EXPERIMENTAL EVALUATION OF RESIDUAL STRENGTH OF AGED GLASS FIBER REINFORCED PLASTICS BY ACOUSTIC EMISSIONS

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Abstract

This study dealt with the acoustic emission characteristics of hydrothermally aged GFRP. Three types of cross-linked polyester resins with different chemical composition and two types of glass woven fabrics with different fiber surface treatment were adopted as matrix and reinforcement respectively, and GFRP specimens were aged under hydrothermal environment. After aging weight change measurement, tensile test with AE monitoring and microscopic investigation were conducted, and relation between tensile strength reduction and AE characteristics was discussed in order to find the possibility to predict the residual strength of the aged GFRP. The relation between tensile strength and the cumulative AE event count showed the linear relation and it suggested that the strength reduction was caused by the internal damage accumulation during the aging process. From this result, it is suggested that prediction of the residual strength after aging might be possible when the damage accumulation during aging process can be monitored.

1 Introduction

Glass fiber reinforced plastics (GFRP) have been widely used as the structural materials (chemical tanks/vessels, pipes, etc.) under severe environments such as hydrothermal, acid and alkaline environments. In such applications, various types of cross-linked polyesters are used as matrix resin since the chemical structure of the resin significantly affects the corrosion resistance of the FRP. In addition, interfacial adhesion between fiber and matrix resin also affects the corrosion resistance of the FRP.

Degradation of the structural GFRP in liquid environment is mainly caused by the diffusion of the environmental liquid into the material. Liquid diffusion into the GFRP is affected both by the chemical structure of the matrix resin and the adhesion at the fiber/matrix interface. Poor adhesion at the interface brings not only liquid diffusion but also liquid penetration through the interface (or interphase) region, and it brings poor load transfer from the matrix to the fiber. Therefore it is important to understand the effect of matrix type and the interfacial adhesion on the degradation behavior of GFRP in liquid environment in order to design the corrosion resistant GFRP effectively.

In our previous work, the degradation behavior of GFRP in liquid environment was evaluated by weight change measurement and mechanical testing after hydrothermal aging of samples [1-4]. This paper also followed this method to evaluate the effect of matrix type and interfacial adhesion on the hydrothermal aging behavior of GFRP. In addition, the author has applied acoustic emission (AE) technique to evaluate the fracture process of the GFRP [5]. AE is a powerful tool to evaluate the fracture process and pattern, and it is possible to understand the strength degradation mechanism due to aging. AE can monitor the damage accumulation during loading process, and it is considered that the damage accumulation is closely related to the material strength. Therefore it is considered that the residual strength of material may be evaluated by applying the AE system.

From these backgrounds, this study dealt with the acoustic emission characteristics of the hydrothermally damaged GFRP. Three types of cross-linked polyester resins and two types of glass woven fabrics were adopted as matrix and reinforcement respectively, and GFRP specimens were aged under hot water environment. After aging weight change measurement, tensile test with AE monitoring and microscopic investigation were conducted, and the effects of aging on the AE characteristics were discussed. In addition, the residual strength prediction concept of the aged GFRP by using AE was discussed.

2 Experimental Procedure

Matrices used were 3 types of cross-linked polyester resins which were different in chemical composition; isophthalic based cross-linked polyester resin (noted as Iso; Polyright FG-283, Dainippon Ink Chemicals, Japan), bisphenol based cross-linked polyester resin (noted as Bis; Polyright FG-387, Dainippon Ink Chemicals, Japan) and vinylester resin (noted as Ve; Ripoxy R806B, Showa High Polymer, Japan). For all the resins cure agent was Methlethylketoneperoxide and catalyst was cobalt naphthanate. Reinforcements used were two types of plain woven glass fabric which were different in fiber surface treatment; acryl-silane treated (noted as AS) and epoxy-silane (noted as ES). AS is a suitable treatment for cross-linked polyester resin, whereas ES is a mismatched treatment for cross-linked polyester resin. Specimen laminates were fabricated by hand lay-up method with 12 plies reinforcement.

