HYBRID COMPOSITE RING WITH MODIFIED RESIN FOR A ULTRA HIGH SPEED ROTOR

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1 General Introduction

Polymeric matrix composites (PMCs) possess superior specific energy density to metals, and therefore are widely used in many applications of high speed rotors such as in flywheel energy storage systems and centrifuge rotors. For a high speed rotor, hoop wound rotor would yield highest performance since the centrifuge forces are best supported in the longitudinal fiber directions. However, the overall resonance frequency and strength of rotors requires enhanced axial directional stiffness and strength together with the hoop direction. Therefore, in this regard, helical wound rotor yielding angle ply lamination has been widely used and the ply angle was optimally selected considering both hoop and axial directional performance. However, to enhance further the overall mechanical performance of the rotors, hybridization of fibers, adopting modified resin and control of fiber volume fraction can be also very critical factors.

Many papers were presented the research results on the rubber modified epoxy ([1]-[5]). In this study, the effects of the volume fraction of *carboxyl-terminated butadiene-acrylonitrile rubber (CTBN)* in the modified epoxy resin system and hybridization of glass and carbon fibers on the hoop directional stiffness and strengths are experimentally measured based on ASTM D2290[6].

10wt% CTBN was employed to a thermosetting epoxy resin in this paper. The static tensile properties and tension-tension fatigue life of both the neat and modified resin systems were firstly investigated.

The neat and modified resins were then infused into hybrid Carbon and E-glass fiber tows to fabricate composite rotors. The hybridization mixing ratio of T700 carbon and E-glass fibers was ranging from 100:0% to 50:50%, and both the static tensile tests and tension-tension fatigue tests were performed on hybrid composite rings using the Split Disk Method. The effects of CTBN and mixing ratio of reinforcements on the stiffness and fatigue life of polymeric matrix composites are discussed in this paper.

2 Experiments

2.1 Materials

A standard thermosetting epoxy resin with epoxide equivalent weight (EEW) of 175g/eq and viscosity of 5500mPa·s at 25°C, “EPIKOTE Resin 166”, was used in this paper. Both the epoxy resin and curing agent were provided by Hexion, Korea. The “Hycar CTBN 1300x8” was a reactive liquid rubber with a molecular weight of 3550g/mol and specific weight of 0.948, supplied by Kukdo Chemical, Korea.

The carbon fiber and glass fiber were applied to fabricate the hybrid composites in the test. The carbon fiber used in this study was “Torayca” T700SC-24000 from Toray Industries Inc., Japan, while E-glass fiber roving was provided by Owen Coring, Korea.

2.2 Fabrication Process of Test Specimens

The neat epoxy was mixed with required amount of CTBN. The mixture was then stirred at room temperature and degassed at a pressure of -1atm. The curing agent was finally mixed with the modified resin and degassed again to avoid bubbles during the curing process. Typically, to fabricate 54g of the toughened epoxy resin, 30g of resin, 15g of curing agent, and 5g of CTBN wad used.

The resin mixture was poured into silicon molds to prepare dogbone-shaped specimens. The filled molds were moved into a curing chamber, and the temperature was set to ramp from 30°C to 80°C in 2 hours, and maintained 80°C for 3 hours, the curing

temperature was ramped again to 120°C and maintained 120°C for 3 hours.
Three different laminates were fabricated using the hybrid filament winding process.
The carbon fiber with a layup sequence of [±50] was applied to both neat and modified resin systems to produce Type-1 and Type-2 composite specimens, respectively. In case of the Type-3 specimens, the glass fiber was added for hoop directional reinforcement to the neat resin system in such a sequence that the final composite laminate has a sequence of [$\pm 50C_3$, $\pm 13G_3$], which means 3 layers of carbon followed by 3 layers of glass. The fabrication process of composite ring specimens are explained in Fig.1.

