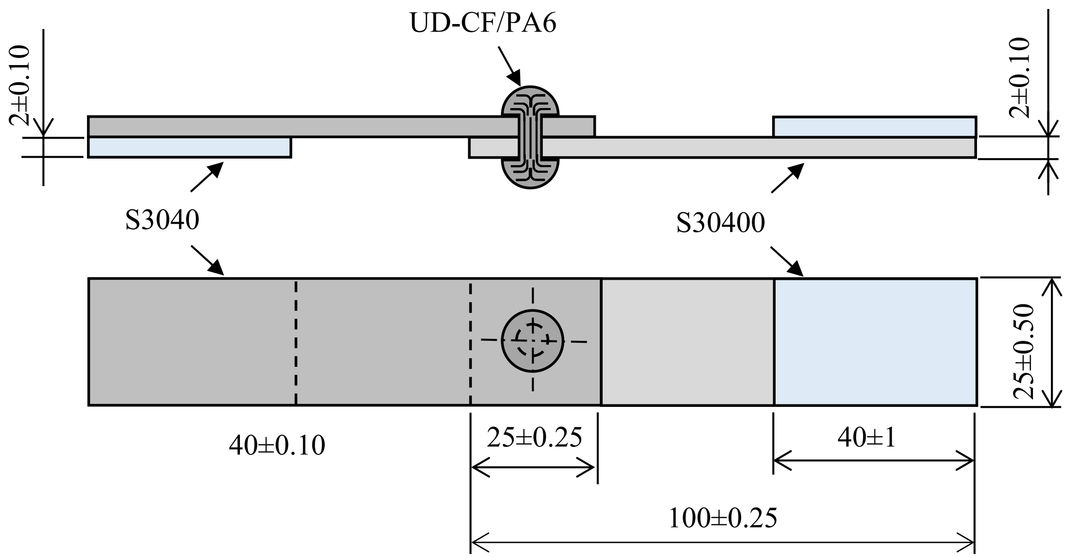
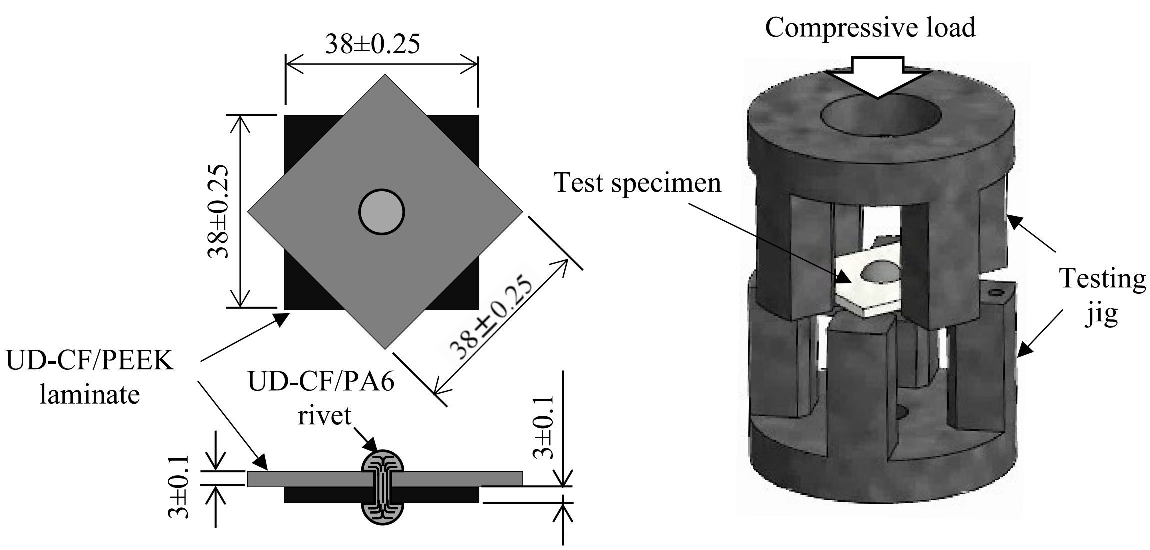


Figure.4 Appearance of single lap tensile shear strength test specimen.



