Materials Research Proceedings 44 (2024) 698-707 https://doi.org/10.21741/9781644903254-75

Hemming for improvement of joint strength in aluminium alloy and carbon fibre-reinforced thermoplastic sheets

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Keywords: Metal/Polymer, Joining, Hemming, Carbon Fibre-Reinforced Thermoplastic, Hot Pressing, Aluminium Alloy Sheet

Abstract. To increase the joint strength in hemmed aluminium alloy and carbon fibre-reinforced thermoplastic (CFRTP) sheets, two kinds of hemming processes were proposed. In a hemming process, hemming was combined with protrusions with structures on the surface on the aluminium alloy sheet. The protrusions with structure were firmly joined to the surface on the sheet by laser cladding with fine ceramic powders, and then the heated and softened CFRTP sheet material was compressed and infiltrating into the protrusions in hot pressing. In the other hemming process, hemming was combined with the aluminium alloy sheet with drilled holes. The heated and softened CFRTP was flowed into the holes in hot pressing. Each hot press condition was investigated. And then, the strength in the pull-out direction and the strength in the peel direction were measured and compared. The joint strengths by the proposed two hemming processes were larger than that by hemming only.

Introduction

To reduce carbon dioxide emissions, the reduction weight in automobile body parts is a method. To reduce the weight, using high specific materials such as ultra-high strength steel, aluminium alloy and carbon fibre-reinforced plastic (CFRP) is effective. It is not easy for automobile bodys to use single material because of the different requirements of each body part. Therefore, many kinds of joining processes are used for joining these materials in assembling automobile body. For joining overlapped two steel sheets, resistance spot welding [1] is generally used. For joining overlapped two aluminium alloy sheets, self-piercing riveting [2] tends to be used. For joining overlapped steel and aluminium alloy sheets, self-piercing riveting and a screw turning tend to be used [3]. The joining process is selected depending on not only sheet combination but also the requirements of joints.

For joining CFRTPs and metals, adhesive bonding [4] and mechanical fastening are conventionally used. Although adhesive bonding is effective for joining CFRTPs and metals, not only adhesive material, but also an adhesive application process and a curing process including temporarily fixing are required. In mechanical fastening, self-piercing riveting without pre-hole is possible to join CFRP and aluminium alloy sheets [5]. A clinching process, which is a method for joining aluminium alloy and CFRP as mechanical fastening without rivets, is placed two sheets in high temperature are pressed by a punch, and the sheets are joined with interlocking [6]. A hole-clinching process, which is using CFRP having a hole, is possible to join in room temperature [7]. On the other hand, CFRTPs and metals are possible to be joined by heating CFRTPs. Friction spot joining [8] and friction stir spot welding [9] are a joining method using the thermal energy generated by the friction between the rotating tool and the metal. Heat is transferred from the metal heated by friction to the CFRTP, and the plastic near the joint interface is heated and joined.

Hemming joints are one of the joints that using plastic deformation [10]. Hemming joint is a joining method in which the edges of the sheet metal that will become the outer sheet are folded back and the sheet that will be the middle sheet is sandwiched between sheets and it is used with bonding in joining automobile parts [11]. Hemming joints can be made by using metal sheet on the bending side and CFRTP on the sandwiching side. However, simply hemmed joint has the problem that the joining force is low because the only the frictional force between the sheets occurs.

In this study, two kinds of hemming processes for joining the aluminium alloy and CFRTP sheets were proposed to increase the joint strength. In these processes, hemming and hot press were used. The heating conditions in hot pressing was investigated to join without defects. And then, the strength in the pull-out direction and strength in the peel direction were measured and compared.

Hemming for improvement of joint strength

The hemming processes for improvement of the joint strength in the aluminium alloy and CFRTP sheets are shown in Fig. 1. The strength of the hemmed joint in the tension shearing and the peel directions are measured by a pull-out testing and a peel testing, respectively. The load of the hemmed joint is only generated by the frictional force between the aluminium alloy and CFRTP sheets. Therefore, two kinds of methods were proposed to improve joint strength using the anchor effect. The first hemming method was combined with protrusions with structures on the surface on the aluminium alloy sheet. The anchoring effect of the protrusions and carbon fibres improves the joining load [12, 13]. In this process, the protrusions with structure were firmly joined to the surface on the sheet by laser cladding with fine ceramic powders, and then the sheet was hemmed, finally the heated and softened CFRTP material was compressed and infiltrating into the protrusions in hot pressing. The second hemming method was combined with drilled holes in the aluminium alloy sheet. The anchoring effect of the flowed CFRTP material into the holes improves the load. In this process, the holes in the aluminium alloy sheet were obtained by drilling, and then the sheet was hemmed, finally the heated and softened CFRTP material was flowed into the hole cavities in hot pressing.