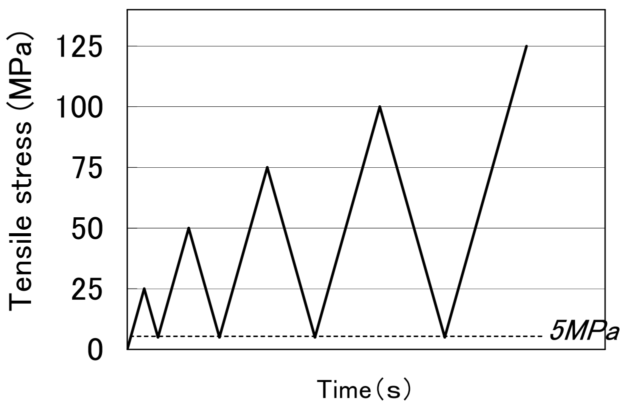

Fig.1 Static tensile test with step stress.

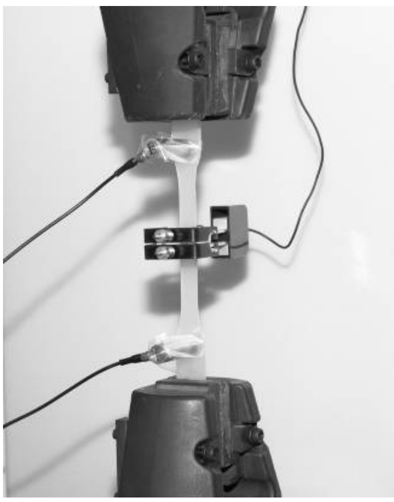

Fig.2 Experimental set-up of tensile test.

In order to discuss the effects of hydrothermal aging on various types of GFRP, all the specimens were immersed in distilled water at 95°C, and weight change and tensile properties were evaluated. Aging times for both evaluations were 3, 5, 10, 30, 50, 100, 300, 500 and 1000 hours.

Weight change was evaluated by weighing the specimens before and after aging. Prior to the immersion, all the specimens were completely dried under vacuum condition at 100°C, and the dried specimen weight before immersion (W_o) was measured. After measurement the specimen was immersed in water for fixed period. Soon after the fixed period of immersion the wet specimen weight (W_w) was measured. Then, the immersed specimen was completely dried again under vacuum condition at 100°C, and the dried specimen weight after immersion (W_d) was measured. From these weighing, the weight gain due to water absorption (M_g) and the weight loss due to material dissolution (M_l) were calculated as follows;

$$M_g = \frac{W_w - W_d}{W_o} \qquad (1)$$

$$M_l = \frac{W_o - W_d}{W_o} \qquad (2)$$

After aging, tensile test was performed in order to evaluate the strength reduction due to aging. In order to discuss the reliable stress level for actual application, the maximum applied stress was increased step by step to final failure as schematically shown in Fig.1. The applied maximum stress was increased 25MPa step and minimum stress level was fixed at 5MPa. Tensile test was performed by Instron type universal testing machine (AG-50KNI, Shimadzu Corporation, Japan) at a constant crosshead speed of 1mm/min in air at room temperature. During tensile test, acoustic emission (AE) from the specimen was monitored

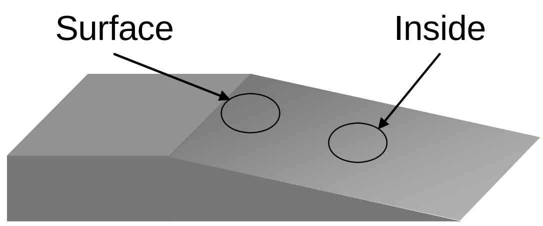

Fig.3 SEM observation of aged specimen.

simultaneously in order to discuss the effects of matrix type and fiber type on fracture behavior after aging. AE signal was monitored by 7600 series AE instrument (NF Corporation, Japan). Two AE transducers with the resonant frequency of 140 kHz were attached onto the specimen as shown in Fig.2, and AE was monitored with the total gain of 50dB and 70dB (different in each transducer) and the threshold of 100mV. From the AE monitoring, the cumulative AE event count was evaluated.

