BASIC STUDY ON WELDING JOINT OF CARBON FIBER REINFORCED THERMOPLASTIC

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Keywords: CFRP, Thermoplastic, Welding joint, CF/PP

Abstract

Recently, carbon fiber reinforced thermoplastics (CFRTP) is expected as lightweight material for automobiles because of its promising high-mechanical properties, high-cycle and low-cost manufacturing and high-recyclability. Regarding automotive production, the technology of joining CFRTP is a key and welding joint is considered high re-workability and high-strength. This is because welding joint does not require any adhesives or mechanical bolts. In this paper, we evaluated the basic mechanical property of welding joint by tensile test. As a result, the joining strength of CFRTP has been found to depend markedly on the interfacial shear strength between carbon fiber and thermoplastic and on joint geometry.

1 Introduction

CFRTP is expected as lightweight material for automobiles because of its promising high-mechanical properties, high-cycle and low-cost manufacturing and high recyclability. At this time, in order to realize the weight saving of an automotive body substantially, it is necessary to use CFRTP for the main structure of an automotive body. Generally, the main structure of an automotive body has a large-sized and complicated form and there are many assembling parts. In the current manufacturing process of automobile, the joining has been one of the key technologies because it is easier to fabricate the automotive body for improving speed of production. When it comes to applying CFRTP to automotive body, welding joint of CFRTP is considered one of promising joining methods. As shown in Figure1, this new joining method is different from some conventional adhesive joints, and it is capable of joining two parts made from CFRTP just by heating them up and applying pressure upon each other without adhesive or fastening like conventional metal welding [1]. This method helps the weight saving and the high-cycle manufacturing. For designing the main structure of an automotive body, it is essential to evaluate the joint strength and to find some designing methods to strengthen the welding joint part with regard with CFRTP. In this research, we evaluated the strength of welding joint of CFRTP. Specifically, we made CFRTP specimens jointed by welding joint method and conducted tensile test on coupons. After the tensile test, we observed the failure part by a scanning electron microscope (SEM).

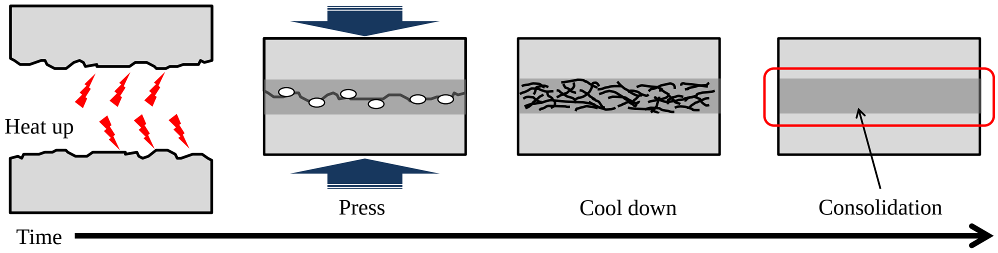


Figure 1. Welding joint process for CFRTP

2 Tensile Tests for Strength of Welding Joint

2.1 Materials Used in This Study

We used polypropylene (PP) as matrix of CFRTP. PP examined in this study is modified by chemical method to improve interfacial strength between CF and PP. This PP have been developed as a part of Japanese national project, "Development of Sustainable Hyper Composite Materials Technology [2]." In the latest studies [3][4], the interfacial shear strength between CF and modified PP is much larger than that between CF and unmodified PP and has come closer to that between CF and Epoxy. We evaluated the three types of CFRTP in combination of three types of PP with two types of CF as the base materials for welding joint. Three types of PP are PP1, PP2 and PP3. PP1 is low modified PP, PP2 and PP3 are high modified in order to improve the interfacial adhesion between CF and PP. Two types of CF are made by Mitsubishi-Rayon or by Toray. On the other hand, we evaluated two reinforced morphology types of CFRTP. One is uni-directional (UD) CFRTP and the other is carbon fiber mat reinforced thermoplastics (CMT) plate. UD is the base material for evaluating the mechanical property of composites and CMT is the isotropic material made from short mono-filament carbon fibers directing randomly. The UD base materials are obtained molding of UD prepreg tapes with carbon fiber volume fraction (V_f) of 45%. The laminate was fabricated through a process of stacking prepreg cut tapes on the mold, heat them up by hot plate, adding pressure on the molds concurrently and cooling down them in the end. We examined two UDs, one, named UD/PP1, is made from CF and PP1 and the other, named UD/PP2 is made from CF and PP2. CMT plate, we call CMT/PP3, is made by Toray, because the advanced technique needed in the molding process. The mechanical properties of these three materials are shown in Table 1.