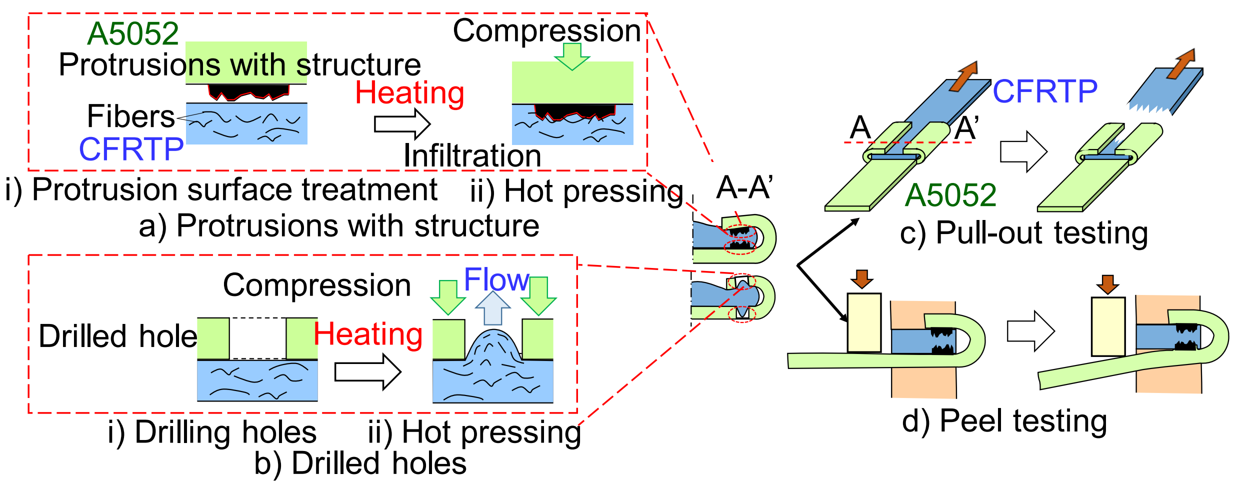

Fig. 1. Hemming processes for improvement of joint strength in aluminium alloy and CFRTP sheets.

Conditions for pull-out and peel tests

The used sheet materials were a 2 mm in thickness of aluminium alloy A5052-H sheet and a 3 mm in thickness of carbon fibre reinforced thermoplastic (CFRTP) sheet. The base material in CFRTP sheet was polyamide MXD6 with short fibres woven in one direction. The material properties are shown in Table 1.

In a pull-put testing, the tensile shear stress is measured by pull-out test specimen in Fig. 2(a). The CFRTP sheet were joined in both edges by hemming, and then the upper sheet was pulledout. In the peel testing, the peel stress was measured by pushing the hemmed specimen with a punch in Fig. 2(b). The CFRTP sheet were joined in an edge by hemming. In the both specimens, the sheet widths and the hemmed length were 20 mm and 6 mm, respectively.

Table 1. Material properties of sheets.

Sheet	Material	Thickness [mm]	Tensile strength [MPa]	Melting point [℃]	Fibre length [mm]
Outer	A5052-H	2.0	242	-	-
Inner	CFRTP (PAMXD6)	3.0	151 (Injection direction)	243	< 0.5

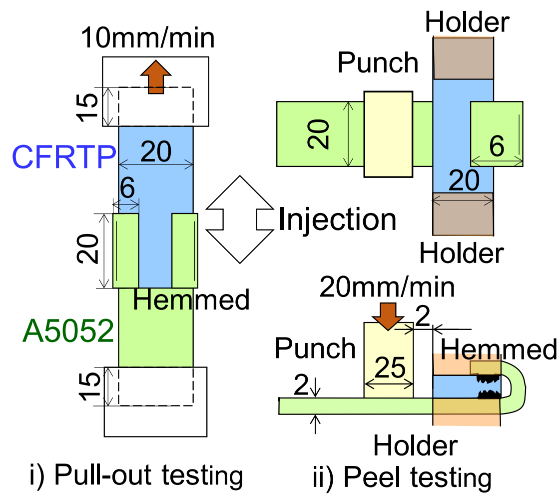

Fig. 2. Conditions for pull-out testing and peel testing.

