SERVO-PRESS FORMING PROCESS AND DAMAGE BEHAVIORS OF CFRTP RIVET HEAD PREPARED USING UD-CF/PEEK ROD

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Keywords: CF/PEEK, Rivet head, Servo-press forming, Tensile test, Damage behavior

ABSTRACT

In this study, a novel CFRTP rivet head servo-press thermoforming apparatus using two servo-press units and a ring-shaped heater in the die was developed and the CFRTP rivet head was thermoformed using unidirectional carbon fiber reinforced polyetheretherketone (CF/PEEK) round rod prepared by prepreg tape thermal pultrusion process. Thermoforming force and displacement during rivet head thermoforming and die clamping force and displacement of the concave die of lower die were controlled individually and precisely by upper and lower servo-press units, then those could be monitored during rivet head thermoforming. Two types of die structures for heating of CF/PEEK round rod were used, and two shapes of rivet heads such as (a) Flat rivet head and (b) Rosette rivet head were used for the comparison. The effects of heat keeping time, thermoforming load and head shape on CF/PEEK rivet head thermoforming process behavior were evaluated by dimensions and density of each part of CF/PEEK rivet, thermoforming load-displacement curve, and the rivet head tensile test. Also, their damage behavior was investigated by non-contact strain filed measurement and the cross-sectional observation.

1 INTRODUCTION

Carbon fiber reinforced thermoset plastic (CFRTS) composites are mostly joined by adhesive bonding. While carbon fiber reinforced thermoplastic (CFRTP) ones are not suitable for adhesive bonding due to their low chemical bonding strength. Therefore, the fusion joining methods such as electric-resist welding, induction welding and ultrasonic welding have been proposed recently. However, only adhesive bonding or welding does not provide sufficient reliability in strength because fatigue and impact loading can cause interlaminar delamination, in particularly multimaterial joining. On the other hand, mechanical fastening with bolts or rivets is high reliable and easy disassemble. However, metallic fasteners have serious problems such as high fastening workload, increased weight, electrolytic corrosion, and damage failure around the drilled hole. Therefore, the authors believe that multi-joining with adhesive bonding or fusion bonding and mechanical fastening is particularly useful for joining thermoplastic CFRP as an improvement measure. Recently, a rivet fastening method in which CFRTP pultruded round rod are electrically heated in a die has been developed to reduce the weight of fasteners and improve their corrosion resistance [1]. The authors have also developed a rivet head thermoforming method from CFRTP pultruded round rod by near infrared ring-shaped heater and a highly practical robotic fastening system using this thermoforming process [2]. This heating method is non-contact, compact and lightweight, it has practical advantages such as being easy to mount on a robot head, it is not easy to heat the rod part inside the fixing tool and the large-diameter rod due to heating from the rod surface, which needs to be improved [3,4].

In this study, a novel CFRTP rivet head servo-press thermoforming apparatus using two servo-press units and a ring-shaped heater in the die was developed and the CFRTP rivet head was thermoformed using unidirectional carbon fiber reinforced polyetheretherketone (CF/PEEK) round rod prepared by prepreg tape thermal pultrusion process. The effects of heat keeping time, thermoforming load and head shape on CF/PEEK rivet head thermoforming process behavior were evaluated by dimensions and density of each part of CF/PEEK rivet, thermoforming load-displacement curves, and the rivet head tensile test. The damage behavior was also investigated by non-contact strain filed measurement and the cross-sectional observation.

2 EXPERIMENTAL MATERIALS AND METHODS

2.1 CF/PEEK round rod

The experimental material used for thermoforming of rivet head is CF/PEEK round rod as shown in Figure 1. The CF/PEEK round rod (d_0=ϕ6.5mm) is fabricated by thermal pultrusion process using CF/PEEK prepreg sheet (Toray Advanced Composites, Cetex® TC1200, fiber volume fraction V_f=59%, glass transition temperature T_g=143°C, melting temperature T_m=343°C). The laboratory-scale thermal pultrusion apparatus with specific compressive insert die was developed originally. However, the CF/PEEK round bar is not perfect circle but elliptical shape, and the outer diameter of round rod was varied from -5μm to +30μm. Then it is turned close to a perfect circle shape by lathe machining, and round rod with and d_1=6.42±0.05mm in outer diameter and l=60±0.1mm in length was prepared for thermoforming of rivet head. Cross-sectional images of CF/PEEK round rod are shown in Figure 2. Carbon fibers are observed to be uniformly dispersed inside the round rod, and no voids and layer structures are observed, indicating that the round rod with high density was prepared by thermal pultrusion process.

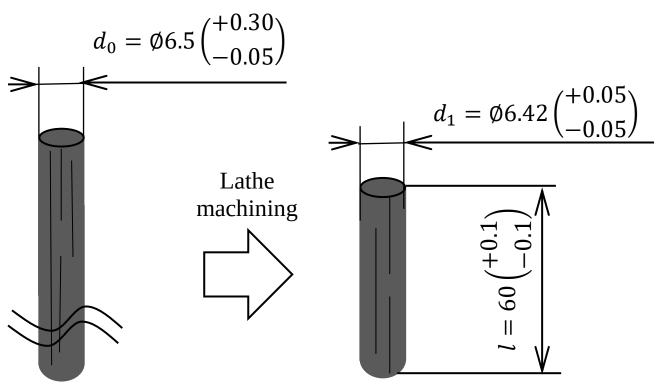


Figure 1: CF/PEEK round rod used for rivet forming.

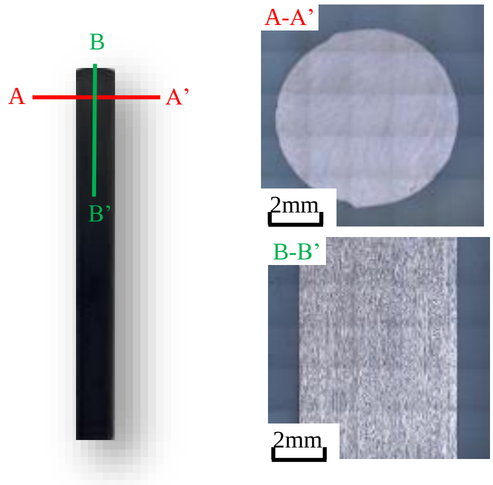


Figure 2: Sectional images of CF/PEEK rod.

2.2 Servo-press thermoforming apparatus for rivet head

Servo-press thermoforming apparatus for CF/PEEK rivet head as shown in Figure 3 was developed. This apparatus consists of two servo-press units (Dai-ichi Dentsu Ltd., DPS-101R3-30FB-X, Max load: p_{Max}=10kN, Rated load: p_r=2.5kN, Max pressing velocity: v_{Max}=222mm/s, Max stroke: L=200mm, Repeated positioning accuracy: y=±0.1mm) installed on upper and lower side of the die, and uses ring-shaped heater (Square Ltd., RH20F45K, 220V-300W) placed inside lower die. The die for thermoforming CF/PEEK rivet head consists of upper die, medium die and lower die. Upper die has a punch for thermoforming CF/PEEK rivet head, and lower die has a concave die for thermoforming the rivet head shape. Interchangeable concave die enables thermoforming of various shapes of CF/PEEK rivet heads. The ring-shaped heater placed in the lower die can stably heat the entire CF/PEEK round rod. The upper servo-press unit moves the heated CF/PEEK round rod through a cylinder in the mold and pressure it into the recess of the lower die to thermoform the rivet head shape. The thermoforming force and displacement during rivet head thermoforming and the clamping force and displacement of the concave mold of the lower die are individually and precisely controlled by the upper and lower servo-press units and can be monitored during rivet head thermoforming.