	UD/PP1	**UD/PP2**	**CMT/PP3**
CF	TR50S (Mitsubishi-Rayon)		T700 (Toray)
PP	PP1	PP2	PP3
Degree of modification	Low	High	High
Tensile Strength[i] [MPa]	33.2	30.4	33.5
Shear Strength[ii] [MPa]	25.9	23.4	26.3
CF/PP			
Volume fraction (V_f)	45%	45%	20%
Interfacial Shear Strength[iii] [MPa]	4.8	17.7	13.3
Interlaminar Shear Strength[iv] [MPa]	6.5	17.4	28.7

Table 1. Mechanical properties of PP and CF/PP

[i]Tensile Test[5], [ii]Iosipescu Shear Test[6], [iii]Fragmentation Test, [iv]Double-notch Shear Strength Test[7][8].

2.2 Test Specimen and Test of Welding Joint

For fundamental examination of joint geometry, we evaluate the single lap joint and the scarf joint. The single-lap joint and the scarf joint, 2 mm thickness of laminate and 12.5 mm or 25 mm length of lap, were conducted by hot plate welding as shown in Figure 2. The single lap joint is the simplest joining method and basic in the evaluation of joint performance. In this joint, the fiber-bridging can be expected, but the load offset and the stress concentration will occur. On the other hand, the scarf joint is the structure that improves the disadvantage of the single lap joint, the load offset and the stress concentration [9]. After joining, we observed the joint specimens by computed tomography (CT) and the images of joint site are shown in Table 2. Upper row of Table 2 shows the joint area of single-lap joint specimens from the view point of width direction and lower shows that of scarf joint specimens from view point of thickness direction. Regarding UD specimen, we cannot find the fiber-bridging at joint area though expected and there is resin part at scarf joint area. On the other hand, regarding CMT specimens, it is difficult to find where the joint surface is in both types of joint. After observation, the joint strength is examined by simple tensile test on these specimens with joint.

