ELECTRICAL NDE METHOD USING IMPEDANCE MEASUREMENT FOR C/C COMPOSITES

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1 Introduction

C/C composites are expected to be applied to high temperature structures in the aerospace field, because of their high strength and high toughness at temperature exceeding 2273K.[1)2)] However, C/Cs has low reliability, because of incipient defects and non-uniform defects such as void, interfacial debonding, delamination and transverse cracks which were caused by the difference of the coefficient of thermal expansion between carbon fiber and matrix.

Especially, it was researched by the previous studies that the interfacial strength between carbon fiber and matrix was a major factor for the strength of C/Cs.[3)4)]

To establish the interfacial condition of C/C, non-destructive evaluation (NDE) by means of electrical method was proposed and verified in this study. Specifically, the correlation between fiber/matrix interfacial condition and electrical data was verified by the measurement of impedance and reactance. Also, mechanical properties were quantitatively estimated by the electrical data. This NDE can be applied for the inspection of C/C both before and after use, which will lead the improvement of C/C's reliability

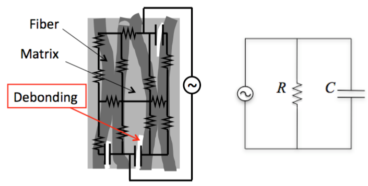
2 Experimental procedure

2.1 Electrical and Mechanical measurement

Unidirectionally reinforced C/C (UD-C/C) and 0°/90°cross-ply C/C (2D-C/C) produced by Across Co. were used in this study where Torayca ® M40 was used as reinforcements and the fiber volume fraction was 50%. And also, 3-dimentional reinforced C/C (3D-C/C) was used where Torayca ® M40 was used as reinforcements and the fiber volume fraction was 48 % with 16% for several direction, x, y and z. The interfacial condition between fiber and matrix was treated at 823K with air by the oxidation treatment (1~5hrs). Mechanical properties; tensile strength, interfacial bonding strength and inter-laminar shear strength, were measured to research the relevance with interfacial condition. Impedance measurement was performed using four point electrodes method which method can cancel a contact resistance occurred during test. In the electrical test, impedance Z, and resistance R, reactance X and a phase angle θ were measured with several frequencies (1kHz~20kHz).

2.2 FEM Analysis

In the present study, it is assumed that C/C is composed of a parallel circuit of *RC* and the interfacial debonding works as a capacitor as shown in Fig. 1. Thus, the role of debonding was analyzed using electrostatic field analysis software, VOLT PHOTO-Series Ver. 7.1, produced by PHOTON Co. The analysis model was composed of two fibers and surrounding matrix, and at three locations of fiber/matrix interface, debondings were introduced as denoted in Fig.2. The electric conductivities of fiber and matrix were assumed to be 1.25E+6$\Omega^{-1}\cdot m^{-1}$ and 6.1E+4$\Omega^{-1}\cdot m^{-1}$, respectively, and the relative permittivity of air was 1.0. The electrodes were placed at both ends of the model, that is, the longitudinal location of UD-C/C. The influence of length and gap size (thickness) of debonding on the electric current was evaluated.



$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + X^2}$$

$$X = \omega C$$

Fig.1 RC circuit model of C/C composite.

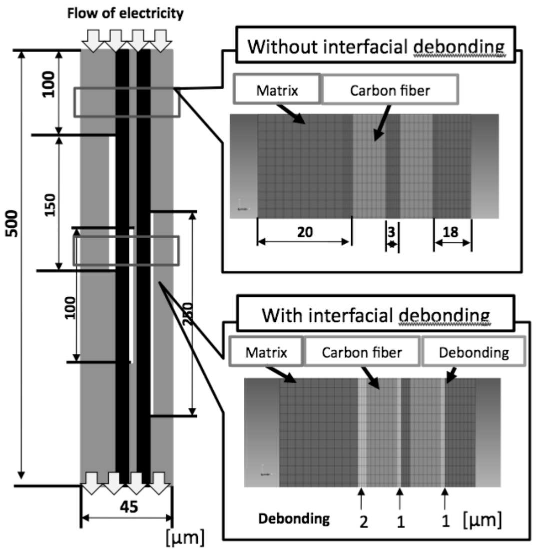
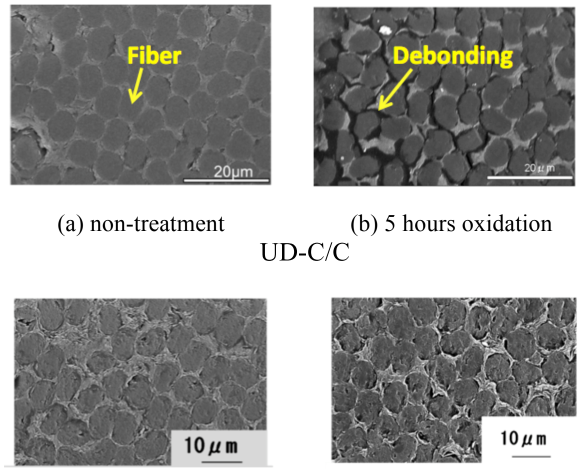


Fig.2 Model of FEM analysis.