Two types of die structures as shown in Figure 4 were used for heating of CF/PEEK round rod. Type A is used to investigate the effects of varying the heat keeping time on head thermoforming, and Type B is used to investigate the effects of varying the thermoforming load and head shape on head thermoforming. Type B has a higher position of ring-shaped heater than Type A so that the lower portion of CF/PEEK round rod can be heated at the center of ring-shaped heater, and insulations are placed around ring-shaped heater.

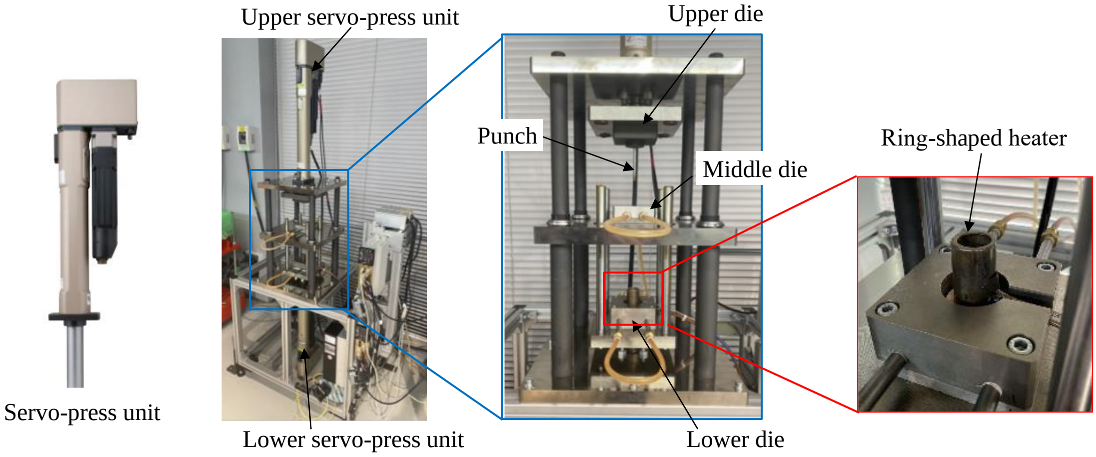


Figure 3: Servo-press thermoforming apparatus for rivet head.

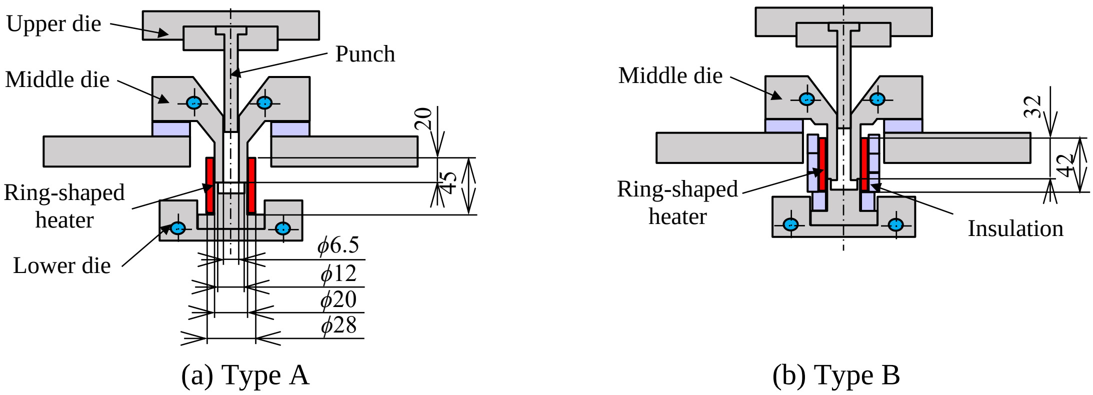


Figure 4: Two types of die structures for heating of CF/PEEK round rod.

2.3 Servo-press thermoforming method of rivet head

The thermoforming process of CF/PEEK rivet head is shown in Figure 5. The CF/PEEK rivet head thermoforming process consists of four steps: (i) CF/PEEK round rod is inserted into a middle die. (ii) The lower servo-press unit raises the lower die, clamps the middle die and the lower die, and simultaneously heats the cavity of the lower die and the lower part of the middle die to above the melting point of PEEK polymer with a ring-shaped of heater inside the die. (iii) The upper die with punch is lowered under precise-control by the upper servo-press unit. The CF/PEEK round rod is then passed through the middle die to fill the cavity of the lower die and cooled below the glass transition temperature of PEEK polymer before forming the rivet head. (iv) The lower servo-press unit descends to release the lower die from the middle die. The upper servo-press then moves the upper die downward and the punch ejects the CF/PEEK rivet from the middle die.

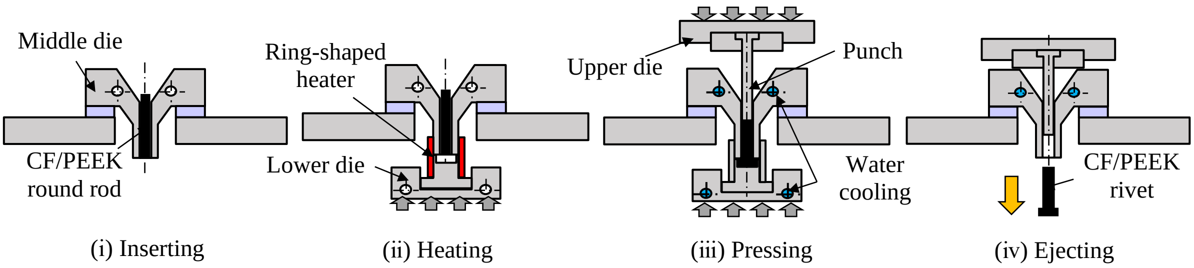
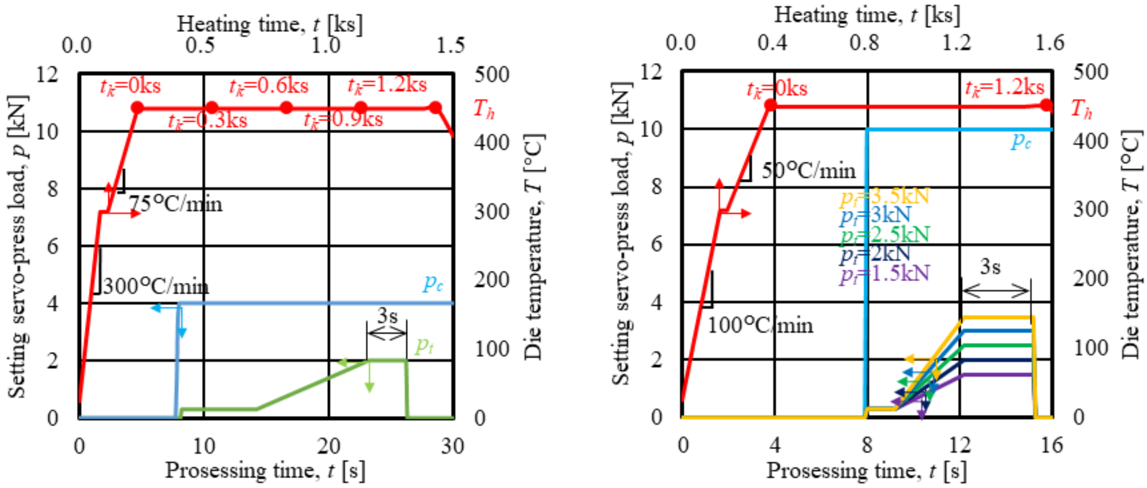


Figure 5: Thermoforming process of CF/PEEK rivet head.