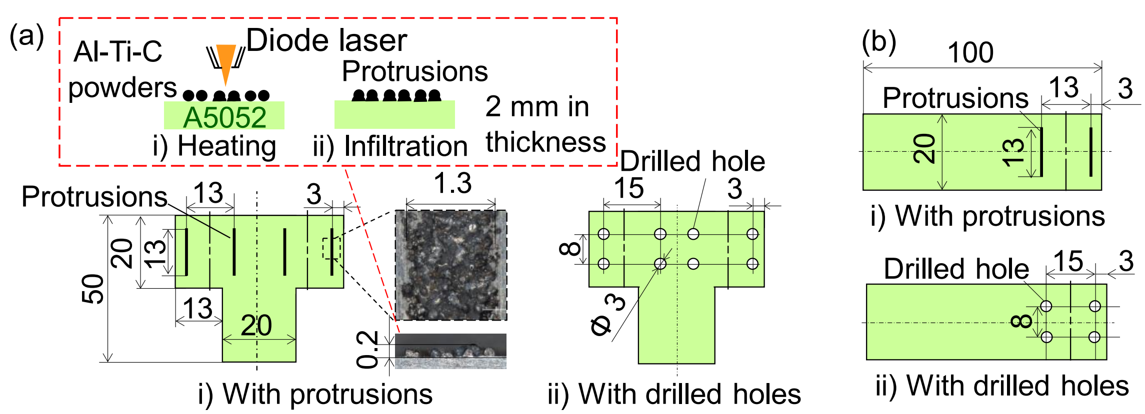

Fig. 3. Specimens for pull-out testing and peel testing.

The specimens for the pull-out testing and peel testing are shown in Fig. 3. The specimens by hemming with the protrusions and by hemming with the drilled holes were prepared for each testing. For hemming specimen with the protrusions, the protrusions, which was made of Al-Ti-C powders, were infiltrated four portions on the aluminium alloy surface. The length and width were 13 mm and 1.3 mm, respectively. For hemming specimen with the drilled holes, total eight holes with 3 mm in diameter were drilled in aluminium alloy sheet. The hemming specimens for peel testing in Fig. 3(b) were used with two portions of the protrusions and four holes, respectively.

Conditions for pull-out and peel tests

The joining process for improvement of the joint strength is shown in Fig. 4. The joining process consists of four-stage bending and hot press. In three-stage bending, aluminium alloy sheet was bent to 90º, 110º, 135º and 180º. Although A5052 was enough ductility to bend to 180º , a punch having sidewall to contact with the outer corner of the bending sheet was used[14]. In 180º-bending, the CFRTP sheet was inserted in bent aluminium alloy sheet. In hot pressing, the sheets were heated by the heated blocks on the aluminium alloy top and bottom surfaces. The heating temperature T_h in the heated blocks and holding force F_s were investigated to join the sheets. The holding time was 10 minutes, and heating temperature was reduced under -2Cº/min to 180ºC after holding time. After 180ºC, the specimens were cool to room temperature under holding force applied.

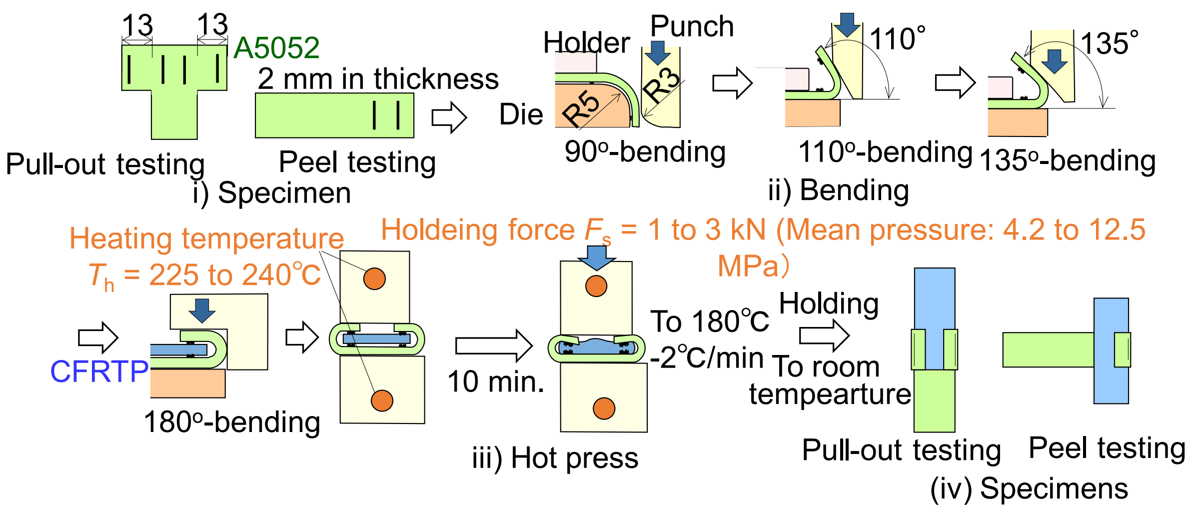

Fig. 4. Joining process for improvement of joint strength.