In order to discuss the internal damage due to aging, the aged specimens were observed by scanning electron microscope (SEM). Aged specimens were cut and polished as shown in Fig.3. Cross-sections near the surface and at the middle portion in thick direction were observed.

3 Experimental Results and Discussion

3.1 Weight Change

Figs.4 and 5 show the changes of the weight gain due to water absorption (M_g) for the AS and the ES specimens, respectively. In the AS specimens, changes of M_g were almost independent of matrix resin at shorter aging time. M_g increased almost linearly against the square root of immersion time to 100 hours aging. After that, the saturated M_g values were slightly affected by the matrix type, however, all of them showed saturation, and therefore the

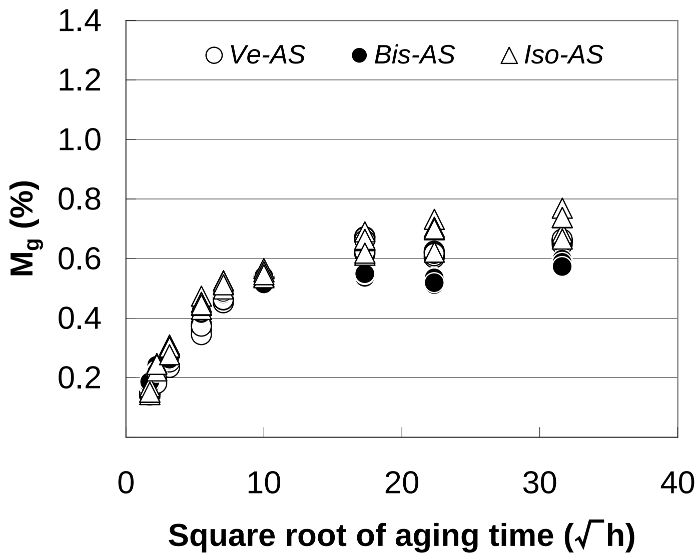

Fig.4 Changes of M_g for AS specimens.

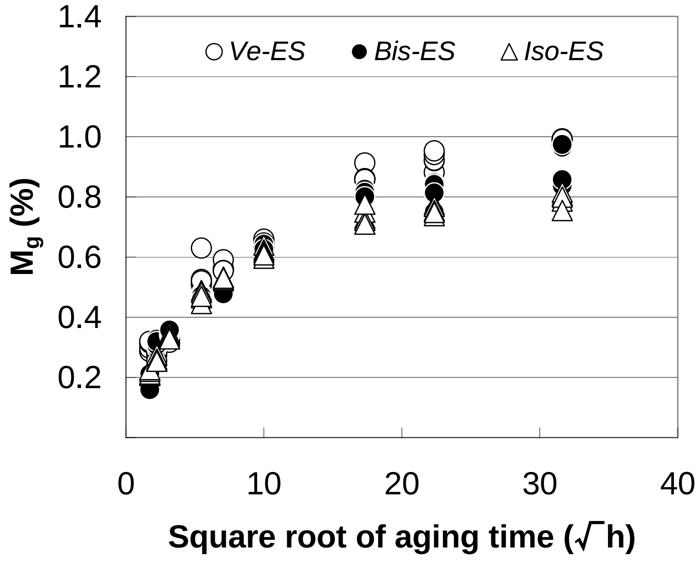

Fig.5 Changes of M_g for ES specimens.

changes of M_g for all of the AS specimens showed typical Fickian diffusion behavior. On the other hand, the changes of M_g for the ES specimens showed the different behavior compared with the AS specimens. Diffusion speed of the ES specimens at shorter aging time was a little higher than the AS specimens and Mg gradually increased even after 100 hours aging time. In the ES specimens the saturation of M_g did not appear in these aging times.

