RELATIONSHIP BETWEEN INTERLAMINAR SHEAR STRENGTH AND REPAIR CONDITIONS OF DELAMINATION BY THERMAL FUSION BONDING IN CF/PA6 LAMINATES

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Abstract

Generally, The repair effectiveness of delamination in fiber reinforced plastics has been evaluated based on the mechanical properties of specimens which include the repaired region. In this study, we evaluated the interlaminar shear strength of region of repaired delamination by thermal fusion bonding (TFB) in carbon fiber reinforced thermoplastic (CFRTP) laminates. Through the interlaminar shear test and fractography, the efficiency of repaired method by TFB was discussed. Cross-ply laminates made of carbon fiber and polyamide 6 (PA6) were prepared and applied impact load to introduce delaminations in the laminates. After the repair by TFB near the melting point of PA6, the repaired laminates were processed into double-notched specimens to measure the interlaminar shear strength at the region of repaired delamination. Intact specimens which had the same thermal history as repaired specimens were also prepared to compare the interlaminar shear strength of repaired specimens. As a result, the interlaminar shear strength of repaired specimen was recovered to 93% of that of intact specimens. Mechanical properties of region of repaired delamination were not recovered completely, while the delamination was seemed to be repaired by TFB in certain condition.

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1. Introduction

Since thermoplastics have high fracture toughness, the interlaminar toughness of carbon fiber reinforced thermoplastics (CFRTPs) is much higher than that of carbon fiber reinforced plastic (CFRP) using thermoset matrices [1]. Due to this advantage, CFRTPs have attracted attention for use in the primary structure of aircraft [2]. However, the interlaminar toughness is generally much lower than the in-plane toughness in CFRP laminates. For this reason, out-of-plane impact causes internal damages, especially delamination [3], while CFRTP is expected to suppress internal impact damage causing a decrease in residual compressive strength. Unfortunately, impact damage in appearance is sometimes too small, although internal damage is widespread in laminates. This damage morphology is well known as barely visible impact damage (BVID) and results in a decrease in residual compressive strength. Thus, suppressing and repairing delamination associated with BVID are important to improve the compression-after-impact (CAI) strength and damage tolerance of CFRP structures. In order to improve the CAI strength of CFRTP laminates, repair using thermal fusion bonding (TFB) is one of the promising ways to recover the compressive strength of laminate with BVID owing to the thermal plasticity of thermoplastic [4]. Generally, the effectiveness of repairing delamination on specimens made of fiber reinforced plastics has been evaluated based on the mechanical properties of specimens which include the repaired region [5,6]. On the other hand, the results suggested that mechanical properties in repaired region was not recovered completely in those repaired conditions [6]. Thus, we should extract the repaired region from laminates to discuss its effectiveness in detail. Authors has investigated the interlaminar shear stress in the region of repaired delamination to find and evaluate the method for the effectiveness of repair by TFB[7].

In this study, we evaluated the effectiveness of repair using TFB on the delamination generated by out-of-plane impact in CFRTP laminate. Interlaminar shear test using double-notched specimen was carried out to evaluate interlaminar shear strength at the region of repaired delamination.

2. Materials

Material preparation was the same as authors' previous study [6]. Laminates were made of TR50S spread fiber tow and polyamide 6 (PA6) unidirectional semipreg, in which the resin was semi-impregnated into the fiber tow, supplied by Mitsuya Co., Ltd. The thickness of the semipreg was 0.043 mm and its fiber volume fraction was 54%.

Cross-ply laminates were prepared and the stacking sequence was $[0_3/90_3]_{6S}$. Laminates were molded using a hot-press machine at a pressure of 1 MPa and a temperature of 553 K for about 7200 s (= 2 h). After that, the laminates were slowly.

3. Specimen and test method

To introduce delaminations in CF/PA6 laminate, impact load was applied to specimen using stainless steel weight which has 0.9979 kg in weight and indenter of 16 mm in diameter [6]. Specimen was held in stainless steel fixture, which had a cut-out hole of 30 mm in diameter. Potential energy applied to specimen was 2.0 J/mm. Delamination in the specimen was observed by ultrasonic inspection.

After impact test, specimens were pressed under the condition of 1 MPa at 373 K, and the condition was maintained for 300 sec (= 5 min) in order to repair the dent. Then, specimens were pressed under the condition of 1 MPa at 483 K to repair the delaminaion by TFB. Here, two kinds of specimens which had different repair time were prepared. Specimens repaired for 300 sec (= 5 min) and 900 sec (= 15 min) were called Repair_5 and Repair_15 in following discussion, respectively. After that, the laminate was slowly cooled down for 5400 sec (= 1.5 hours) under the pressure [6].