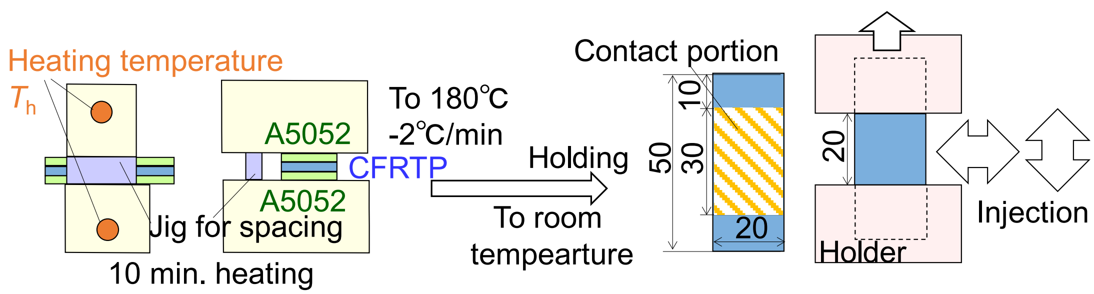

Fig. 5. Tension test conditions for CFRTP.

To investigate the material properties of CFRTP sheet after hot pressing, tension testing in room temperature of once heated CFRTP sheet was performed. The conditions of tension testing for CFRTP sheet are shown in Fig. 5. The CFRTP sheet was 50 mm in length and 20 mm in width, and then the sheet was sandwiched between two aluminium alloy sheets. The sheets were heated by the heated steel blocks on the aluminium alloy top and bottom surfaces as same as in hot pressing. After cooling to room temperature, tensile testing was carried out. The effects of the heating temperature T_h and injection direction were investigated.

The tensile force and stress of CFRTP sheet at room temperature without heating are shown in Fig. 6. The tensile force was increased with increasing of stroke. When the force in both the directions reached at a peak, the force suddenly dropped with fracture. The force in the injection parallel direction was higher than that of the injection vertical direction. Therefore, the injection parallel direction in the specimens was used in this study.

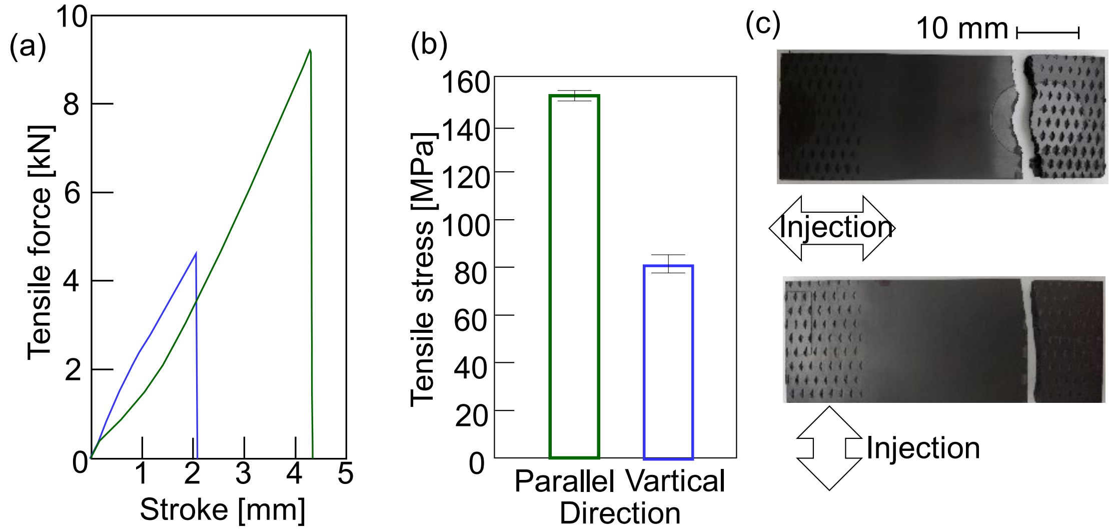

Fig. 6. Tensile force and stress of CFRTP at room temperature.