Figs.6 and 7 show the changes of the weight loss due to material dissolution (M_l) for the AS and the ES specimens, respectively. M_l of the AS specimens increased a little even after aging, and it is considered that material dissolution did not occur in the AS specimens independent of the matrix type. In the ES specimens the M_l to 50 hours aging was almost the same with the AS specimens, however, after that the M_l gradually increased with aging time for all the matrix type. This suggested that the internal damage occurred by the result of material dissolution in the ES specimens. Such internal damage brought the continuous increase of M_g at longer aging time.

3.2 Tensile Properties

Figs.8 and 9 show the strength reduction due to aging. The initial strength (strength for virgin

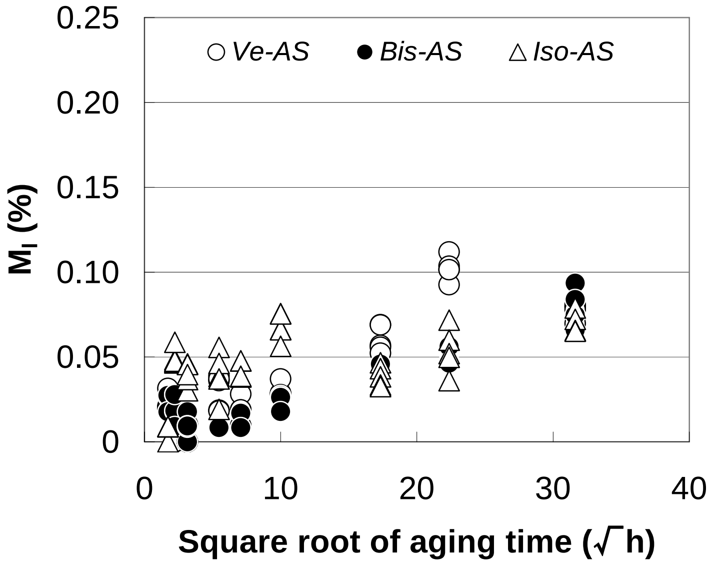

Fig.6 Changes of M_l for AS specimens.

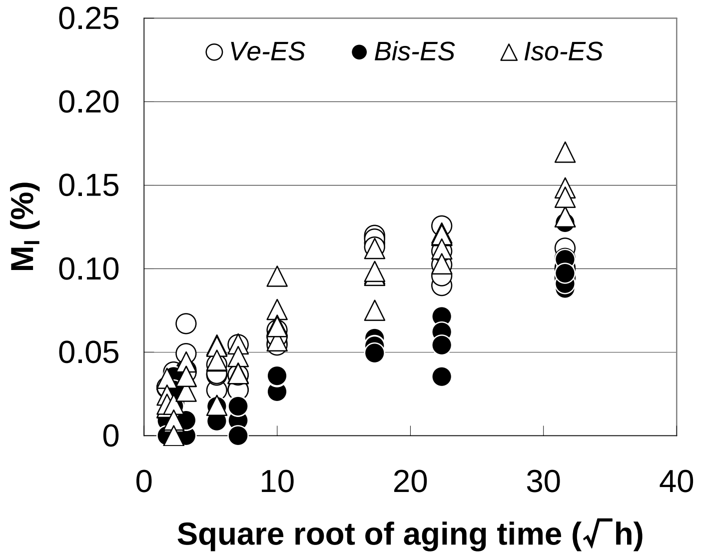

Fig.7 Changes of M_l for ES specimens.

specimen) was almost the same independent of the fiber surface treatment. However, the strength reduction was affected by both the matrix type and the fiber surface treatment. In all the matrix type, the strength of the ES specimen was reduced at shorter aging time than the AS specimen. However, the bottom of strength reduction was almost the same independent of the fiber surface treatment. The effect of matrix type on the strength reduction was not clear in these aging times.