Interlaminar shear test using specimens with double-notch was carried out to evaluate the efficiency of TFB on repairing the delamination. Here, we prepared specimens without repaired delamination (Intact) for the reference. In addition, we also prepared specimens without delamination and applied the same thermal history of repair test for 15 min (Intact_HT). Specimens for interlaminar shear test were cut from repaired laminates (Fig. 1) including repaired delamination between the middle 90° layer and 0° layer. Then, notches were introduced to repaired delamination area to apply the shear stress. Specimen geometries for interlaminar shear test were as follows: Length was 80 mm, width was

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6 mm, thickness was 3 mm, the notch depth was about 1.7 mm, notch width was 1 mm, and notch distance was 3 mm. We prepaired 4 specimens in each type of specimen.

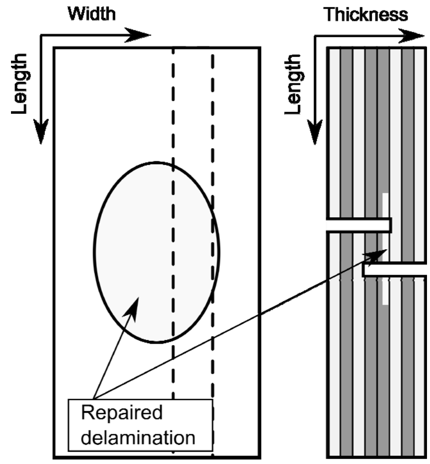

Figure 1. Schematic image of specimen preparation for interlaminar shear test with double-notch [7].

4. Results and discussion

Figs. 2a, 2b, 2c and 2d show fracture morphology of Intact, Intact_HT, Repair_5, and Repair_15 specimen at the side surface, respectively. In Figs. 2a and 2b, interlaminar crack and intralaminar crack connected each other continuously. This fracture morphology was observed in all Intact specimens and two Intact_HT specimens. It was suggested that intralmiar crack initiated from the bottom of notch to the interlaminar and then the crack propagated along the interlamiar. Although this observation result indicated that the strength obtained from intact specimens was not interlaminar shear strength strictly, the strength obtained from intact specimens was regarded as interlaminar shear strength in this study. Fig. 2c shows that Repair_15 specimen was split completely remaining a part of 90° layer on the right side fracture surface. This fracture morphology was observed in two Intact_HT specimens and one Repair_15 specimen. Fig. 2d shows that Repair_5 specimen was split completely without transverse crack. This fracture morphology was observed in three Repair_15 specimens and all Repair_5 specimens. If the mechanical properties is completely recovered in the region of repaired delamination, the fracture morphology in the specimen should be similar to that of intact specimen. Thus, this observation suggested that the strength obtained from specimen with repaired delamination was interlaminar shear strength.

Figs. 3 and 4 show that typical fracture surfaces of Repair_5 and Repair_15 after the interlaminar shear test, respectively. Since most region in both surfaces are covered by matrix resin, this observation indicates that crack propagated in the resin. At least, it was suggested that the adhesiveness between carbon fiber and matrix was better than that between matrix and matrix.

The average value of interlaminar shear strength obtained from specimen with repaired delamination was shown in Table 1. Here, value of the strength of Intact and Repair_5 was quoted from our current research [7]. The Interlaminar shear strength of Intact_HT was higher than that of Intact. Possibly, this strength increase resulted from increasing crystallinity and/or stress relaxation by heat treatment. In addition, it was difficult to compare both strength precisely because the time from the specimen preparation to the test was different for each specimen. The Interlaminar shear strengths of Repair_5 and Repair_15 were lower than that of Intact_HT (71% and 93%, respectively). These results indicate that increase of repair time is effective to recover interlaminar shear strength in the region of repaired delamination, although the repair temperature is less than or equal to the melting point of matrix resin. At the same time, the result suggests that the damaged region is not repaired completely under

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conditions in this study, although the delamination disappeared by TFB.

5. Conclusion

In this study, we evaluated the effectiveness of repair using TFB on the delamination generated by out-of-plane impact in CFRTP laminate through interlaminar shear test using double-notched specimen. The results are summarized as follows.

- Increase of repair time is effective to recover interlaminar shear strength in the region of repaired delamination, although the repair temperature is less than or equal to the melting point of matrix resin.
- The damaged region is not repaired completely under conditions in this study, although the delamination disappeared by TFB.Acceptance to copyright agreement