(a) non-treatment (b) 5 hours oxidation
UD-C/C

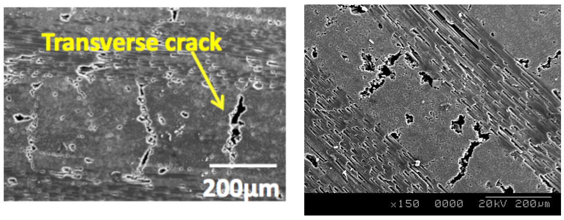
(a) non-treatment (b) 5 hours oxidation
2D-C/C

Fig.4 The interfacial debonding condition of UD and 2D-C/C by SEM.

3 Result and discussion

3.1 Result of experiment

The debonding rate of UD, 2D-C/C which was calculated by the equation in Fig.3 was increased with oxidation treatment as shown in Fig.3-4. At the same time, delamination and transverse crack in 2D, 3D-C/C were expanded by the oxidation treatment as a Fig. 5-6. That is, the weight loss by the oxidation means increase of interfacial debonding in UD-C/C, it means increase of interfacial debonding and delamination of 2D-C/C, and it means expansion of delamination in 3D-C/C.



(a) non-treatment (b) 5 hours oxidation

Fig. 5 Cross sectional views of 3D-C/C by SEM.

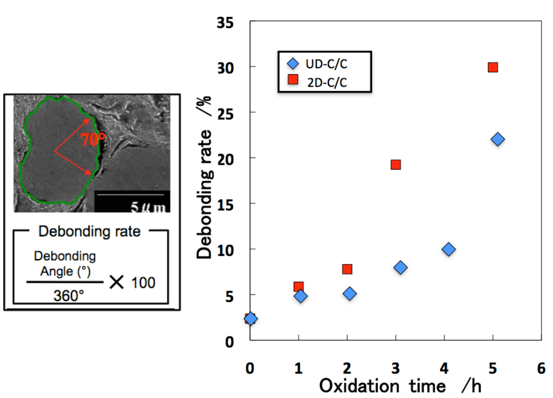
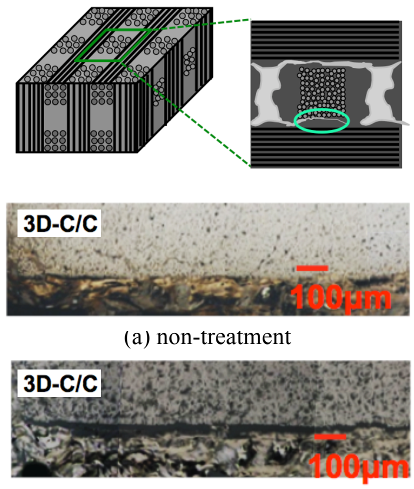


Fig.3 Relation between debonding rate and the time of oxidation treatment in UD- and 2D-C/C



(a) non-treatment

(b) 5 hours oxidation

Fig. 6 Condition of bundle/bundle interface in 3D-C/C.

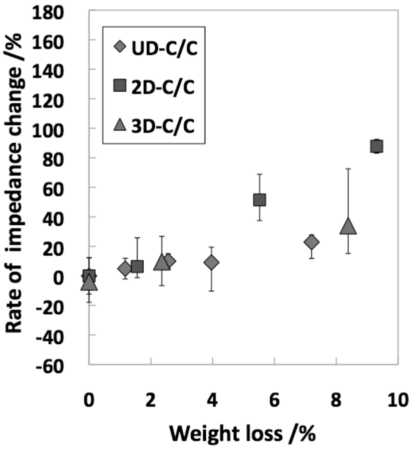


Fig. 7 Impedance change of C/C composites with time of oxidation treatment.

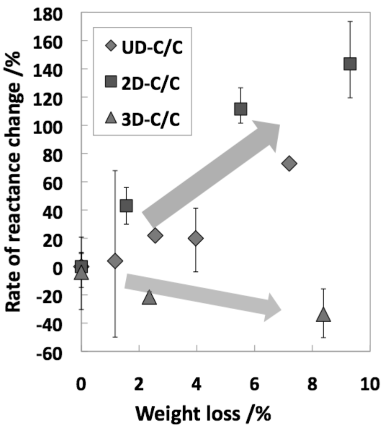


Fig. 8 Rate of reactance of C/Cs with weight loss.

Figure 7 shows results of impedance measurement. Impedance value increased with the increase of oxidation time, respectively. The relation between electrical data and interfacial condition was confirmed from this result.

And also, rate of reactance, which shows the amount of the change of reactance, of UD and 2D-C/C increased with the increase in weight loss as denoted in Fig. 8. This behavior was caused by increase of the working as a condenser of the interfacial debonding (<1μm) with increase of debonding rate. On the other hand, rate of reactance of 3D-C/C decreased with the weight loss. In the case of 3D-C/C, the change in the condition of interface between matrix and fibers was not seen. However, an expansion by the oxidation treatment of the micro cracks (<1μm) on the tip of delamination was verified. Hence, the degradation of the working of interfacial debonding as a condenser was caused.