3.3 Acoustic Emission Characteristics

Fig.10 shows the stress history and the cumulative AE event counts during the tensile test for the virgin and the 1000 hours aged Ve-AS specimens. The tendencies of AE characteristics during tensile test were little affected by matrix resin, and therefore the results of only Ve resin system were shown here. In virgin specimen, cumulative AE event count was a few below 200MPa of applied stress, and after that it increased step by step with increasing the applied stress. In the 1000 hours aged specimen, the AE event count increased over 150 MPa of applied stress, and the event count at final failure was quite a few compared with the virgin specimen. In both cases, however, AE generated only in loading process, and it did not generate in unloading process.

Fig.11 shows the stress history and the cumulative AE event counts during the tensile test for the virgin and the 1000 hours aged Ve-ES

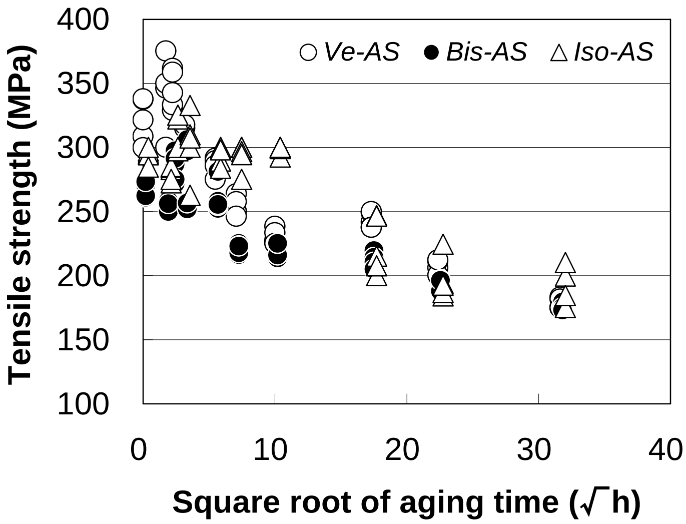

Fig.8 Changes of tensile strength for AS specimens.

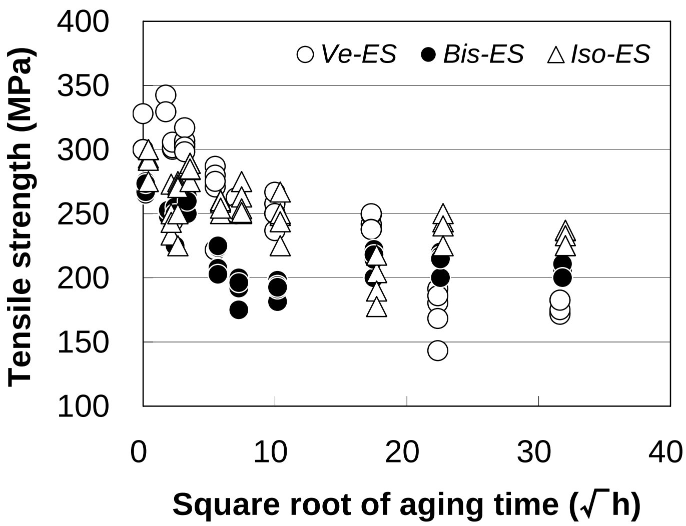

Fig.9 Changes of tensile strength for ES specimens.

specimens. The cumulative AE event count curves for ES specimens were quite different from the AS specimens. The event count continuously increased from the low applied stress level, and its increment at each stress step was a few compared with the AS specimens. This means that fracture progression in ES specimen was quite slow compared with AS specimen. In addition, AE generated in unloading process in ES specimen, and such behavior was clear in the virgin specimen. This result suggested that the friction at the damaged interface occurred in ES specimen, and also suggested that interfacial adhesion was quite poor in ES specimen.

From these results, it is obvious that the fracture mechanism is completely different between the AS and the ES specimens. Such tendencies were almost the same independent of the matrix type.