In this study, the effects of heat keeping time and thermoforming load on the thermoforming of CF/PEEK rivet heads were investigated. The effect of the heat keeping time was investigated by setting the servo-press load of the upper servo-press unit to p_t=2kN, one of the lower servo-press unit to p_c=4kN, pressing velocity of the upper servo-press to v=1mm/s, the setting temperature of the ring-shaped heater to T_h=450°C, and the heat keeping time to t_k=0.3, 0.6, 0.9, and 1.2ks. The effect of the thermoforming load was investigated by setting the servo-press load of the upper servo-press unit to p_t=1.5, 2, 2.5, 3 and 3.5kN, one of the lower servo-press unit to p_c=10kN, the pressing velocity of the upper servo-press unit to v=5mm/s, the setting temperature of the ring-shaped heater to T_h=450°C, and the heat keeping time to t_k=1.2ks. The setting of servo-press units and the ring-shaped heater that were used to investigate the effects of the heat keeping time and the thermoforming load on the thermoforming of CF/PEEK rivet head are shown in Figure 6(a) and Figure 6(b).



(a) Effect of heat keeping time (b) Effect of thermoforming load

Figure 6: Setting of servo-press units and ring-shaped heater.

2.4 Head tensile test method of rivet

Mechanical property of CF/PEEK rivet head was evaluated by the tensile test as shown in Figure 7. The head part of the CF/PEEK rivet was fixed to a specific jig and the shank part of the rivet was gripped, and a tensile load was applied at a crosshead speed of v=1mm/min using a universal material testing machine (Shimadzu Co., AG-50kNXDplus). To investigate the damage behavior of CF/PEEK rivet head, the cross-section of CF/PEEK rivet head was observed before and after the head tensile test using a digital microscope (OLYMPUS Co., DSX500). Furthermore, CF/PEEK rivet head with a longitudinal half-section was subjected to the head tensile test, and the strain generated on CF/PEEK rivet head surface was measured using a three-dimensional strain distribution measuring device (GOM, Aramis^{TM}) with digital image correlation (DIC) method.

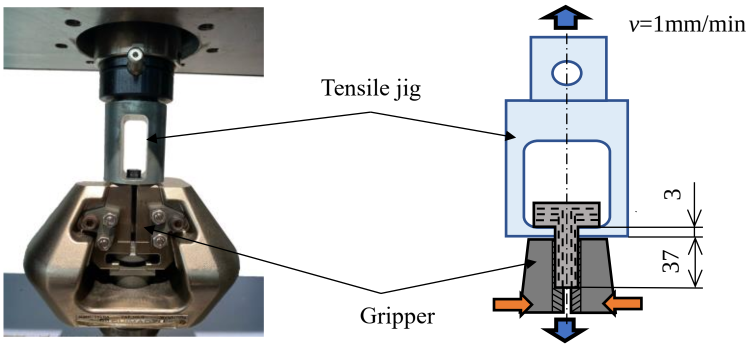


Figure 7: Head tensile test method.

3 RESULTS AND DISCUSSIONS

3.1 Temperature distribution in round rod

The temperature distribution inside the CF/PEEK round rod was measured with a thermocouple inserted into the round rod when heated with a ring-shaped heater attached to the heating die. Figure 8 shows the internal structure and the measuring results of two types of heating dies, Type A and Type B. For Type A, the maximum temperature reaches to T=320°C at y=1mm, while for Type B, the temperature reaches to T=340°C at y=20mm, which is above the melting point of PEEK polymer. It is found that type B has a higher temperature rise inside the CF/PEEK round rod than type A.

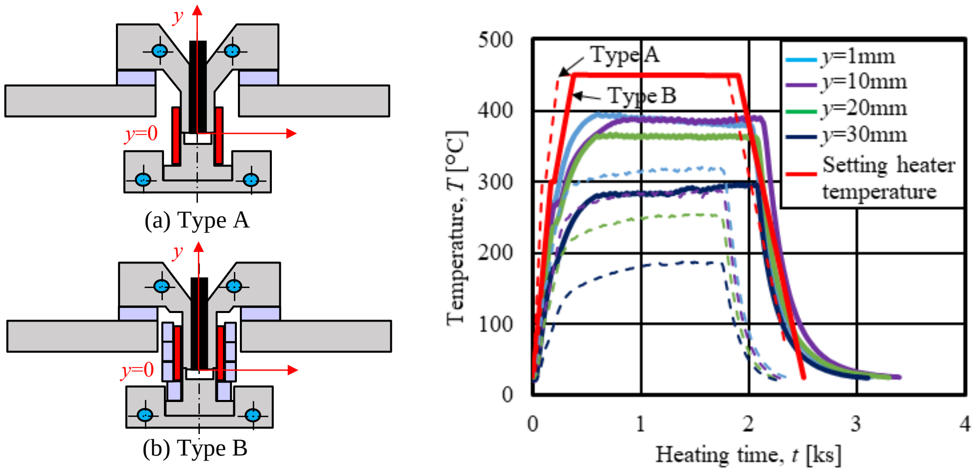


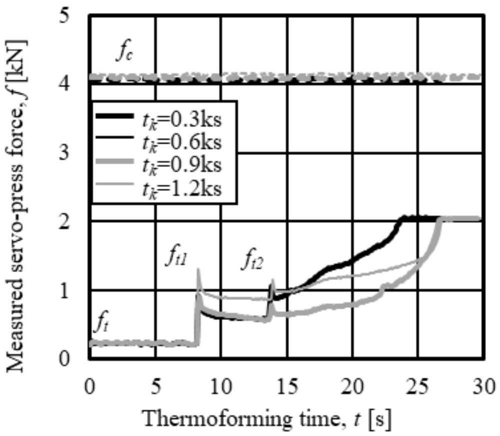
Figure 8: Two types of heating dies and temperature distribution in CF/PEEK round rod.