2.3 Static Tensile Tests and Tension-Tension Fatigue Tests

The epoxy resin and composite specimens for static tensile tests were prepared according to ASTM D638 [6] and ASTM D2290[7], respectively. A universal test machine with a constant tensile speed of 1mm/min was employed to the static tensile tests for both resins and composites. The fatigue tests of resin systems were performed with the condition of stress ratio R=0.1 and cyclic loading frequency f=1 Hz. In case of composite fatigue tests, the strain control scheme was applied such that the maximum strain was 0.57%. In order to get the residual strain, a force control scheme was applied so that when the load was below zero the machine stopped. A loading frequency f= 0.25 Hz was set to the fatigue test for composite specimens. The preparation for composite ring tests are shown in Fig.2. The experimental setups for static and fatigue tests of composites are shown in Fig.3 and Fig.4, respectively.

3 Results and Discussions

3.1 Static Properties and Fatigue Behaviors of Resin Systems

The comparison of tensile properties between neat and modified epoxy resins are listed in Table 1. The Young's modulus and ultimate tensile strength (UTS) of the modified epoxy decreased by about 20%, due to the presence of the rubber particles. The similar results can be found in Ref.[1] and [2]. It was reported by Arias, et al.[4] that the modified epoxy has lower UTS because the higher possibility of stress concentration exists on the resin system including rubber particles. While the failure strain of the modified epoxy was almost two time of the neat one.
The tension-tension fatigue tests with stress ratio R=0.1 at room temperature were performed to investigate the fatigue behaviors of two kinds of resin systems. The fatigue life versus maximum stress (S-N) curves of the resin systems are presented in Fig.5. It is easily observed that at a lower stress level the fatigue life of modified epoxy is much longer than neat one since the rubber particles play a role on alleviation of the crack propagation. Basquin's equation was employed to fit the S-N curve based on the test data:

$$\sigma = A\left(N_f\right)^B \tag{1}$$

where A is the fatigue strength coefficient (FSC) and B is fatigue strength exponent (FSE). The values of FSC and FSE of neat and modified epoxies are listed in Table 2. Based on these values and above Basquin's equation, the fatigue lives of two kinds of resin systems can be estimated and compared each other. As an example, when the maximum stress is 35Mpa, the fatigue life of neat epoxy is 10000s. However, the modified epoxy has a fatigue life of 120000 s under the same stress level, which is more than 10 times of neat one.

3.2 Static Properties and Fatigue Behaviors of Composites

Three different combinations of composites were tested in this study. Table 3 explains the compositions of each composite as well as its Young's modulus in the hoop direction. It is clear that Type-3 is the stiffest because it was enhanced by glass fiber in the hoop direction.
It is critical to evaluate the deformations of high speed composite rotors. In this paper, the maximum limit of a cycle loading was controlled through strain value which was 0.57%, and the minimum stress value was controlled in such a way that the machine stopped when the load decreased to zero and the residual strain could be observed after given loading cycles.
The variation of residual strain curves with respect to number of loading cycles of Type-1 and Type-2 are shown in Fig.6.
Initially, residual strains of two types of composites were almost the same until N_f was about 2000. After

then, the residual strain of Type-1 increased rapidly, while Type-2 kept the previous increase rate until N_f was up to 10000. In the region of N_f =2000-10000, the residual strain of Type-2 was about 20-40% lower than that of Type-1. This phenomenon can be explained as the effect of rubber particles contributing to absorbing the energy to reduce the damages of the structure. The similar toughening mechanism was also presented by Manjunnatha, et al.[5] that the cavitation of the rubber particles can reduce the crack propagation rate. When N_f reached 10000-20000, the propagation of the damage of Type-2 accelerated meaning that the strain energy acceded the maximum value the rubber particles could accept.

The effect of the mixing ratio of reinforcements on the degree of damage was also studied in this paper. Fig. 7 presents the similar trend as Fig. 6 except that the values of residual strains in most test region are different. Type-3, which was enhanced using glass fiber in the hoop direction besides the reinforcement in the ±50°direction by the carbon fiber, exhibited superior ability to prevention from damage to Type-1 which was only enhanced in the ±50°direction using the carbon fiber. Despite the viscoelastic behavior possessed by the matrix, the glass fiber reinforcement in the hoop direction was much stiffer than the resin system so that much less deformation occurred on Type-3 than Type-1. It is noticed that the residual strain of Type-3 was 70% less than that of Type-1 when N_f was less than 50000.