(a) Test specimen (b) Pull through strength test

Figure.5 Appearance of test specimen and pull through strength test [8].

Respective tests were carried out to evaluate a joint strength by using universal testing machine (Shimadzu Co., Ltd., AG-50 kN XDplus). The cross-head speed was set to the v=1mm/min. Tensile shear strength, τwas calculated by the equation (1):

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

Where τ,: Single lap shear strength (MPa), A_L: Overlap area (mm), P: Maximum tensile force (N)

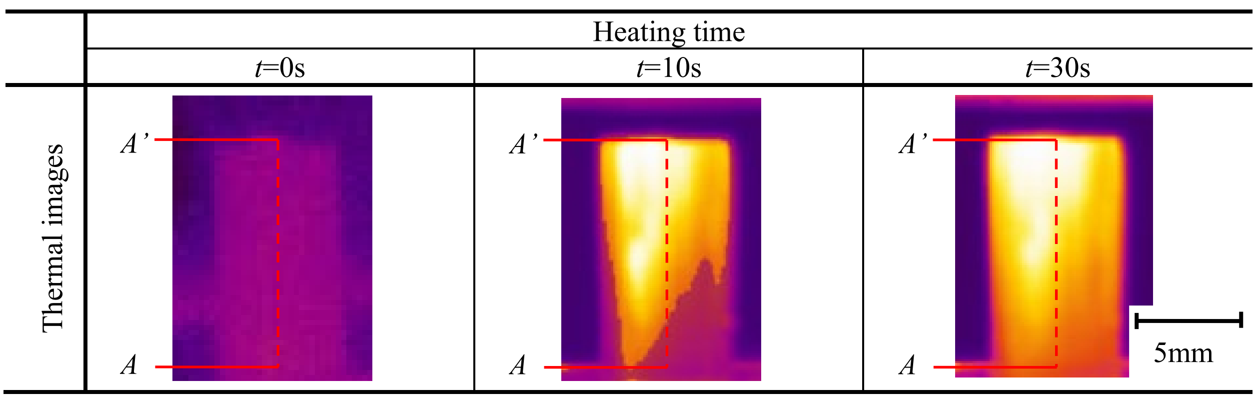
3. EXPERIMENTAL RESULT AND DISCUSSION

3.1 Temperature Distribution of CFRTP Rivet

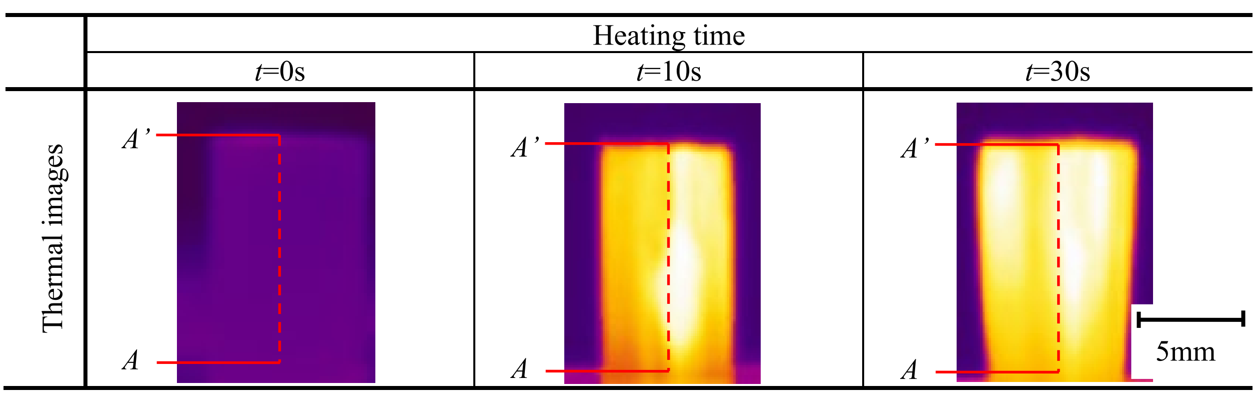
Figure.7 shows the temperature distribution of UD-CF/PA6 rivets heated at varied heating position under same output. Heating is performed for each time at an infrared output of 100V, 0.2kW. Figure.7 (a) shows the case of heating from oblique upward direction, and Figure.7 (b) shows the case of heating from horizontal direction. From these thermal images, it was found that the temperature of rivets increased with increasing the heating time.