3.2 Effect of heat keeping time (Type A)

3.2.1 Thermoforming behavior of rivet head (Type A)

Figure 9 shows the thermoforming force (f_t) and die clamping force (f_c) measured by the upper and lower servo-press units when thermoforming of the CF/PEEK rivet head while varying the heat keeping time. The first peak force (f_{t1}) is the maximum frictional force exerted when the CF/PEEK round rod moves inside the middle die. The second peak force (f_{t2}) is the force generated when the tip of the CF/PEEK round rod contacts the lower die. Though the die clamping force (f_c) is slightly higher than the set load, the control is almost stable, and it can be seen that the thermoforming force (f_t) has little effect.

Figure 10 shows the results of the first peak force (f_{t1}) and kinematic frictional force (f_{t1}'). The first peak force (f_{t1}) is more affected by the outer diameter of the CF/PEEK round rod and its error than the heat keeping time, so it is necessary to fully consider the dimensional accuracy when processing the outer circumference of the CF/PEEK round rod.



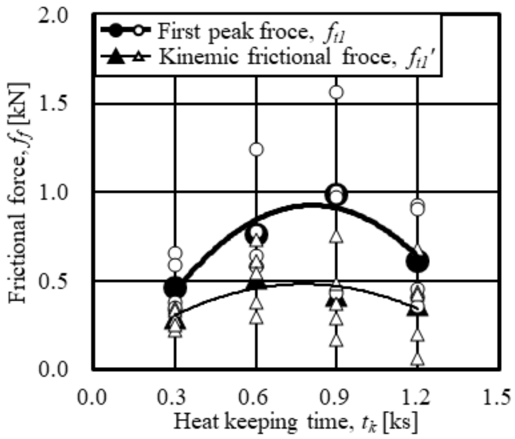
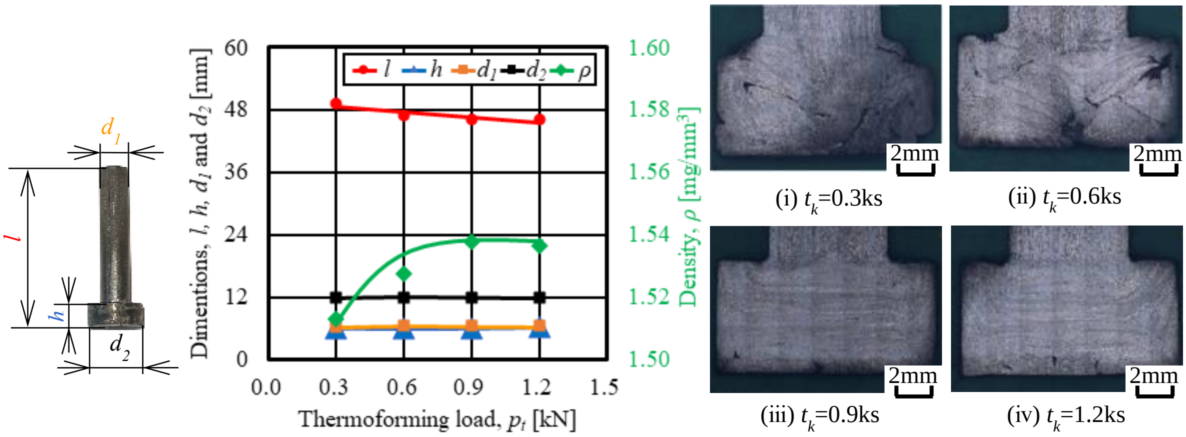


Figure 9: Thermoforming and die clamping forces. Figure 10: First peak and kinematic frictional forces.

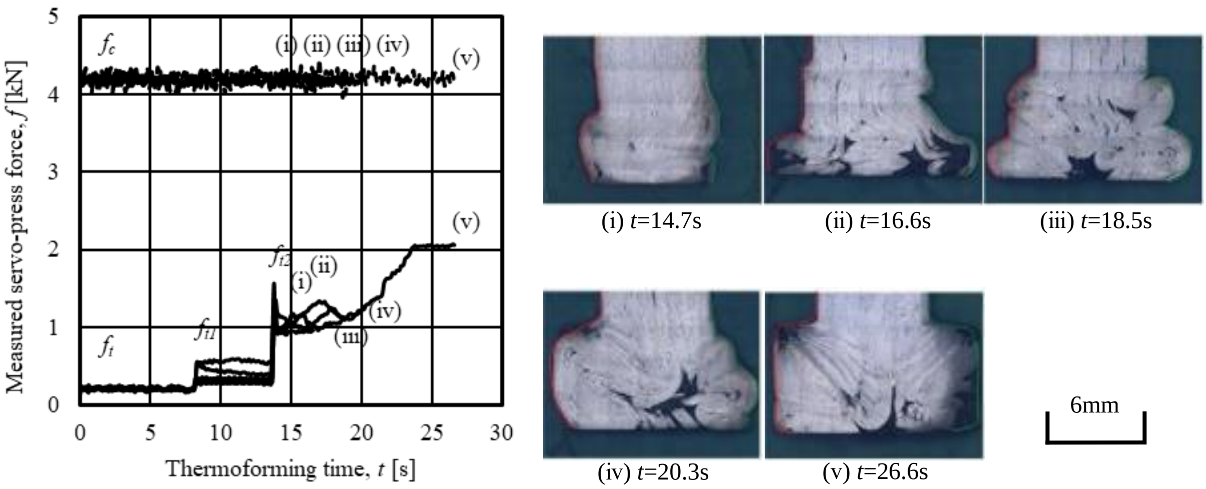
Figure 11(a) and Figure 11(b) shows the dimensions and density of each part of the CF/PEEK rivet and cross-sectional images of the CF/PEEK rivet head when the head was thermoformed by changing the heat keeping time. As shown in Figure 11(a), the density of CF/PEEK rivets tended to increase as the heat keeping time. On the other hand, the head outer diameter (d_1) and head height (h) of CF/PEEK rivet were almost constant regardless of the heat keeping time, while the rivet length (l) tended to decrease. This is probably because the amount of PEEK polymer melted at the bottom of the CF/PEEK round rod increased and the PEEK polymer filling rate at the top increased, as shown in cross-sectional images in Figure 11(b).



(a) Dimensions and density (b) Cross-sectional images

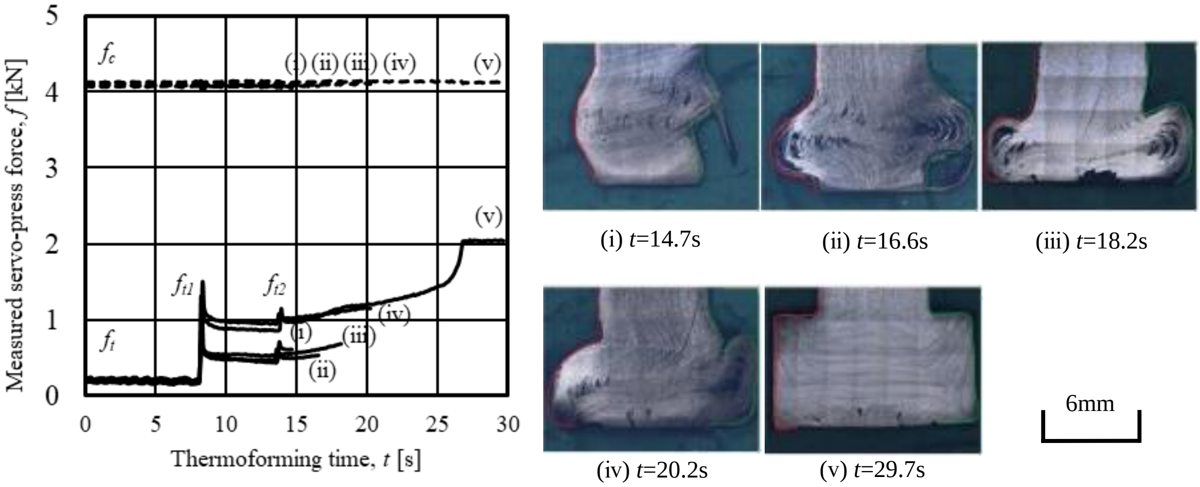
Figure 11: CF/PEEK rivet thermoformed by changing the heat keeping time.