The degradation of interlaminar shear strength according to increase in rate of impedance of 2D-C/C because of the effect by the delamination or transverse crack was shown in Fig.9. This result means that the relation between the data of impedance and interlaminar shear strength has correlativity. In contrast, the change in shear strength due to increase in rate of impedance was not confirmed in the case of 3D-C/C regardless of expansion of delamination. From this result, it was suggested that the mechanisms of the fracture of interlaminar were different in case of 2D and 3D-C/C.

Figure 10 shows the relation between tensile strength and rate of reactance of UD and 2D-C/C. The tensile strength of C/C is increased with the increase of rate of reactance up to 10%. The advancement of tensile strength and the increase of reactance *X* are most likely caused by the increase of the interfacial debonding between fiber and matrix. In the region of rate of reactance being larger than 10%, the tensile strength decreased with the increase of rate of reactance due to mixed factor of some defects. The correlation between reactance *X* and tensile strength was shown from this result, and it was suggested that the mechanical properties of UD, 2D-C/C could be forecasted using electric measurement.

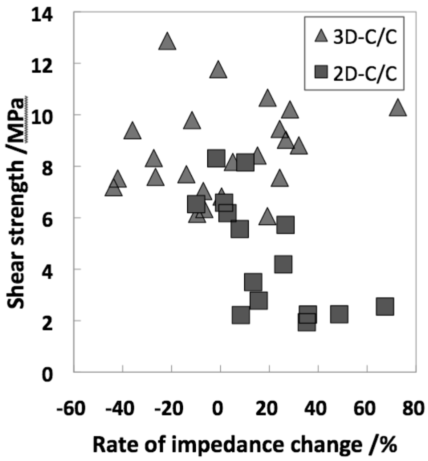


Fig. 9 Relation between shear strength and rate of impedance of UD, 2D-C/C.

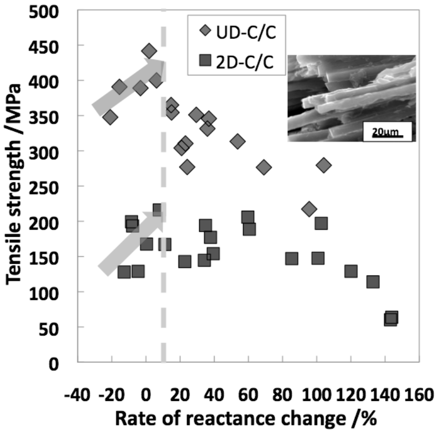
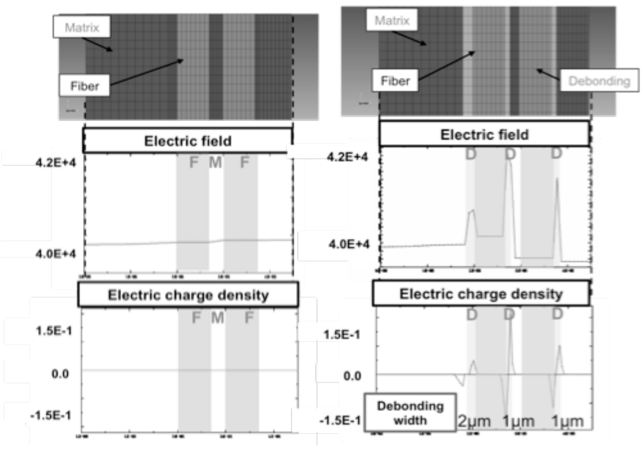


Fig. 10 Relation between tensile strength and rate of reactance of UD, 2D-C/C.

3.2 Analysis Result

Figure 11 shows the analysis result. The graphs of electric field and electric charge density without and with debonding are shown in Fig. 11 a) and b), respectively. The data were plotted in the transverse direction of fiber, and the abscissa shows the location of the model.



a) Without debonding **b)** With debonding

Fig. 11 Results of electric field and charge density in electrostatic analysis.

From Fig. 11, it is found that the electric field and electric charge density are affected by the interfacial debonding. Thus, it is supposed that the interfacial debonding behaves as a capacitor, even if the electric current is applied parallel to the fiber direction. The thickness of debonging has influence to electric properties. As can be seen in Fig. 11 b), the 1μm-thick debonding affects electric properties more than the 2μm-thick debonding. This result shows that narrow-gap delamination plays a role as capacitor, just like a commonly used capacitor, and small-gap defects like debondings have large influence on the reactance. Therefore, the possibility of the interfacial debonding detection by an electric measurement was suggested.

4 Conclusion

During a series of tests, the following conclusions were obtained.

The impedance Z of C/Cs increased in the increase in oxidation time. It was confirmed that increase of Z was caused by the degradation of electrical flow area occurred by oxidation.

The rate of reactance of UD and 2D-C/C increased in the increase of the oxidation time. The possibility that working of interfacial debonding (<1μm) as condenser was suggested.

In case of 2D-C/C, it was shown that the interlaminar shear strength depended on weight loss.

This phenomenon was not looked at 3D-C/C.

The correlativity of tensile strength of UD and 2D within the limited range was shown by the tensile strength.

From these results, it was suggested to be able to forecast mechanical properties using electrical measurement.

Reference

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