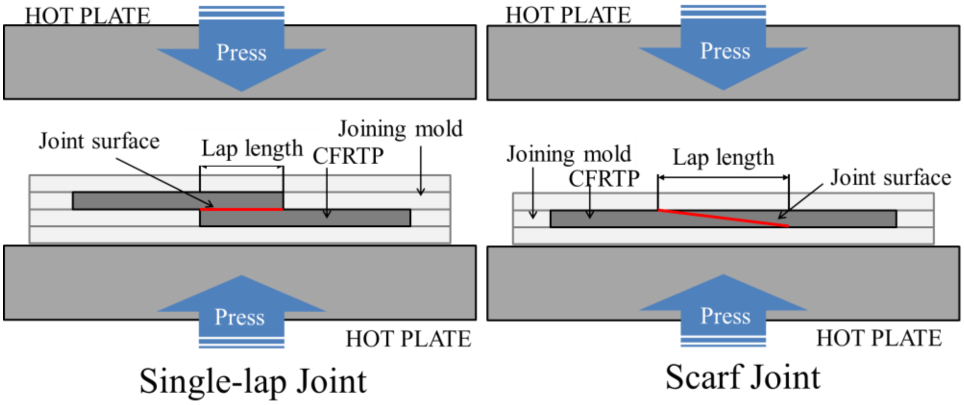


Figure 2. Joint geometries; (Left) Single-lap joint, (Right) Scarf joint

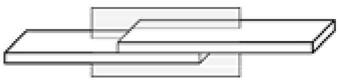
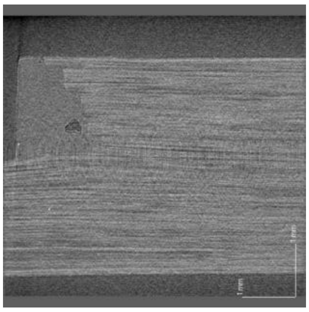
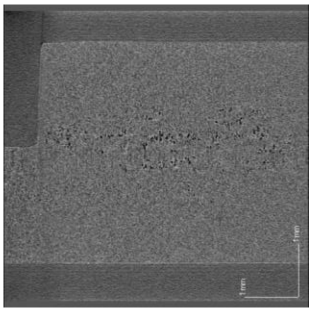
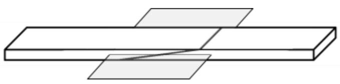
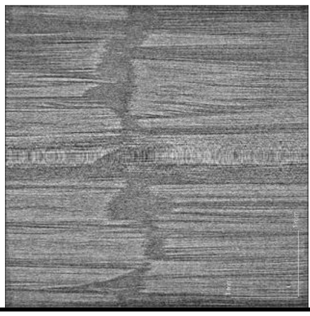
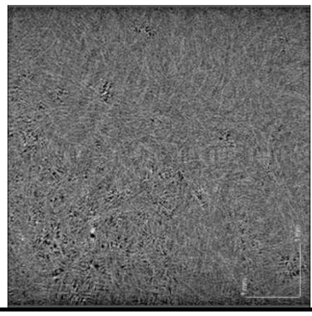
Section	UD	CMT
		
		

Table 2. Cross section at joint sight

2.3 Result of Tensile Test for Joint Strength

We evaluate performance of the welding joint by the tensile test. From the result of the test, the assumed shear strength τ_j^* can be derived from the following equation (1) where P means maximum load, b means width of specimens and L means lap length.

$$\tau_j^* = \frac{P}{bL} \tag{1}$$

The test result is shown in Figure 3-4. Figure 3 means the result of specimens with single-lap joint and the shear strength for UD materials is assumed to correlate strongly with interfacial shear strength between carbon fiber and PP as matrix (blue dot-line). On the other hand, the strength of that for CMT is much larger than the interfacial shear strength. The joint shear strength of UD has relation with the interlaminar shear strength and that of CMT is smaller than the interlaminar shear strength and close to the interfacial shear strength. Figure 4 means the result of specimens with scarf joint and that the shear strength of scarf joint is larger than interfacial shear strength (blue dot-line). The red line in Figure 4 means shear strength of only PP and the shear strength of scarf joint is speculated being associated in some way with that of PP.