Figure 12(a) and Figure 13 (a) show the thermoforming force (f_t) and die clamping force (f_c) measured by the upper and lower servo-press units during head thermoforming when the heat keeping time is t_k=0.3ks and 1.2ks. Figure 12(b) and Figure 13(b) show the cross-sectional images of the CF/PEEK rivet head thermoforming stage when the heat keeping time is t_k=0.3ks and 1.2ks. As shown in Figure 12(b), the PEEK polymer in the thermoformed portion of the head is not completely melted and buckles at the softened portion, resulting in the thermoformed head. As shown in Figure 13(b), only the tip of CF/PEEK round rod is not completely melted, and the surrounding melted portion is thermoformed into the head shape.



(a) Thermoforming and die clamping forces (b) Cross-sectional images of CF/PEEK rivet head

Figure 12: Rivet head thermoformed after heating for t_k=0.3ks.



(a) Thermoforming and die clamping forces (b) Cross-sectional images of CF/PEEK rivet head

Figure 13: Rivet head thermoformed after heating for t_k=1.2ks.

3.2.2 Head tensile test of rivet (Type A)

Figure 14 and Figure 15 show the load-displacement curves and the maximum head tensile load (P_{Max}) obtained from head tensile test of CF/PEEK rivet thermoformed with varying the heat keeping time. As shown in Figure 14, the head tensile load becomes nonlinear near the displacement amount δ=0.35mm, but there is almost no difference due to the heat keeping time, and after reaching the maximum head tensile load, the load gradually decreases. In addition, as shown in Figure 15, the maximum head tensile load was very low at P_{Max}=2.5kN at the heat keeping time of t_k=0.3ks, but remained almost constant at P_{Max}=4.5kN at t_k=0.6ks or longer, it showed a high head tensile load. Therefore, it was found that the maximum head tensile load is affected by the heat keeping time. Figure 16 shows the cross-sectional images of the CF/PEEK rivet head after head tensile testing. At heat keeping time was t_k=0.3ks and 0.6ks, longitudinal cracks due to fiber orientation were observed inside the rivet head, and at heat keeping time t_k=0.9ks and 1.2ks, delamination occurred at the bottom inside the rivet head.

The damages to the CF/PEEK rivet heads thermoformed at heat keeping time of t_k=0.3ks and 1.2ks, which was clarified by the results of this experiment is described in detail in the next chapter.

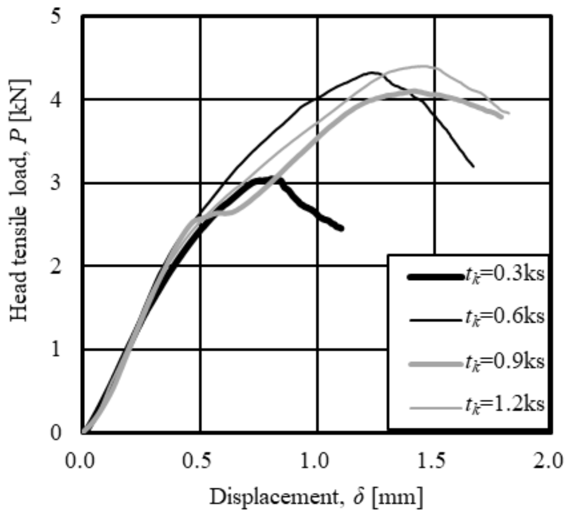


Figure 14: Load-displacement curves.

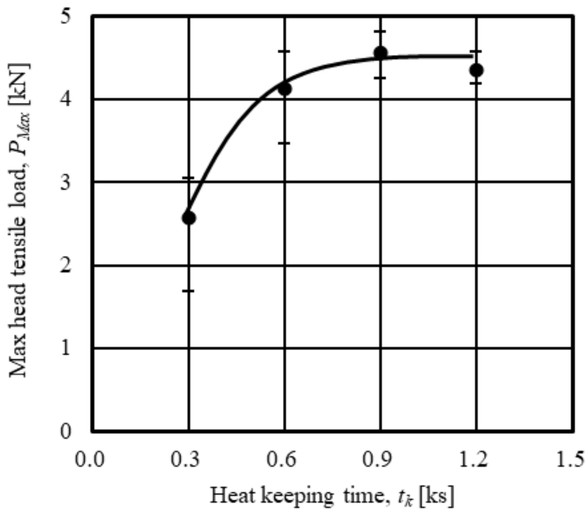
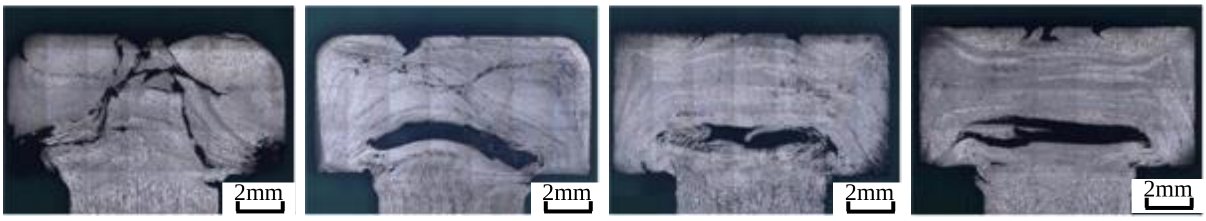


Figure 15: Max head tensile load vs. heat keeping time.



(i) t_k=0.3ks (ii) t_k=0.6ks (iii) t_k=0.9ks (iv) t_k=1.2ks

Figure 16: Cross-sectional images of CF/PEEK rivet head after head tensile test.

The CF/PEEK rivet heads thermoformed at the heat keeping time of t_k=0.3ks and 1.2ks were polished to the longitudinal half-section and the head tensile tests were performed. Figure 17 shows the load-displacement curves and the longitudinal strain distributions obtained from the test. The maximum head tensile load of the CF/PEEK rivet thermoformed at heat keeping time of t_k=0.3ks is as small as P=0.5kN, and the longitudinal strain rises sharply at the initial stage of the small displacement around δ=0.2mm. On the other hand, the maximum head load of the CF/PEEK rivet thermoformed at the heat keeping time of t_k=1.2ks reaches P=1.6kN, which is about three times higher than that of the rivet thermoformed at t_k=0.3ks, and the longitudinal strain increased when the displacement was more than δ=0.6mm.