The comparison of residual strains of three types of composites in the same loading cycles is shown in Table 4.

4 Conclusions

In this paper, the effects of rubber particles on the static and fatigue performance of resin systems are firstly investigated. The influences of the hoop directional e-glass reinforcement on the mechanical behaviors of composites used for high speed rotors are also presented. Based on the test results performed, the following conclusions are obtained in this study:

1. Although the Young's modulus and UTS of the rubber particles-modified epoxy resin are relatively lower, the failure strain and fatigue behavior is much better than the neat one.
2. The modified epoxy-based carbon fiber reinforcement plastic (CFRP) has a less residual strain than the neat epoxy-based one when the number of loading cycles is less than 20000, due to the presence of the rubber particles.
3. E-glass fiber reinforcement in the hoop direction reduces the residual strain in a large degree because of the stiffness of fiber dominant instead of the resin in the hoop direction when the number of loading cycles is less than 50000.

Table 1. Static tensile properties of epoxy resins

Material	UTS(Mpa)	E(Gpa)	Failure strain(%)
Neat epoxy	67.7	2.86	5.90
Modified epoxy	53.0	2.35	11.14

Table 2. Fatigue properties of epoxy resins

Material	FSC(Mpa)	FSE
Neat epoxy	110.94	-0.126
Modified epoxy	80.35	-0.071

Table 3. Three types of composite specimens and values of Young's modulus

Type	Composition (wt%)		E(GPa)
	Resin : CTBN	Carbon : Glass	
1	100:0	100:0	15.50
2	90:10	100:0	12.08
3	100:0	50:50	31.05

Table 4. Residual strains(%) of composites in given number of loading cycles

No. of Cycles	Type-1	Type-2	Type-3
1	0.095	0.121	0.028
2000	0.158	0.158	0.046
5000	0.215	0.168	0.061
10000	0.288	0.182	0.099
20000	0.351	0.217	0.189
50000	0.356	0.359	0.320
100000	0.362	0.366	0.330

Fig.1. Fabrication of composite rings: 1.winding 2.wound rotor 3.cutting 4.finished specimens.

Fig.2. Preparation for split disk tests: 1.specimens 2.polishing 3. strain gauge attachment 4.assembling

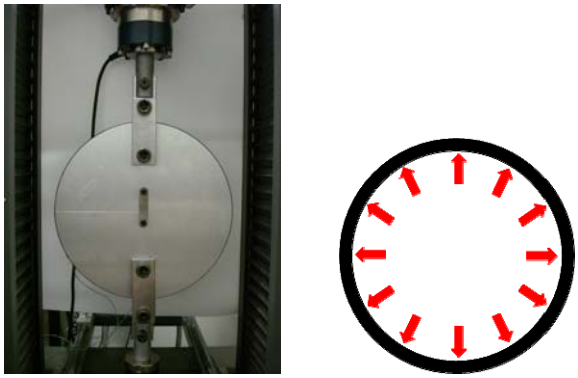

Fig.3. Experimental setup for the static tensile test of composite ring specimens.

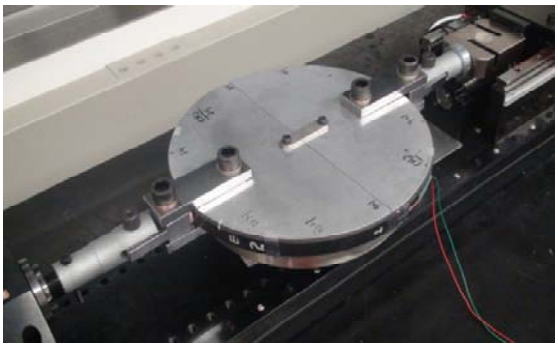

Fig.4. Experimental setup for the tension-tension fatigue test of composite ring specimens.