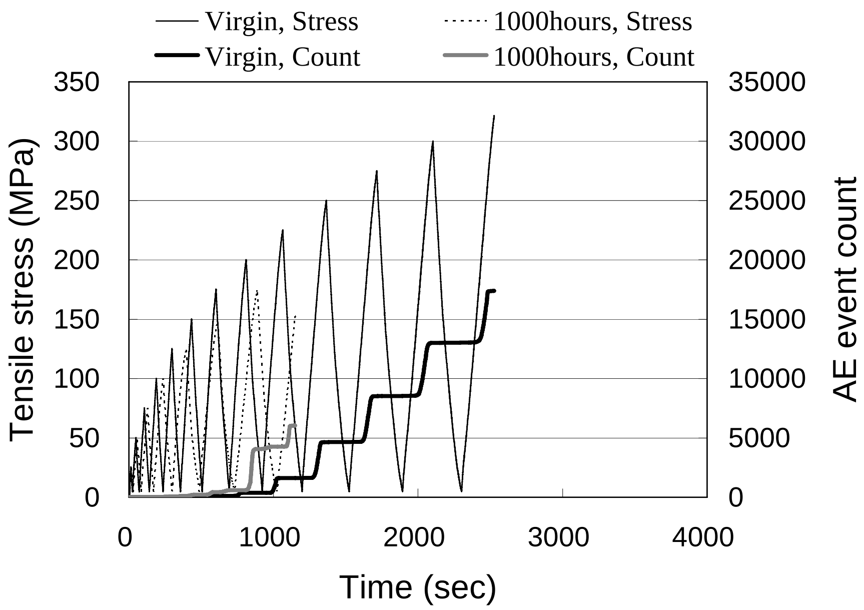

Fig.10 Stress histories and cumulative AE event counts for Ve-AS virgin and 1000 hours aged specimens.

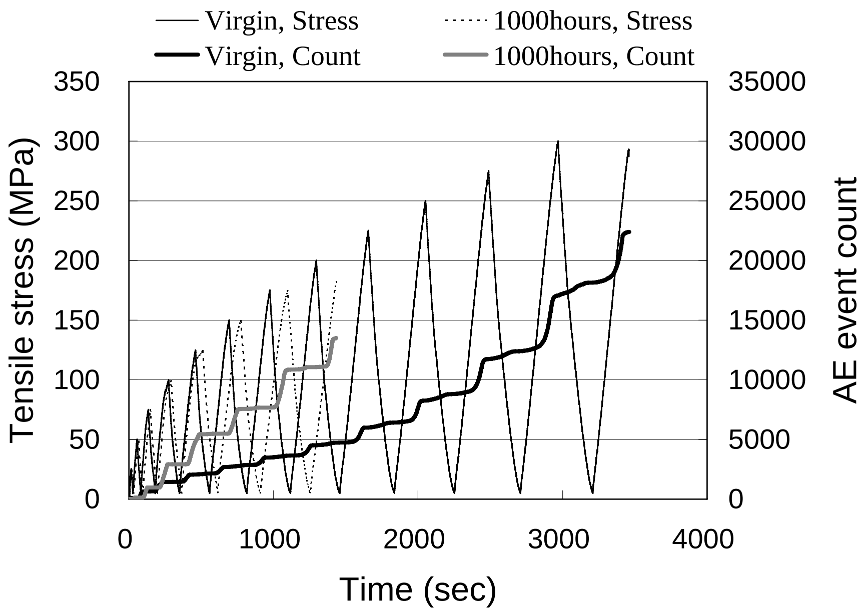

Fig.11 Stress histories and cumulative AE event counts for Ve-ES virgin and 1000 hours aged specimens.