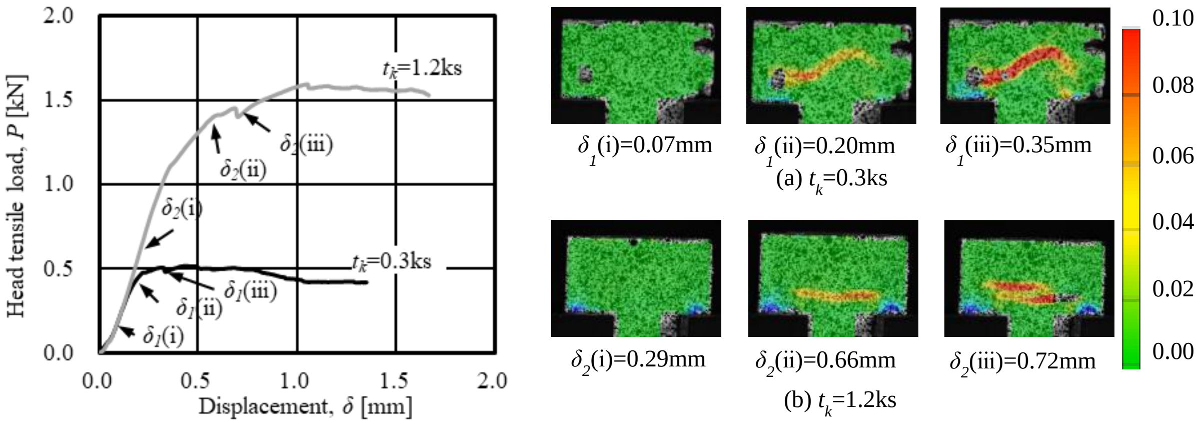


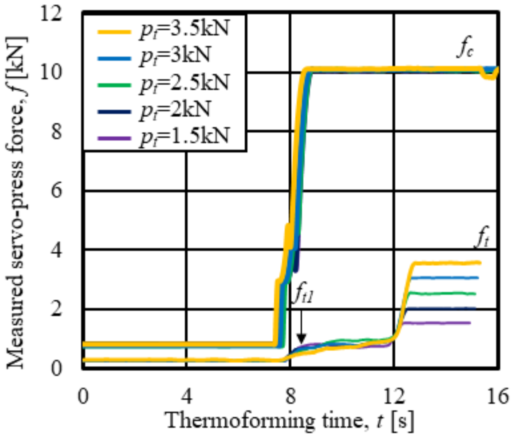
Figure 17: Load-displacement curves and longitudinal strain distribution images of CF/PPEK rivet.

3.3 Effect of thermoforming force (Type B)

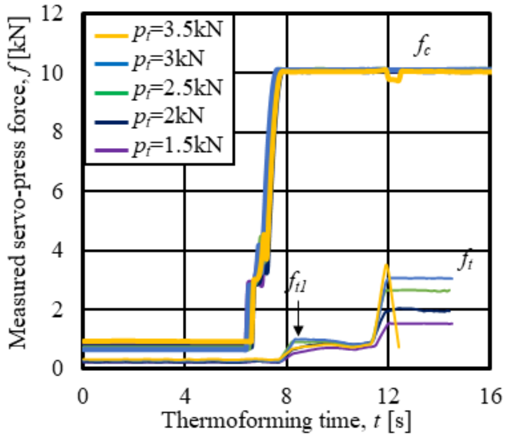
3.3.1 Thermoforming behavior of rivet head (Type B)

Two shapes of rivet heads, Flat and Rosette, were thermoformed at various thermoforming loads (p_t). Figure 18 shows the thermoforming force (f_t) and die clamping force (f_c) measured by the servo-press units during thermoforming. The first peak force (f_{t1}), the maximum frictional force exerted by the CF/PEEK round rod as it moves in the middle die, is constant at about 0.5kN. In addition, the second peak force (f_{t2}), which is the force applied when the tip of CF/PEEK round rod comes into contact with the lower die, was very small and could not be measured. This is probably because the CF/PEEK round rod is sufficiently melted. When the thermoforming load (p_t) was less than p_t=3kN, the die clamping force (f_c) was stable, and the head could be thermoformed.

Figure 19 and Figure 20 show the cross-sectional images of the CF/PEEK rivet head and the dimensions and density of each part of the CF/PEEK rivet when thermoforming is performed at various thermoforming loads. Density tended to increase up to a thermoforming load of p_t=3kN, but above a thermoforming load of p_t=3.5kN, the density decreased, burrs occurred, and rivet head height increase by about 0.2mm. Due to the disturbance of the die clamping force (f_c), the polymer pressure expanded the gap between the middle die and the lower die, and it is thought that burrs and a decrease in density occurred inside the rivet head. Both shapes of rivet heads showed the same trends.

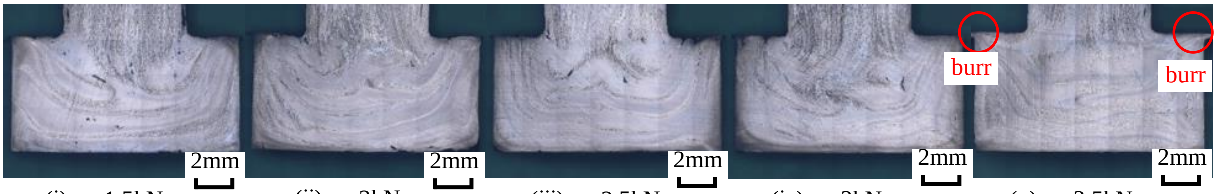


(a) Flat rivet head



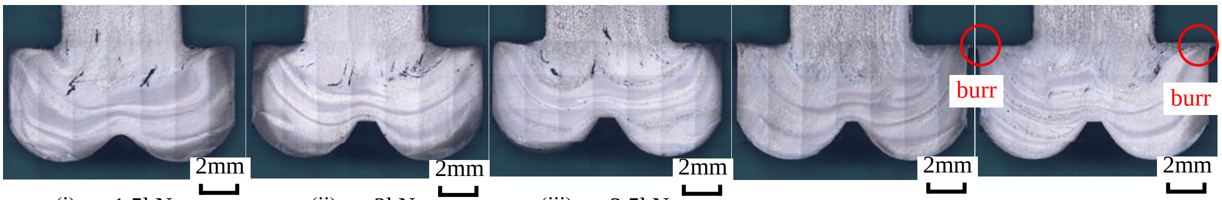
(b) Rosette rivet head

Figure 18: Thermoforming and die clamping forces.