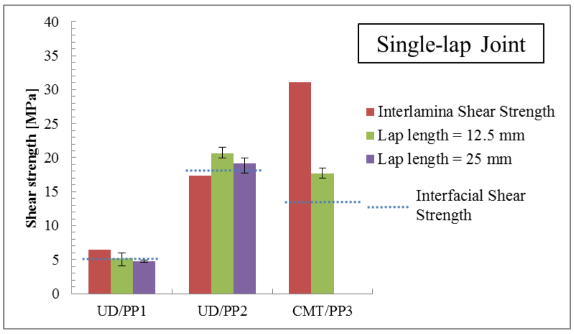


Figure 3. Shear strength at single-lap joint part

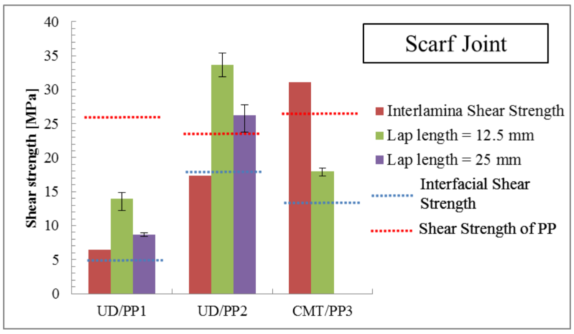


Figure 4. Shear strength at scarf joint part

3 Discussion

3.1 UD Single-Lap Joint

Regarding UD materials (UD/PP1 and UD/PP2), the shear strength of single-lap joint is not much different from lap lengths. The difference between the shear strength of single-lap joint by length is smaller than that of scarf joint. This trend comes out the opposite of a usual adhesive joint. The shear strength is as strong as interlaminar shear strength of base material and the interlaminar shear strength is same as the interfacial shear strength. We observed the failure surfaces by SEM. Figure 5 shows the failure surface of UD/PP1 single-lap joint and we can see carbon fiber falling out from the matrix. As to UD/PP2, the interfacial failure and the failure of PP exist side by side in the joint failure. The left image of Figure 6 shows most segment of failure surface of UD/PP2 single-lap joint. This shows the interfacial shear failure consists mostly of the joint failure. However, the shear strength of UD/PP2 joint is a little larger than the interfacial shear strength because the joint failure takes in the failure of PP, not only interfacial failure, shown as the right picture of Figure 6. Thus, this explains mainly the strength of single-lap joint is affected by the interfacial shear strength of base material and the joint surface becomes congruent with base material by full consolidation. The strength of joint may be derived from the interfacial strength of base material.

Figure 5. UD/PP1 failure surface of single-lap joint

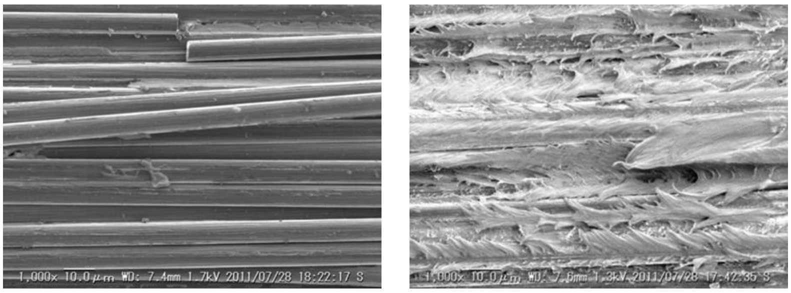


Figure 6. UD/PP1 failure surface of single-lap joint;
(Left) Failure of interface, (Right) Failure of PP.

3.2 UD Scarf Joint

Concerning UD scarf joint, the joint shear strength is stronger than that of single-lap joint and the interfacial shear strength, as shown in Figure 7. The improvement of joint shear strength is greater than the effect of less stress concentration. By observing Figure 8, which is CT image of scarf joint part from across the width point of sight, we find there is resin layer at joint surface. Therefore, we think the scarf joint shear strength become stronger with increasing rate of the segment, where PP is broken.

Figure 9 shows the failure surface and both images are taken at same scale factor. The shear strengths of scarf joint are different between the lap length 12.5 mm and 25 mm. The shear strength of 25 mm scarf joint is smaller than that of 12.5 mm because more carbon fibers are exposed and interfacial wreck is dominant, with 25 mm scarf joint. On the other hand, as to 12.5 mm scarf joint, the strength of PP has huge effect on the shear strength of scarf joint.