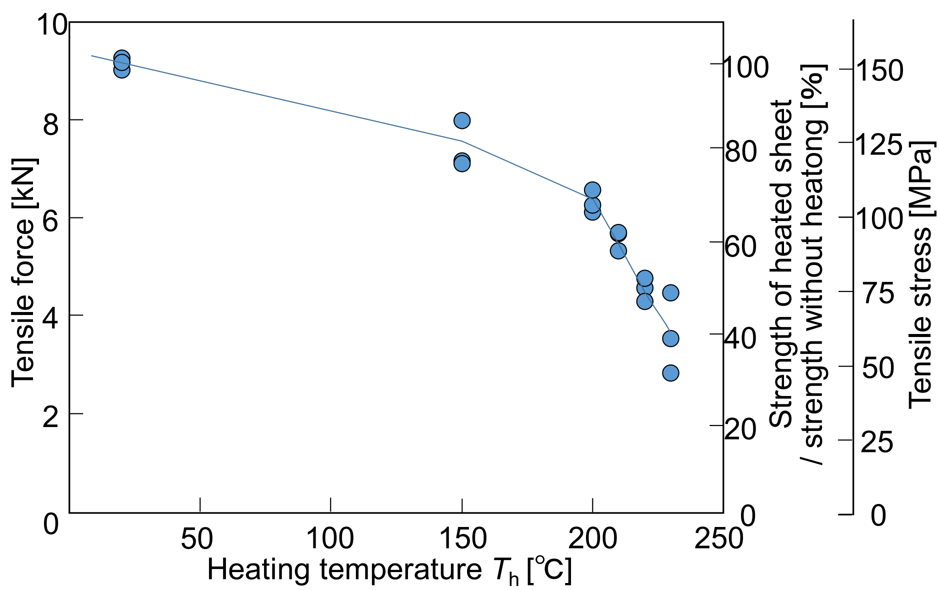

Fig. 7. Effect of heating temperature on tensile force and stress of CFRTP.

The effect of heating temperature on the tensile force and nominal stress of the CFRTP sheet is shown in Fig. 7. The tensile force and nominal stress of the CFRTP sheet were reduced by heating. At 230°C in hot pressing, the strength of the heated sheet was reduced to about 40% of the strength without heating.

Results in hot pressing

The aluminium alloy sheet was successfully bend in four-stage bending without defects. The effect of the heating temperature on the joinability in hot pressing to flow the CFRTP into protrusions with structures is shown in Fig. 8. In high holding force, the cracks were observed on the surface of CFRTP sheet because of large material flow in the longitudinal direction. In insufficient heating temperature, CFRTP material was unfilled into the protrusions. The CFRTP material was infiltrating into the protrusions in appropriate holding force and appropriate heating temperature.

The effect of the heating temperature on the joinability in hot pressing to flow the CFRTP into the holes is shown in Fig. 9. In high holding force, cracks were observed on the surface of CFRTP sheet. Although the voids in all CFRTP cross-section were observed, we classified cross-section having CFRTP flow into the holes without cracks as joined. The joining range including the voids in CFRTP sheet was higher temperature and was wider than that by hot pressing to flow CFRTP into protrusions with structures.

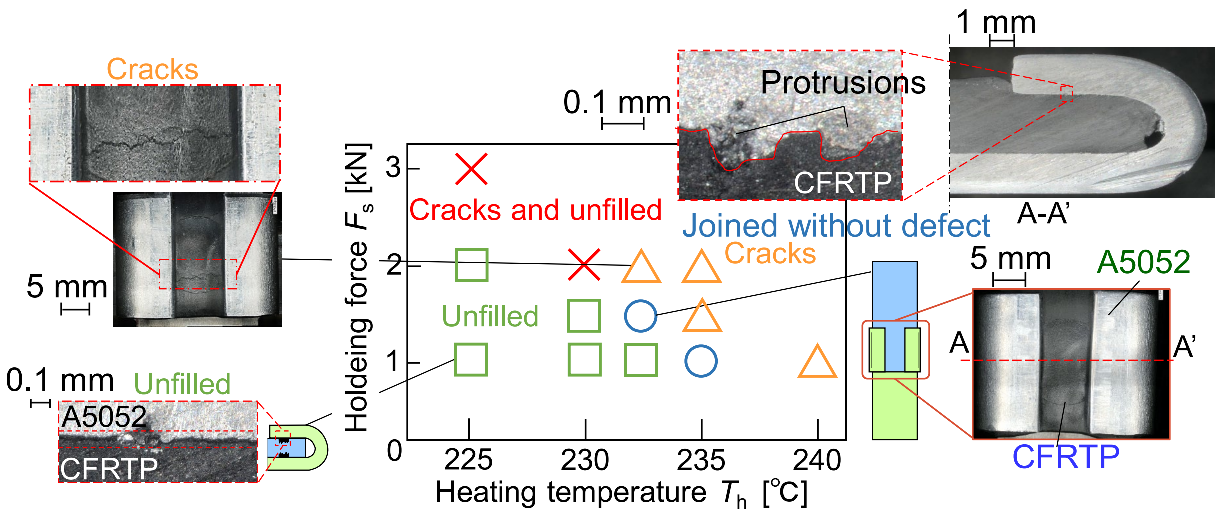

Fig. 8. Effect of heating temperature on joining ability in hot pressing to flow CFRTP into protrusions with structures.