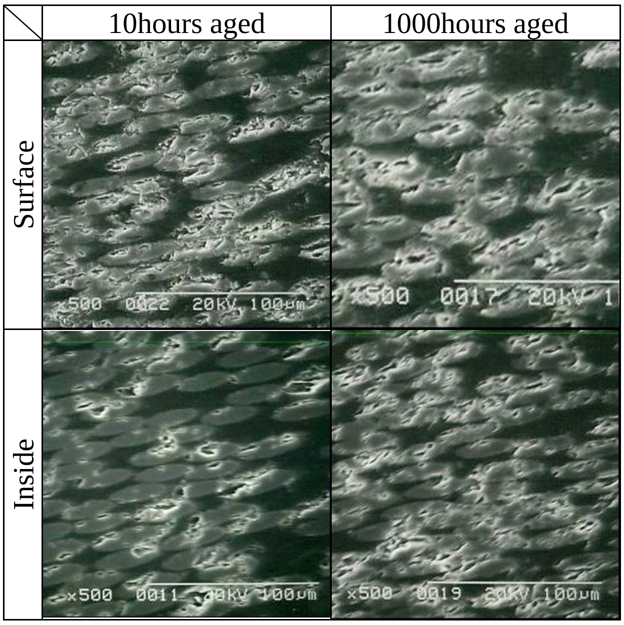

Fig.12 Cross-sectional micrographs of 10hours and 1000hours aged specimens for AS specimens.

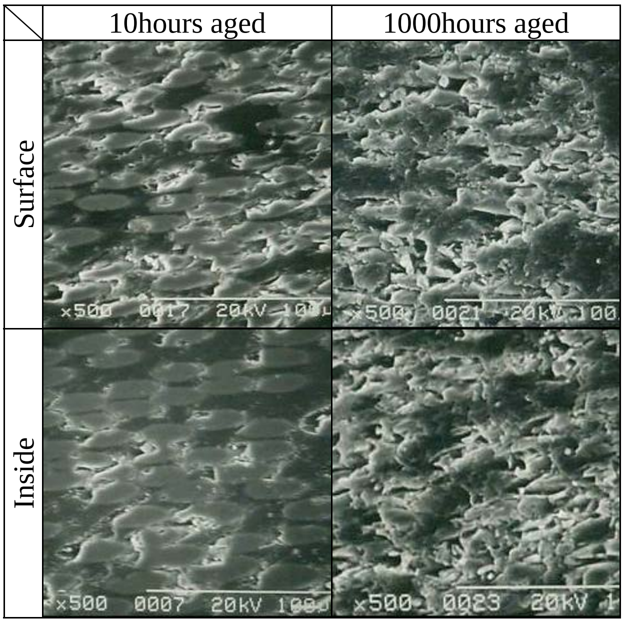

Fig.13 Cross-sectional micrographs of 10hours and 1000hours aged specimens for ES specimens.

3.3 Microscopic Observation

Fig.12 is the cross-sectional micrographs of the 10 and 1000 hours aged Ve-AS specimens. In the Ve-AS specimen, the fiber damage was occurred, however, the adhesion between fiber and resin was still good even after 1000 hours aging. Fig.13 is the cross-sectional micrographs of the 10 and 1000 hours aged Ve-ES specimens. In the Ve-ES specimen, the debonding between fiber and resin was observed around fibers, and it caused the gaps around and inside the fiber bundle. Such damages brought the strength reduction after aging. This result also showed the poor interfacial adhesion in the ES specimens. The damage pattern by aging was little affected by the matrix type, and the damages in Iso and Bis specimens were almost the same with Ve specimen.

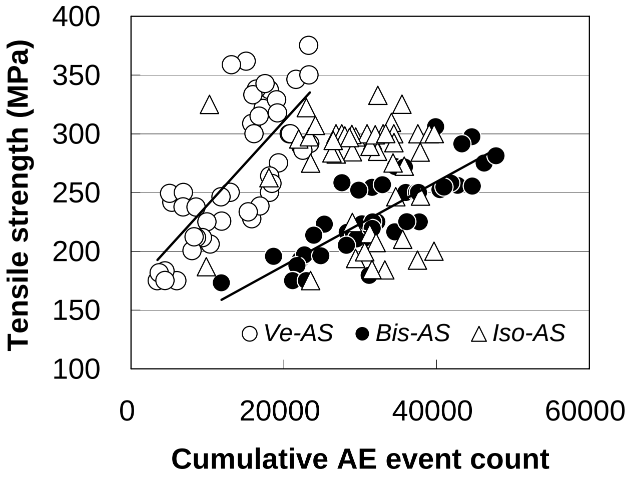

Fig.14 Relation between tensile strength and cumulative AE event count for AS specimens.