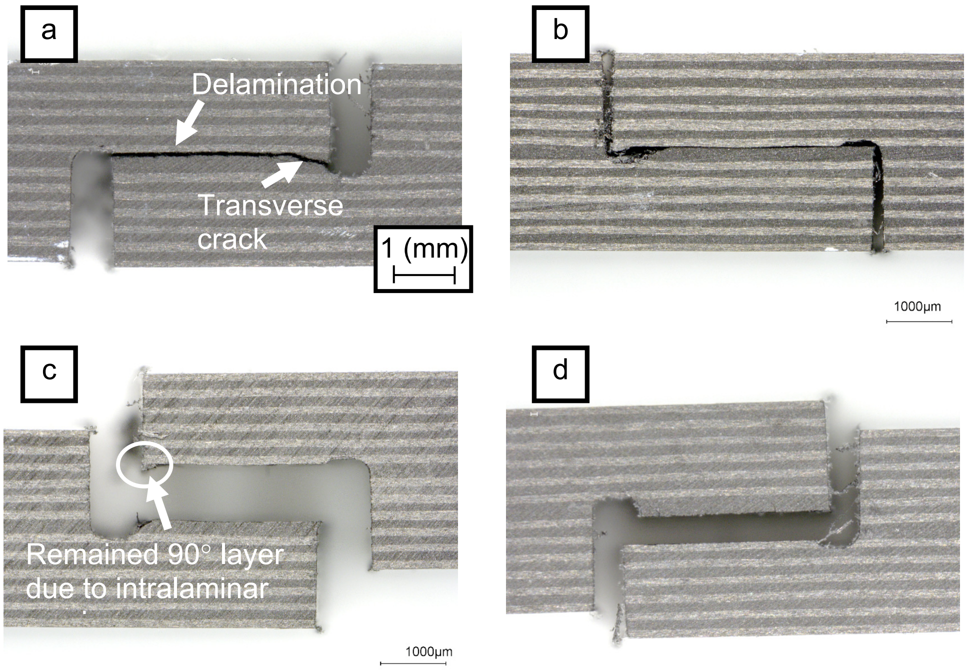

Figure 2. Crack shape in (a) Intact, (b) Intact_HT, (c) Repair_5, and (d) Repair_15 specimen after interlaminar shear test.

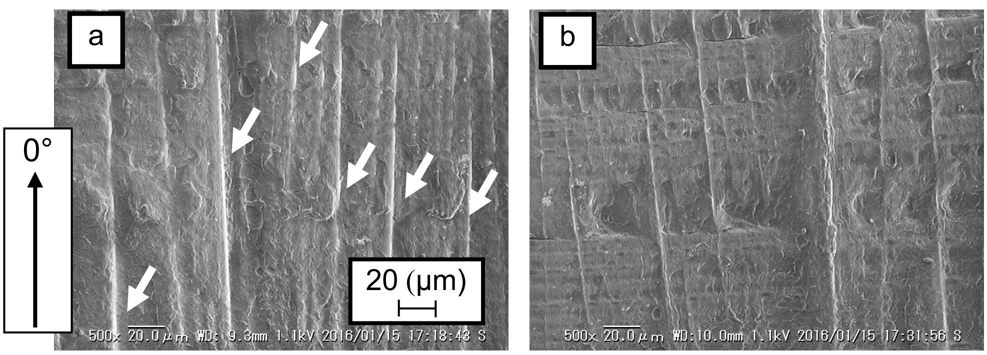

Figure 3. Fracture surface of (a) 0° layer (b) 90° layer of Repair_5 specimen with repaired delamination after interlaminar shear test: arrows indicate sticking of matrix resin on carbon fibers.

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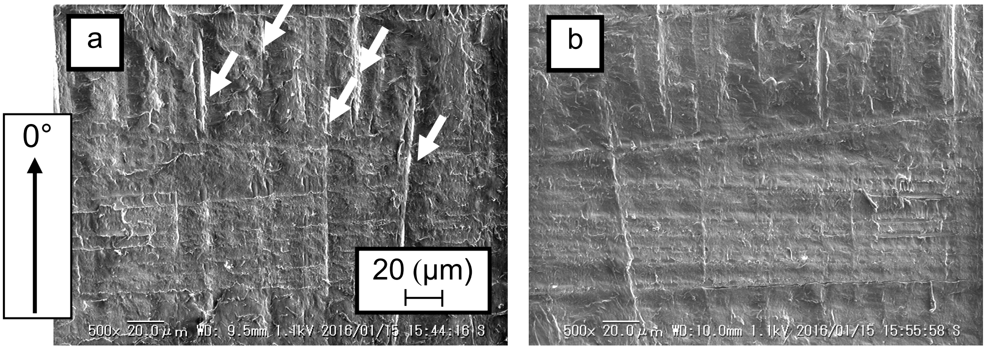

Figure 4. Fracture surface of (a) 0° layer (b) 90° layer of Repair_15 specimen with repaired delamination after interlaminar shear test: arrows indicate sticking of matrix resin on carbon fibers.

Table 1. Comparison of interlaminar shear strength.

Specimen Type	Interlaminar Shear Strength (MPa)	Standard Deviation (MPa)
Intact	51.2	1.14
Intact_HT	61.9	1.02
Repair_5	44.0	3.13
Repair_15	57.7	4.49

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