In case of heating from oblique upward direction shown in Figure.7 (a), the heating time was required compared to heating from a horizontal direction because temperature difference between top and bottom of rivet is occurred. Thus, such a low heating speed is caused by a setting of heating position. The temperature elevation rate of rivets in the infrared heating is extremely dependent on the irradiation direction of heater used to heating. Therefore, it is necessary to consider the shape of infrared lamp unit possible uniform irradiation from omnidirectional in the future.

In the case of heating from horizontal direction shown in Figure.7 (a), the heating rate was faster than heating from oblique upward direction. It was found that the most part of rivet was heated more than melting temperature of PA6 polymer in *t*=30s. It was obvious that the tip of rivet expanded slightly when the PA6 polymer was melted. Attribute the expansion of the rivet is attributed to the tension of carbon fiber. Increasing the output of infrared heating promotes thermal degradation of the surface matrix polymer.



(a) Heating from oblique upward direction



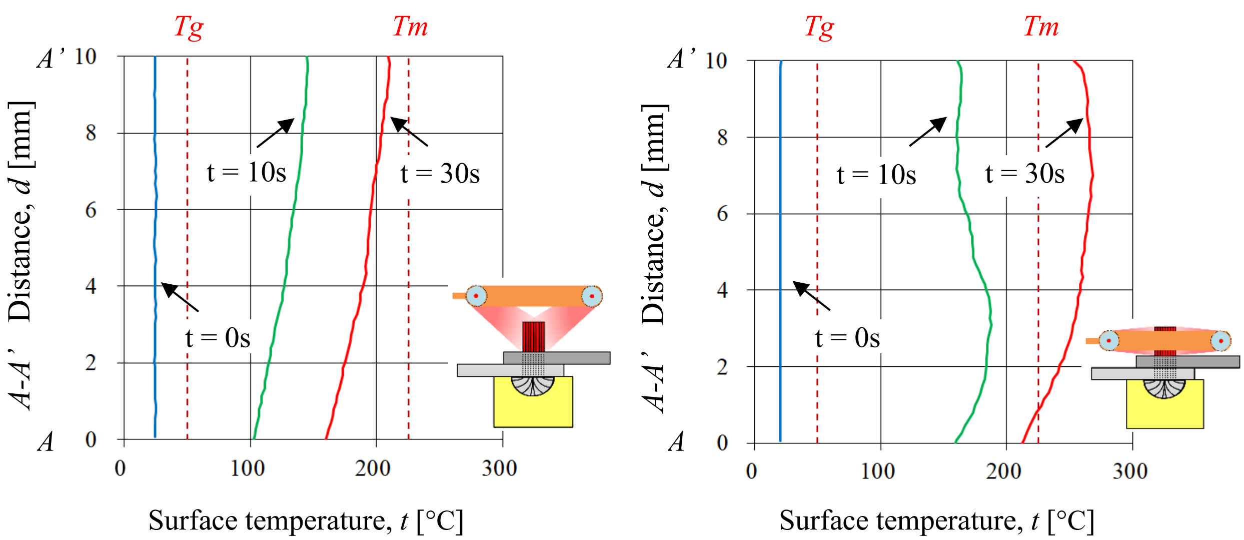
(b) Heating from horizontal direction

Figure.7 Surface temperature distribution result by infrared camera of UD-CF/PA6 rivets in the case of heating from oblique upward and horizontal direction.

Figure.8 shows the temperature profiles of UD-CF/PA6 rivet heated by varied heating device. In case of the heating from oblique upward direction shown in Figure.8 (a), the heating temperature did not increase higher at over *t*=30s. It was also identified that the temperature difference occurred remarkably due to the irradiation position of the infrared heating. This is because the heater in the upper oblique direction directly heats mainly the upper part of the rivet tip.

On the other hand, in case of the heating from oblique upward direction shown in Figure.8 (b), the temperature was higher at the end of rivet close to the infrared heater. In case of horizontal heating for 10s, the temperature increase due to infrared reflection from the specimen is confirmed at 0-2mm. The above is obvious from surface temperature distribution and temperature profile by infrared camera of UD-CF/PA6 rivets using infrared heating.