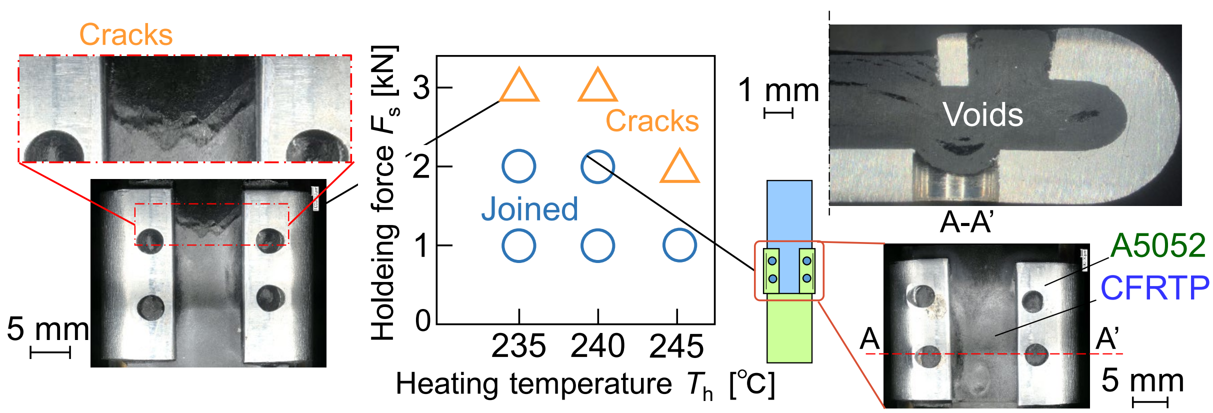

Fig. 9. Effect of heating temperature on joining ability in hot pressing to flow CFRTP into holes.

Joint strength

The pull-out load-stroke curves are shown in Fig. 10. All pull-out loads increased sharply, and then, suddenly dropped. In the load by hemming with the drilled holes, the CFRTP was fractured at the peak load. In the other loads after the peak loads, the loads reduced gradually with long stroke by pull-out in the hemmed portions.

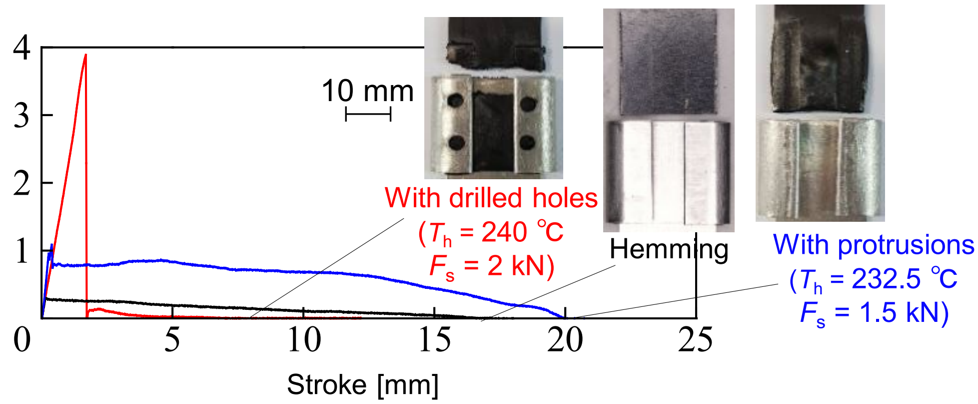

Fig. 10. Pull-out load-stroke curves.