(i) p_t=1.5kN (ii) p_t=2kN (iii) p_t=2.5kN (iv) p_t=3kN (v) p_t=3.5kN

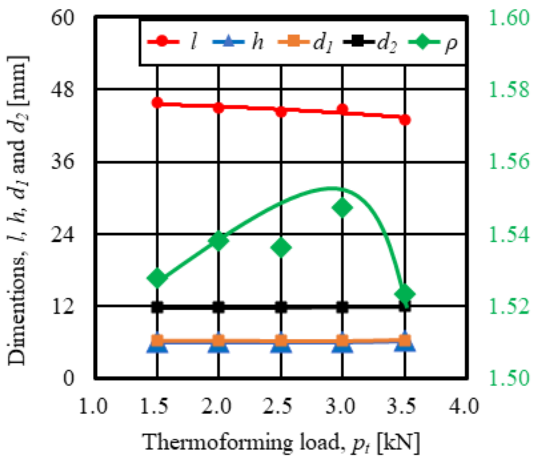
(a) Flat rivet head



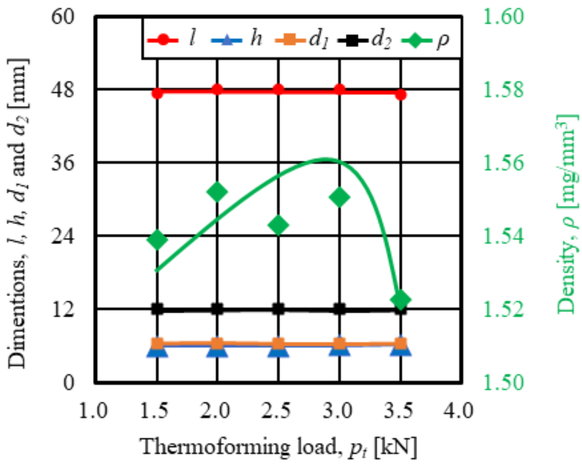
(i) p_t=1.5kN (ii) p_t=2kN (iii) p_t=2.5kN (iv) p_t=3kN (v) p_t=3.5kN

(b) Rosette rivet head

Figure 19: Cross-sectional images of CF/PEEK rivet head.



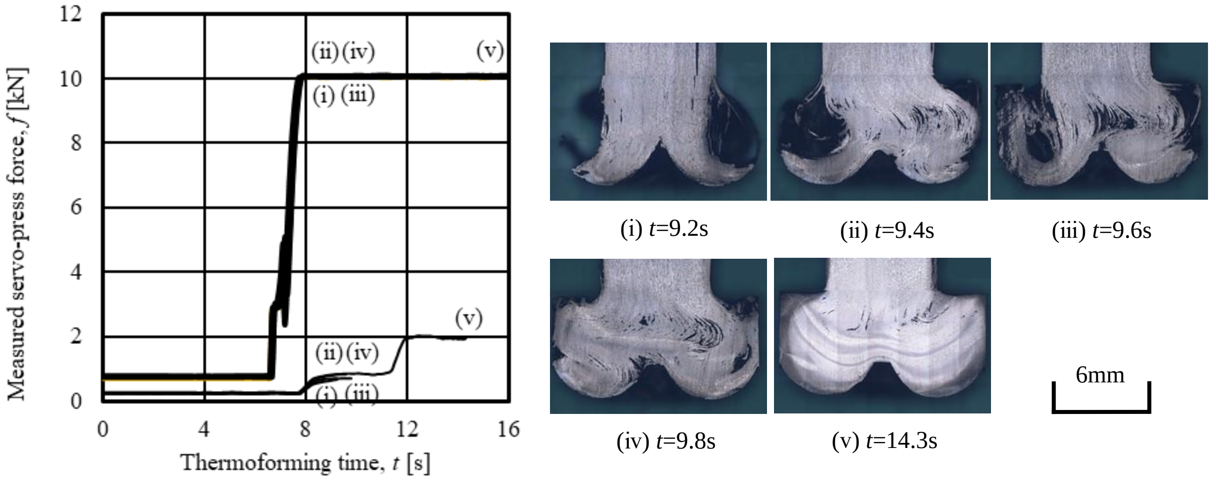
(a) Flat rivet head



(b) Rosette rivet head

Figure 20: Dimensions and density of each part of CF/PEEK rivet.

The thermoforming force (f_t) and die clamping force (f_c) measured by the servo-press units during head thermoforming of the Rosette rivet are shown in Figure 21(a). Cross-sectional images of the rivet head thermoforming stage are shown in Figure 21(b). The trigger initially opens the fiber along the die, but then buckled and the head is thermoformed, as shown in Figure 21(b). It is believed that uniform Rosette rivet head can be thermoformed by reducing the head height, thus preventing fiber buckling and thermoforming.



(a) Thermoforming and die clamping forces (b) Cross-sectional images of CF/PEEK rivet head

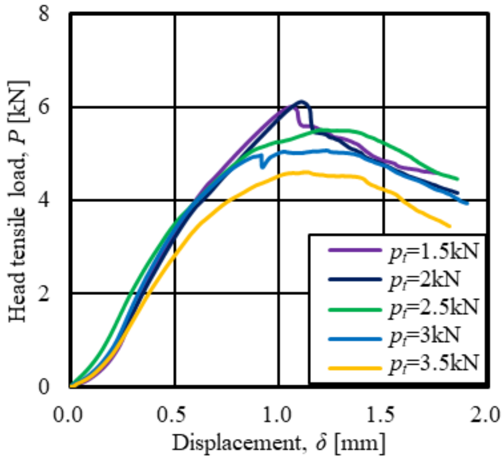
Figure 21: Rosette rivet head thermoforming (p_t=2kN).

3.3.2 Head tensile test of rivet (Type B)

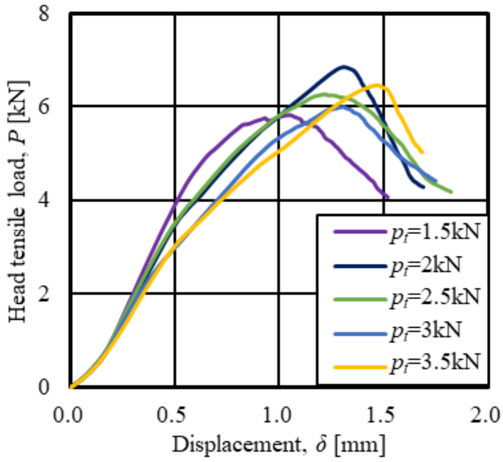
The load-displacement curves obtained from head tensile tests of Flat and Rosette CF/PEEK rivet heads thermoformed at various thermoforming loads are shown in Figure 22(a) and Figure 22(b). The maximum head tensile load (P_{Max}) in that test is shown in Figure 23(a) and Figure 23(b). As shown in Figure 22(a), the head tensile load of the Flat rivet head becomes nonlinear around the displacement of δ=0.4mm decreased sharply. On the other hand, when the thermoforming loads was above the thermoforming load of p_t=2.5kN, the load decreases slowly after reaching the maximum head tensile load. As shown in Figure 22(b), the head tensile load of the Rosette rivet head became nonlinear around δ=0.4mm, similar to the Flat rivet head. Then, after reaching the maximum head tensile load for all Rosette rivet head thermoformed under all conditions, the head tensile load decreased slowly.