From these experimental results, it was identified that the temperature difference occurred significantly due to the irradiation position of the infrared heater under same output. And also, it is clarified from the results shown in Figure.7 that the heating position in the infrared heating is extremely dependent on infrared ramp position.



(a) Heating from oblique upward direction (b) Heating from horizontal direction

Figure.8 Temperature profiles of UD-CF/PA6 rivet heated by varied heating device.

3.2 Fastening Behavior of CFRTP Rivet

Figure.9 shows the effects of processing time on fastening load and moving distance of the upper mold. At the upper mold moving distance, a high-speed approach is performed from *z*=0mm to *z*=-21mm, and work search is performed from *z*=-21mm to *z*=-31mm. During the high-speed approach at *t*=0 to 0.1s, the fastening load was *P*=0kN because the upper mold and the UD-CF/PA6 rivet head were not contacted. At about *t*=0.33s during the work search, the upper mold and the tip of the UD-CF/PA6 rod contacted each other. Shift to the fastening speed after reaching the set load *P*=0.3kN.A peak due to the speed change can be confirmed at *t*=0.6s. Subsequently, the fastening load increased linearly pre to *P*=2kN of the set load. The rivet fastening process was completed at about *t*=1s. After the molding, the set load is maintained during cooling of UD-CFRTP rivet.

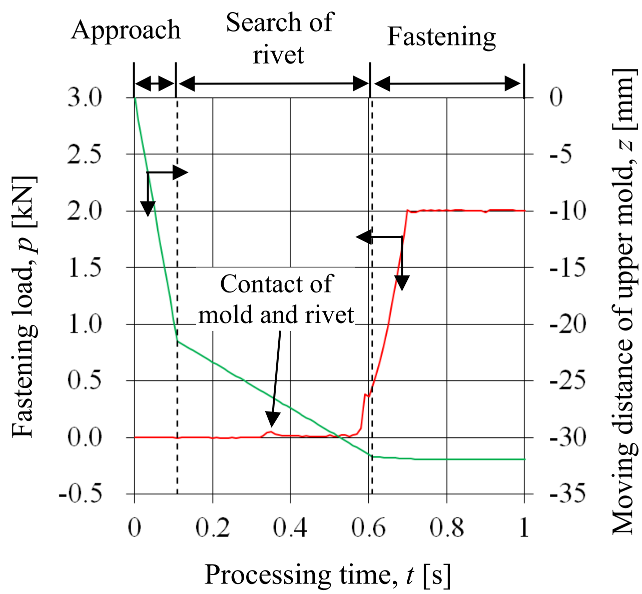


Figure.9 Effects of processing time on fastening load and moving distance of upper mold.

Figure 10 shows the observed images of the UD-CF/PA6 rivet forming process at different processing times when the rivet tip temperature reaches 250°C. When the processing time was about t=0.4s, the rivet head began to be formed by the mold attached to the tip of the servo press unit.

As shown in Figure 10 (a), the UD-CF/PA6 rivet heated from oblique upward is formed so as to wrap in while spreading from the tip due to local top heating. Above forming process, the polymer selectively forms from a portion having a low viscosity.

On the other hand, in the case of horizontal heating shown in Figure 10 (b), the entire heating section is molded so as to expand. From the results, the heating position has an influence on the molding process.