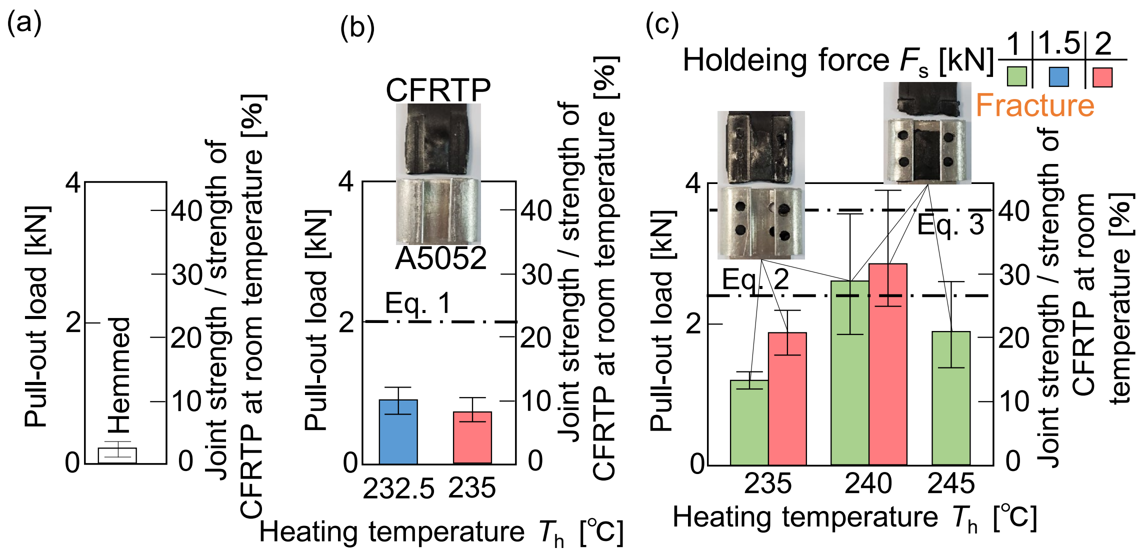

Fig. 11. Pull-out loads for (a) hemmed, (b) hemmed with protrusions and (c) hemmed with drilled holes.

The pull-out loads for joints by hemming, hemming with protrusions and hemming with the holes were summarized in Fig. 11. The estimated pull-out load for joints by hemming with protrusions is

$$P_p = \sigma A_p, \tag{1}$$

where, σ and A_p are joint strength in the protrusions and area of the protrusions, respectively. σ = 30 MPa was used from reference [13]. The estimated pull–out load for joints by hemming with holes is

$$P_h = C\ \sigma_b\ A_h, \tag{2}$$

where, C, σ_b and A_h are constant, tensile strength of the CFRTP and the area of holes, respectively. C = 0.8 and σ_b at 230°C were used. The estimated tensile load of CFRTP is

$$P_c = \sigma_b\ A_c, \tag{3}$$

Materials Research Proceedings 44 (2024) 698-707 https://doi.org/10.21741/9781644903254-75

where, A_c is the cross-sectional area of the CFRTP sheet. The load by the hemmed joint was very small. The loads by hemming with protrusions in T_h= 232.5°C and 235°C were similar. However, the both loads do not reach to the load from Eq. 1. It seems that the material flowing into the structure may not be enough. Although the loads by hemming with holes in high temperature tended to show fracture in the CFRTP sheet, the CFRTP material in holes was fractured in the load in lower temperature. The loads at 240°C were almost in the estimated loads between Eq. 2 and Eq. 3.

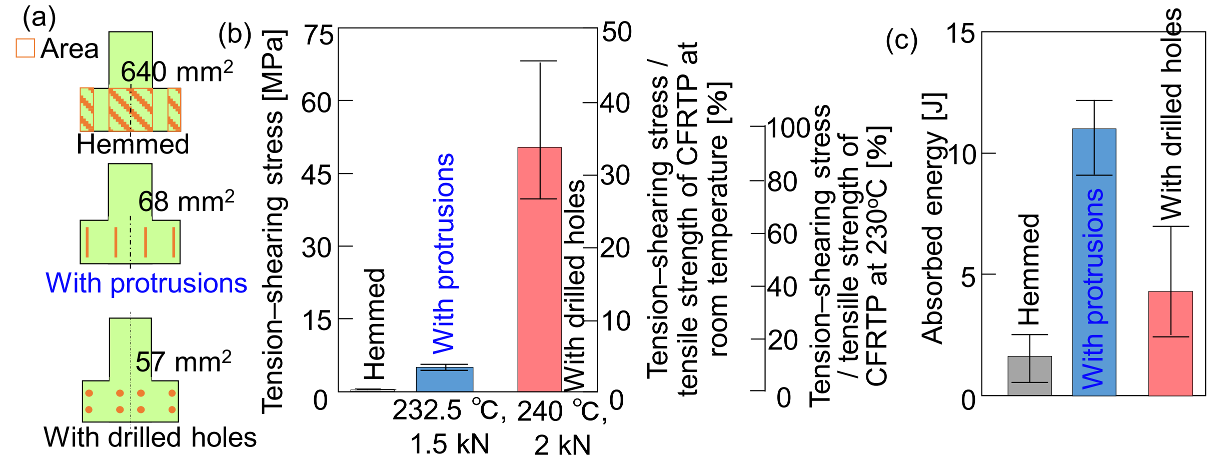

Fig. 12: (a) Joint area, (b) tension–shearing stress and (c) absorbed energy of joints.