As shown in Figure 23(a), the maximum head tensile load of the Flat rivet head was as high as P_{Max}=6.1kN when the thermoforming load was p_t=2kN, and the maximum head tensile load decreased. However, even if the thermoforming load was p_t=3.5kN, the maximum head tensile load was as high as P_{Max}=4.6kN. As shown in Figure 23(b), when the thermoforming load p_t=2kN, and the maximum head tensile load of the Rosette rivet head reaches P_{Max}=6kN and the maximum head tensile load of the Rosette rivet head under other conditions is P_{Max}=6.8kN. The Rosette rivet head was found to be less sensitive to thermoforming loads.

Cross-sectional images of the Flat and Rosette CF/PEEK rivet head after head tensile testing are shown in Figure 24(a) and Figure 24(b). Both types of CF/PEEK rivet heads had similar fractures. The rivet heads with thermoforming load of p_t=1.5kN and p_t=2kN fractured mainly due to delamination inside the head. On the other hand, the rivet heads with thermoforming loads above p_t=2.5kN fractured due to numerous cracks that occurred in the lower part of the head. It is believed that the carbon fibers had already buckled and broken due to excessive thermoforming load. Therefore, the maximum head tensile load may have decreased with increasing thermoforming load for Flat rivet head, and did not decrease but did not increase for Rosette rivet head. In the future, the rivet head height should be varied to reduce buckling of the carbon fiber inside the head for thermoforming. In this way, the delamination inside the head may be suppressed and the maximum head tensile load may be increased.

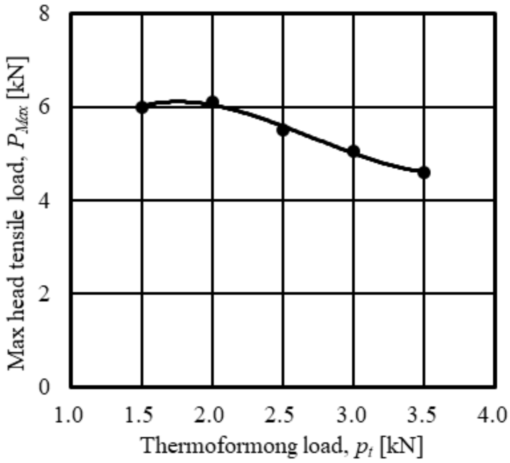


(a) Flat rivet head

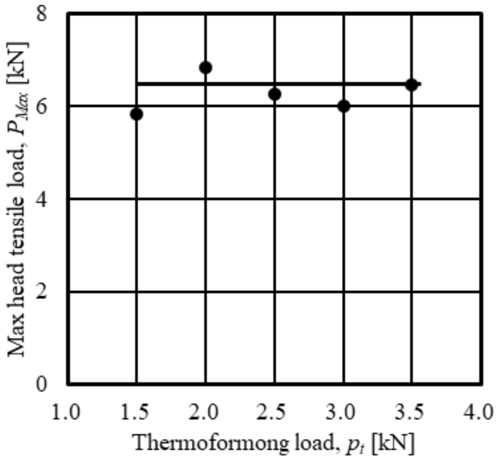


(b) Rosette rivet head

Figure 22: Load-displacement curves.

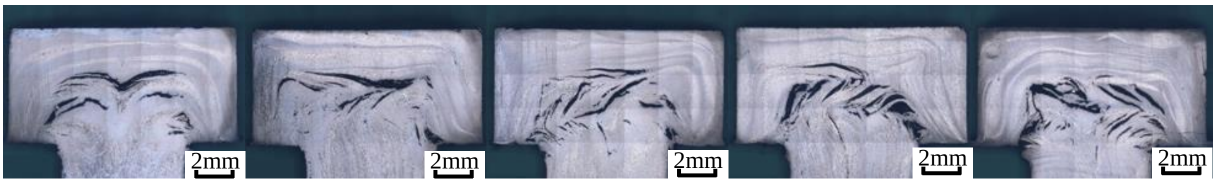


(a) Flat rivet head



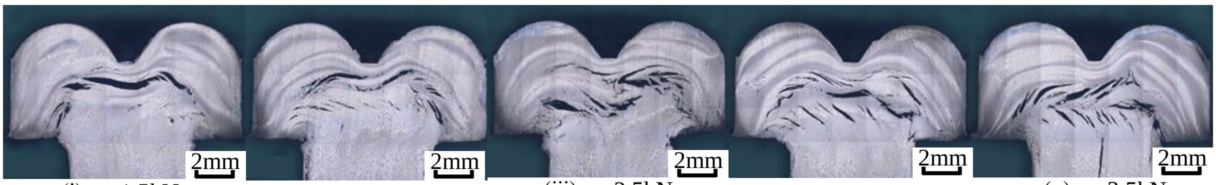
(b) Rosette rivet head

Figure 23: Max head tensile load vs. thermoforming load.



(i) p_t=1.5kN (ii) p_t=2kN (iii) p_t=2.5kN (iv) p_t=3kN (v) p_t=3.5kN

(a) Flat rivet head



(i) p_t=1.5kN (ii) p_t=2kN (iii) p_t=2.5kN (iv) p_t=3kN (v) p_t=3.5kN

(b) Rosette rivet head

Figure 24: Cross sectional images of CF/PEEK rivet head after head tensile test.

4 CONCLUSIONS

In this study, CF/PEEK round rods were heated with a ring-shaped heater attached to the heating die and thermoformed with the upper and lower servo-press units. As a result of investigating the effects of heat keeping time and thermoforming load on the thermoforming behavior of the CF/PEEK rivet head and damage behavior during the head tensile test, the following findings were obtained.

1. It is obvious from the experimental results of changing the heat keeping time that frictional resistance is generated when the heated CF/PEEK round rod moves through the die, and this resistance force changes depending on the heat keeping time. The head tensile strength was low at a heat keeping time of 0.3ks, but a stable high head tensile strength was obtained at a heat keeping time of 0.6ks or longer.
2. It was found that the damages behavior inside the head varies greatly depending on the heat keeping time. At a heat keeping time was 0.3ks, the head breaks due to the dispersion of longitudinal cracks, whereas with heating, the head breaks due to delamination when the heat keeping time was 1.2ks.
3. It is found from the experimental results of changing the heating position of the ring-shaped heater and changing the thermoforming load and head shape, the frictional resistance when the heated round rod moved inside the die was almost constant.
4. The head tensile strength of the Flat rivet reached its maximum when the thermoforming load was 2kN, and thereafter, as thermoforming load was increased, the head tensile strength increases even though the high head tensile strength was maintained.
5. The state of damage inside the rivet head depends on the thermoforming load. At thermoforming load of 1.5kN and 2kN, rivet failure was dominated by delamination within the head, whereas for thermoforming load was 2.5kN and above, rivet failure occurred along the direction of buckled carbon fibers. Numerous cracks were observed at the bottom of the head.
6. The head tensile strength of the Rosette rivet was not affected by the thermoforming load and remained nearly constant even at high head tensile loads. In addition, there was no significant difference in the state of breakage of the rivet head, and delamination inside the head was predominant.

In the future, the thermoforming and damage behavior of the rivet head should be investigated in more detail when the fiber orientation of the rod and the height of the thermoformed head are varied.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Economy, Trade and Industry (METI), Strategic Foundational Technology Improvement Support Operation 2019-2021. The authors would like to thank Dai-ichi Dentsu Ltd. and METI for the grant.

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