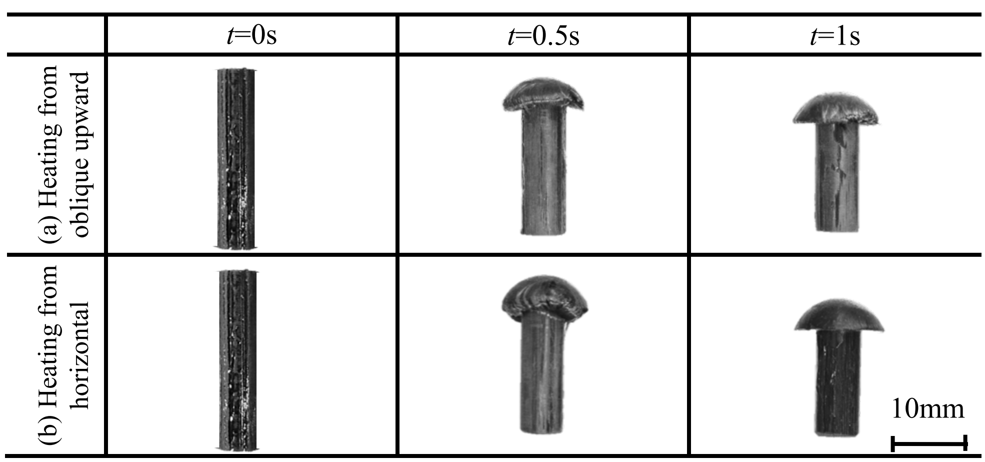


Figure.10 Observation images of UD-CF/PA6 rivet at various processing time.

3.3 Cross-Sectional Images of CFRTP Rivet

A cross section of the rivet subjected to horizontal heating was observed. Figure.11 shows sectional images of UD-CF/PA6 rivets at various press molding start temperature in a rivet tip. In the case of the

T=200ºC, the fracture and the buckling of carbon fibers occurred significantly in the overall rivet because the molding temperature was lower than melting temperature of PA6 polymer. There are also many voids inside the rivets. The shank structure remains in the center of the head due to insufficient heating, which can be confirmed from flow line of the carbon fiber. Even in *T*=220ºC, the fracture and the buckling of carbon fiber occurred partially in the head, it can be seen a structure in which the carbon fiber did not flow but bend in the upper part of a rivet-head. In the rivets formed at *T*=240ºC, it was found that voids and Local fiber buckling of inside the rivets were less than the rivets formed at *T*=200ºC and *T*=220ºC because the temperature of the rivet has reached more than the melting temperature of PA6 polymer. Furthermore, the bent structure of the carbon fiber in the upper part of the head is not seen, and the whole of the carbon fiber is the re-orientation.

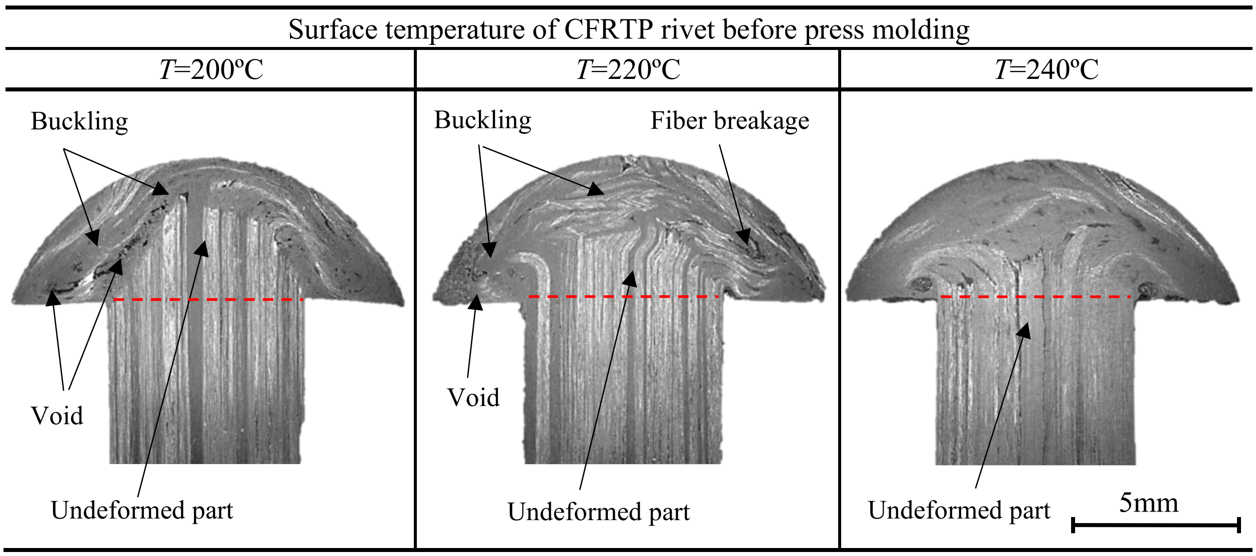


Figure.11 Cross-sectional images of UD-CF/PA6 rivets molded at various surface temperature of CFRTP rivet before press molding.