The tension–shearing stress and absorbed energy of joints are shown in Fig. 12. The load was divided by the area to show as tension–shearing stress. The area of hemmed sheets was defined the flange portions. The area of hemming with protrusions was defined the area of the all protrusions. The area of hemming with holes was defined the area of all holes. The stress of joint by hemming with holes was the highest. Although the ratio of the tension–shearing stress and the strength at room temperature was about 34%, the ratio of the stress and the strength of CFRTP at 230°C was about 92%. The absorbed energy in hemming with protrusions was the highest because of medium pull-out load and long stroke as shown in Fig. 10.

The peeling load-stroke curves are shown in Fig. 13. The peeling load of the hemmed sheets was not measured because of the unfixed sheets. The loads of the joint by hemming with protrusions and hemming with the holes increased with increasing the stroke. In the both joints, the loads dropped rapidly by occurrence of fracture on the lower surface. Finally, the fracture occurs on the upper surface, and then the sheets were separated.

The peeling stress and absorbed energy of joints are shown in Fig. 14. The load was divided by the area to show as peeling stress. The peeling stress and tension–shearing stress of joints by hemming with protrusions were same in Fig. 12, although the peeling stress of joints by hemming with holes was about 10% of tension–shearing stress. It seems that the protrusions with structures were effective for loading in the both pull-out and peel directions.

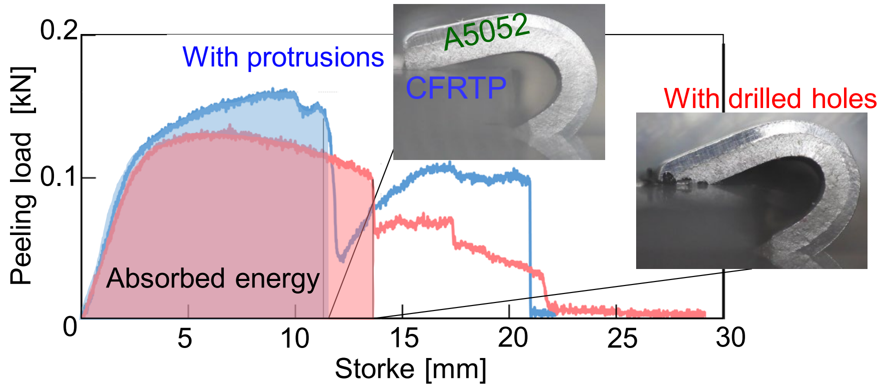

Fig. 13. Peeling load-stroke curves.

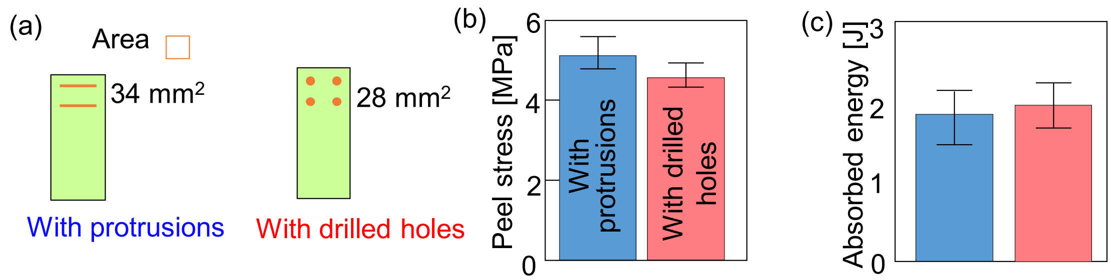

Fig. 14. (a) Joint area, (b) peeling stress and (c) absorbed energy of joints.

Conclusion

Two hemming processes for joining the aluminium alloy and CFRTP sheets were proposed to increase the joint strength. The main conclusions of this study are as follows:

1) In the process of hemming with the protrusions with structure, the CFRTP material was infiltrating into the protrusions in appropriate holding force and appropriate heating temperature.
2) In the process of hemming with the holes, the joining range was wider, although CFRTP sheet included the voids.
3) The tension–shearing stress of joint by hemming with holes was the highest. The ratio of the stress and the strength of CFRTP at 230°C was about 92%.
4) The peeling stress and tension–shearing stress of joints by hemming with protrusions were same. It seems that the protrusions with structures were effective for loading in the both pull-out and peel directions although the stresses were about 5 MPa.

This work was partly supported by “Knowledge Hub Aichi” which is a Priority Research Project of the Aichi Prefectural Government and by Foundation of Public Interest of Tatematsu. We would like to thank Tomohiro Maeda (Kisoh Co., Ltd) for his support and comments.

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