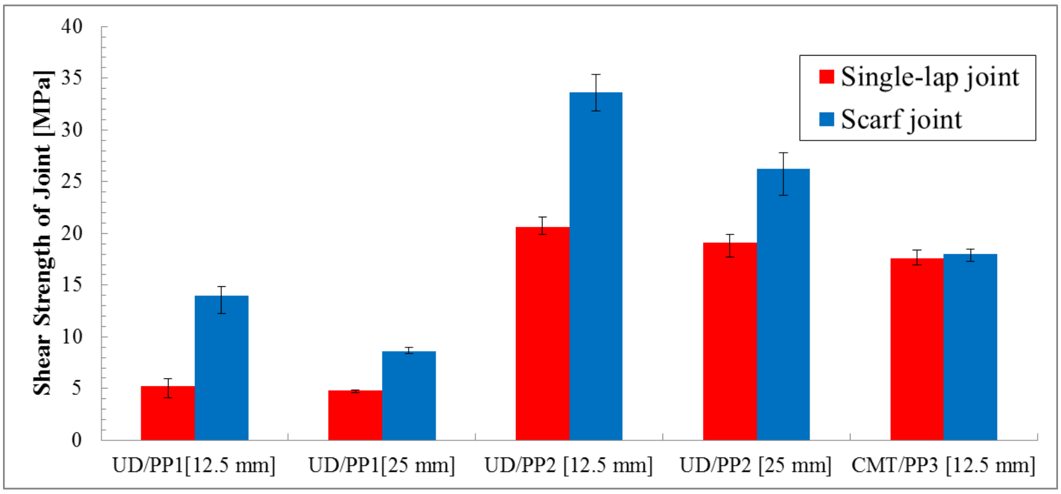


Figure 7. Comparison of difference of shear strength between joint geometry

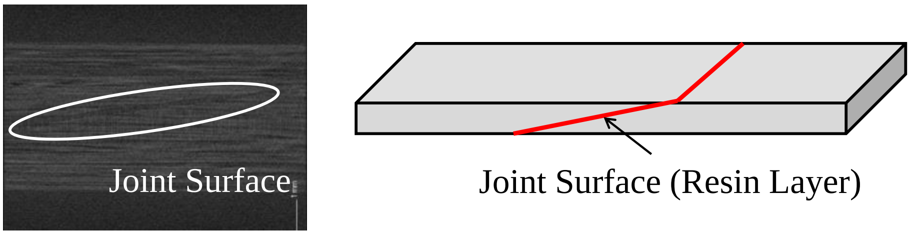


Figure 8. Joint surface of UD scarf; (Left) CT image, (Right) Schematic image

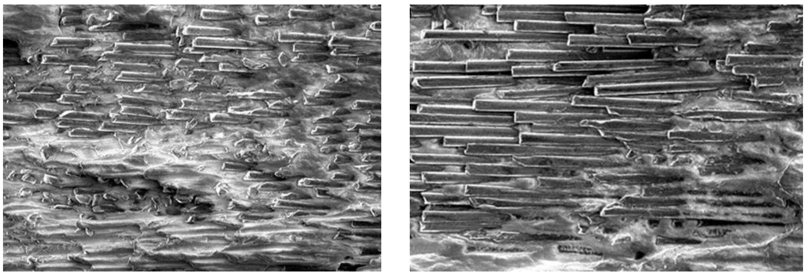


Figure 9. Failure surface by SEM; (Left) Lap-length 12.5 mm, (Right) Lap-length 25 mm.

3.3 CMT Single-Lap Joint and Scarf Joint

We were not able to evaluate the shear strength of 25 mm joint on CMT specimens because tensile strength of this base material is smaller than the joint strength. Thus, we evaluate only 12.5 mm joint. Regarding CMT specimens with 12.5 mm lap-length, the shear strength of single-lap joint is similar to that of scarf joint as shown in Figure 7, but in case of UD, the joint shear strength differs between joint geometries. And the joint shear strength is much smaller than the interlaminar shear strength. The conditions of joint part is different from that of base material, however the UD shear strength of each joint is equal to or greater than the interlaminar shear strength of the base material. The shear strength of joint is a bit larger than the interfacial shear strength because respective carbon fibers in CMT material tangle three dimensionally each other and build fiber bridging in some measure.

Figure 10-11 show the failure image of single-lap joint and scarf joint by SEM. We can find the fibers falling out from the matrix and PP being torn off from both images.

Figure 10. CMT/PP3 failure surface of single-lap

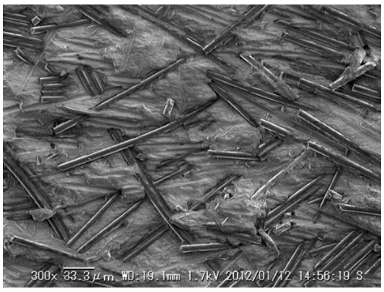


Figure 11. CMT/PP3 failure surface of scarf joint

4 Conclusion

We evaluated the strength of welding joints by conducting simple tensile tests and observing the failure surfaces. Regarding UD materials, the shear strength of joint part is controlled mainly by the interfacial shear strength between carbon fiber and matrix PP, and the joint geometry also affects the joint shear strength. On the contrary, as to CMT materials, the joint geometry has little impact on the shear strength of joint part, but the joint shear strength has relevance to the interfacial shear strength. However, what effects CMT joint strength is still uncertain and much careful analyses for joint of CMT materials are needed.

Acknowledgement

A part of this work belongs to Japanese METI-NEDO project "Development of Sustainable Hyper Composite Technology" (2008fy-2012fy).

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