3.4 Single Lap Tensile Shear Strength

Figure.12 shows the single lap tensile shear strength test specimen which S30400 plates was fastened by UD-CF/PA6 rivet in the case of the horizontal heating.

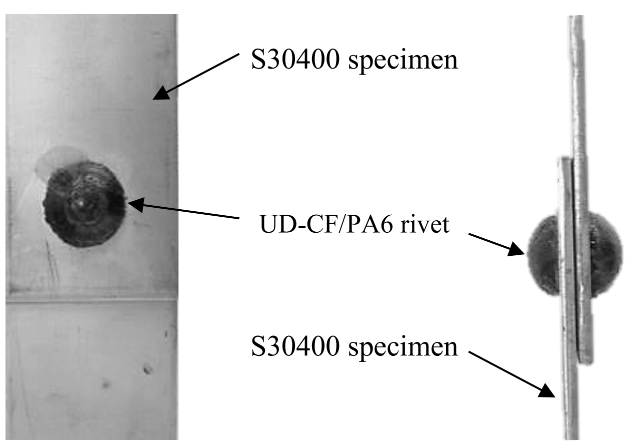


Figure.12 Photograph of single lap shear strength test specimen by UD-CF/PA6 rivet fastening.

Figure.13 shows the comparison of single lap tensile shear strength joined by epoxy adhesive bonding, Al5052 rivet and UD-CF/PA6 rivet fastening. The material used for test specimen was S30400 plates. In case of epoxy adhesive bonding specimen, the tensile shear strength was extremely low compared to AL5052 and UD-CF/PA6 rivet specimens because the joining surface was bonded by only anchor effects. On the other hand, the UD-CF/PA6 rivet specimen showed about three times higher tensile shear strength than the isotropic AL5052 rivet specimen. This is because the unidirectional carbon fibers are positioned vertically between the two plates, and the rigid carbon fibers have greatly resisted the shear deformation of the two plates. From these experimental results, it was obvious that the joining strength of UD-CF/PA6 rivet is higher than that of the other joint methods. The high availability of UD-CF/PA6 rivet as mechanical fastener was proved.

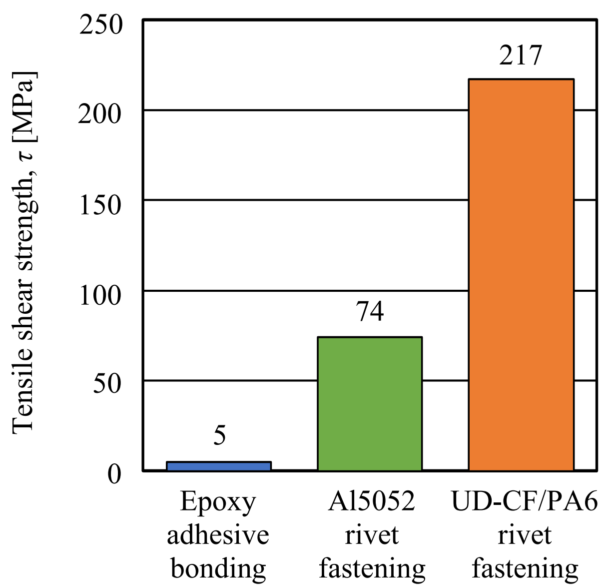


Figure.13 Comparison of single lap tensile shear strength by various joining methods.

3.5 Pull through strength

Figure.14 shows the pull through strength test specimen which UD-CF/PEEK laminates was fastened by UD-CF/PA6 rivet in the case of the horizontal heating.

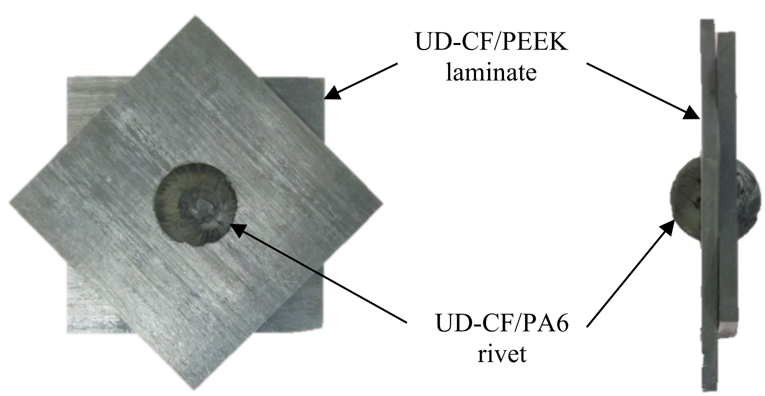


Figure.14 Photograph of pull through strength test specimen by UD-CF/PA6 rivet fastening.