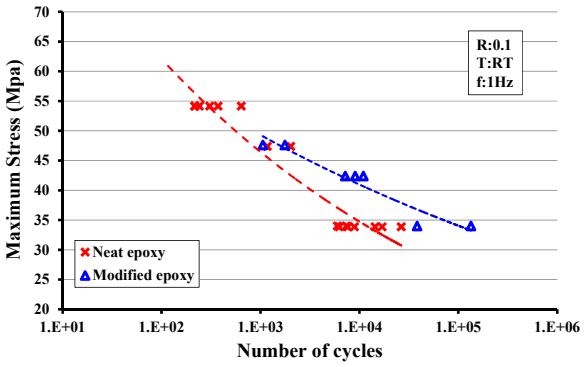

Fig.5. Maximum stress versus fatigue life of neat and modified epoxy resins.

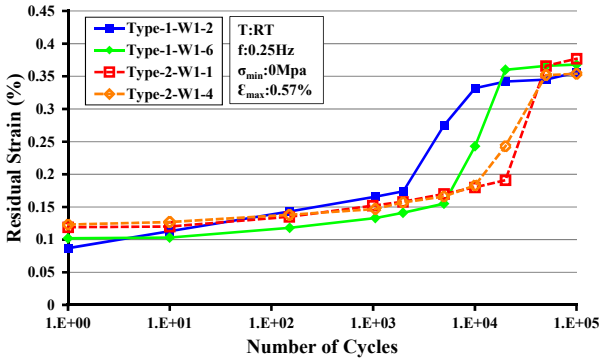

Fig.6. Comparison of residual strain with respect to number of cycles: Type-1 & Type-2.

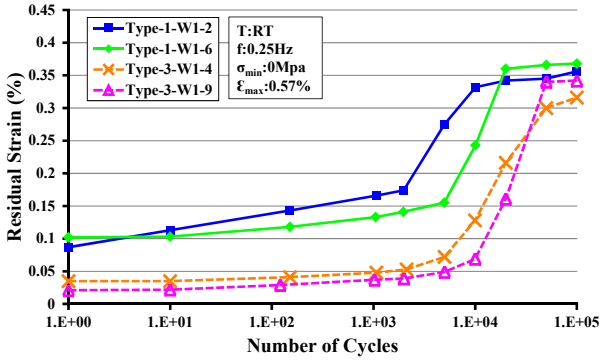

Fig.7. Comparison of residual strain with respect to number of cycles: Type-1 & Type-3.

References

[1] C. Manjunatha, A. Taylor and A. Kinloch "The cyclic-fatigue behavior of an epoxy polymer modified with micron-rubber and nano-silica particles". *Journal of Materials and Science*, Vol. 44, No. 16, pp 4487-4490, 2009.

[2] C. Manjunatha, S. Sprenger, A. Taylor and A. Kinloch "The tensile fatigue behavior of a glass-fiber reinforced plastic composite using a hybrid-toughened epoxy matrix". *Journal of Composite Materials*, Vol. 44, No. 17, pp 2095-2109, 2010.

[3] K. Jin, Y. Huang, Y. Lee and S. Ha "Distribution of Micro Stresses and Interfacial Tractions in Unidirectional Composites". *Journal of Composite Materials*, Vol. 42, No. 18, pp 1825-1849, 2008.

[4] L. Arias, M. Frontini and J. Williams "Analysis of the damage zone around the crack tip for two rubber-modified epoxy matrices exhibiting different toughenability". *Journal of Polymer*, Vol. 44, No. 5, pp 1537-1546, 2003.

[5] C. Manjunatha, S. Sprenger, A. Taylor and A. Kinloch "The tensile fatigue behavior of a glass-fiber reinforced plastic composite using rubber particle modified epoxy matrix". *Journal of Reinforced Plastics and Composites*, Vol. 29, No. 14, pp 2170-2183, 2010.

[6] American society for testing and materials "*Standard method for apparent hoop tensile strength of plastic or reinforced plastic pipe by split disk method*". American society for testing and materials, PA, 1964..

[7] American society for testing and materials "*Standard method for tensile properties of plastics*". American society for testing and materials, PA, 2003.