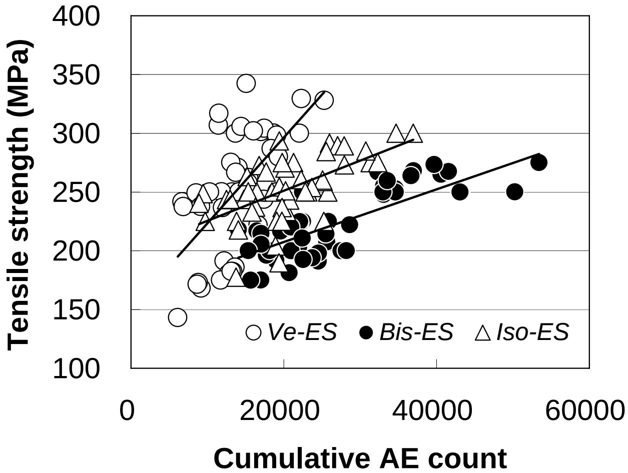

Fig.15 Relation between tensile strength and cumulative AE event count for ES specimens.

3.3 Discussion

Figs.14 and 15 show the relations between the tensile strength and the cumulative AE event count to final failure for the AS and the ES specimens, respectively. In all the specimens the linear

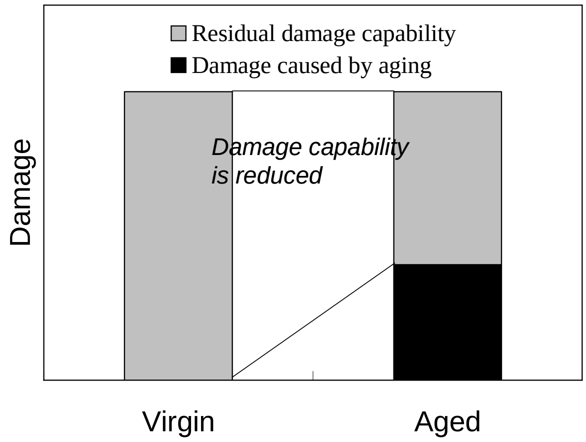

Fig.16 Concept of residual strength prediction,

correlations were obtained between the tensile strength and the cumulative AE event count independent of the matrix type and the fiber surface treatment. From these results, it is clarified that the strength reduction due to hydrothermal aging is caused by the reduction of the damage tolerance under tensile loading. It can be assumed that the total damage tolerance of the material is a constant independent of the loading and the environmental histories. Therefore it is considered that the internal damage is accumulated during the hydrothermal aging and the damage tolerance of the aged specimen is reduced (Fig.16). As a result, the tensile strength of the aged specimen is reduced. Therefore the residual strength after aging can be possible if the damage accumulation during aging process can be monitored by acoustic emission.

The residual strength prediction procedure proposed here is the following process;

1. Obtain experimentally the relation between tensile strength and cumulative AE event count by using test samples.
2. Monitor damage accumulation of the material during service condition by AE instrument.
3. By comparing the relation between strength and event count and monitored cumulative event count, the residual strength can be predicted successfully.

However, the AE monitoring instrumentation during service condition should be developed in order to apply this residual strength prediction concept.

4 Conclusion

This study dealt with the acoustic emission characteristics of the hydrothermally damaged GFRP, and the relation between tensile strength reduction and the AE characteristics was discussed in order to find the possibility to predict the residual strength of the aged GFRP. The relation between tensile strength and the cumulative AE event count showed the linear relation and it suggested that the strength reduction due to aging was caused by the internal damage accumulation during the aging process. From this result, it is suggested that the prediction of the residual strength after aging might be possible when the damage accumulation during the aging process can be monitored.

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