Figure.15 shows the comparison of pull through strength joined by ultrasonic welding and UD-CF/PA6 rivet fastening. The material used for test specimen was UD-CF/PEEK laminate. The ultrasonic welding is performed at a frequency of 40kHz and a spot diameter of 6 mm. The UD-CF/PA6 rivet was destruction at the rivet head in pull through strength test. The rivet exhibited a high pull through strength by the effect of the rivet head reinforced with fiber against. In case of ultrasonic welding specimen, thermal decomposion of layers occured in the inside of UD-CF/PEEK laminated plate. As a result, the value is low due to the ultrasonic welding energy loss.

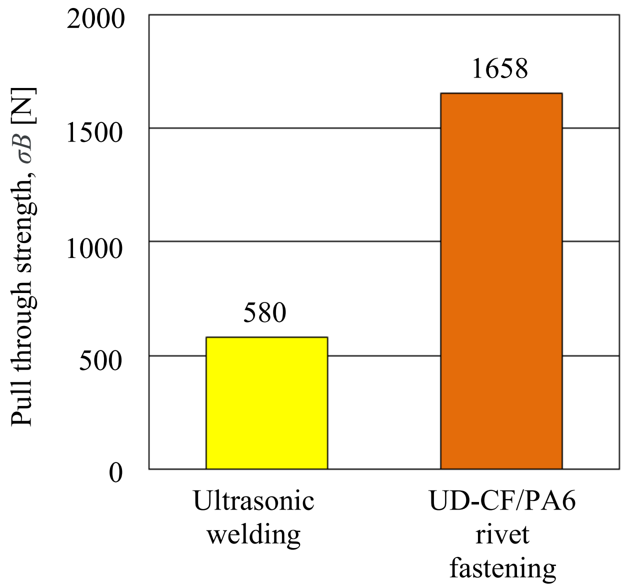


Figure.15 Comparison of the pull through strength test specimen by varied joining methods.

4. SUMMARY

This study proposed a new method for fastening CFRTP rivets, using a portable fastening system with compact servo press. Molding processes for CFRTP using high precision servo press are extremely, significant for improved accuracy of reproduction with processing technologies and molding processes. In this study, the result revealed the relationship between the heating process and material characteristics in UD-CFRTP rivet, using the infrared heating device and the portable fastening system with servo press. In case of UD-CFRTP rivet, mechanical strength was high because unidirectional carbon fiber was orientated continuously within the matrix polymer. The conclusions of this study are follows.

1, The rivet head shape and rivet fastening were formed by the servo press unit and the pressing mold. Rivet fastening operation controlled and monitored the tightening load in the rivet fastening work and showed optimum conditions for rivet fastening.

2, A near-infrared heater was used for heating source of UD- CFRTP round rod. From heating results, that became clear difference of in a heating process arise by the heating position of the infrared heater. The difference of the temperature distribution was affected on the deformation behavior and fiber orientation of UD-CFRTP rivet head.

3, A UD-CF/PA6 rivet fastening had extremely higher shear strength than a conventional of aluminum rivet and epoxy adhesion. The tensile shear strength of the UD-CF/PA6 rivet was 200MPa, which was higher than aluminum rivet and epoxy adhesion.

4, The structure where rivet head and body are united by continuous carbon fibers, consequently the CFRTP rivet joining is increased extremely high durability toward shear force. The UD-CF/PA6 rivet exhibited a high pull through strength by the effect of the rivet head reinforced with fiber against.

The high availability of UD-CFRTP rivet as mechanical fastener was shown from these results. The next step in this study is to investigate the dependence of mechanical strength on the fastening process, including the forming loads and heating equipment, and the process of fastening CFRTP rivets.

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