Fatigue Response of Centrally Notched Hybrid Quasi-Isotropic Composite Laminates at Elevated Temperature

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Abstract

The high performance hybrid composite laminates of Mg sheets sandwiched by APC-2 guasi-isotropic laminates were fabricated. Then, the hybrid specimen was drilled a hole of 4mm diameter centrally. First, we received the mechanical properties of ultimate nominal strength and longitudinal stiffness from tensile tests at elevated temperature. The notched strength at 150°C is almost 50% of the unnotched specimen at RT. However, the longitudinal stiffness has no obvious drops and changes irregularly.

Then, the cyclic tension-tension (T-T) tests were conducted at elevated temperature. The applied load vs. cycles (P-N) curve was adopted instead of conventional S-N curve. The P-N curves go downwards as the temperature increasing. However, it is interesting to find that the curves are close, but positions are completely reversed, if the load normalized by its own ultimate load at the corresponding temperature. That strongly hints the fatigue resistance of hybrid composite laminate is not significantly reduced.

1 Introduction

Composite materials have replaced conventional metals in industries due to their superior properties, such as high specific strength and stiffness, for recent years. However, the notch problem can not be avoided in many structural and engineering applications. Until now, there exists plenty of research work of notch effects, such as analysis of stress concentration, free edge effect, damage, and failure mechanisms. For example, Rybick et al. [1] investigated a composite plate with an elliptical hole and obtained the three-dimensional stress field analytically and numerically. Interlaminar stresses at the free edge, circular and elliptical holes will result in delamination as a main failure mechanism of a composite laminates plate. Tang [2] achieved the interlaminar stresses around a circular hole in composites plates. Vaidya et al. first set up a failure criterion in notched thin laminates [3] and then studied the ply thickness effect in the criterion in notched composites [4]. Also, the damage and inelastic deformation mechanisms in both notched thermosetting and thermoplastic matrix laminates were investigated. Additionally, Persson et al. [5] studied the effect of holemachining defects on the strength and fatigue life of notched composite laminates due to varied cyclic loading. Whitworth et al. [6] analyzed the fatigue response and behavior of both notched and unnotched graphite thermoplastic composite laminates. Ferreira et al. [7] obtained the fatigue response of glass-fiber-reinforced polypropylene composites under different test conditions and notched effect. Bathias [8] investigated the effect of notch on failure mechanism in advanced composite materials and predicted their lives. Takemura and Fujii [9] adopted fracture mechanics to evaluate the step-by-step fatigue damage in a centrally notched GRP composite laminate due to the combined tension-torsion cyclic loading. As for toughened composites, Brillhart et al. [10] obtained the effects of thickness and temperature on PEEK fracture response due to fatigue loading. Sun et al. [11] investigated the elastic-plastic behavior of AS-4/PEEK thermoplastic composite subjected to temperature variation. Mahieux et al. [12] did experiment to find out the failure mode of unidirectional high performance thermoplastic composite due to end-loaded bending at elevated temperatures when stress rupture. As for the temperature effect on matrix PEEK (Poly-Ether-Ether-Ketone) and composites due to varied loadings, the related references are limited. Jones et al. [13] obtained the mechanical properties of PEEK for engineering applications. Gao and Kim [14] did the parametric study of cooling rate on the interlaminar fracture toughness in carbon Fiber/PEEK composites. The medium rate would result in an optimal degree of crystallinity and high fracture toughness. Dimitrienko [15] investigated the mechanical behavior of composite materials and structures at high temperature. Sjogren and Asp [16] studied the effect of temperature on the growth of delamination in a Carbon/Epoxy composite due to cyclic loading. In thermoplastic composite laminates under static and fatigue loads, Lee and Jen [17] investigated the characteristics of strength, life, elastic constants and failure mode, and studied the theoretical formulation to predict fatigue strength and life at various stress ratios [18]. In AS-4/PEEK composite laminates Lee and Jen [19] obtained fatigue behavior at variable fatigue loading at varied stress ratios and frequencies, and developed the well-established fatigue failure criterion of muti-block loading to predict the life due to variable fatigue loadings [20]. According to the research results of these studies it can be found that that PEEK matrix reinforced with AS-4 carbon fibers (APC-2) is so far one of the best thermoplastic composite materials.

Until now, it is well-know that fiber-reinforced aluminum laminates (FRALL) have been successfully fabricated and commercialized [21]. The aramid fiber-reinforced aluminum laminates (ARALL) were marketed by the Aluminum Company of America for wide applications, such as aircraft lower wing skin, fuselage and tail skins [22]. Moreover, carbon fiber-reinforced aluminum laminates (CARALL) show a superior crack propagation resistance under T-T fatigue loading [23]. However, the above mentioned FRALLs contain epoxy-resin polymer. The service temperature is not expected to exceed 373K. Hence, their applications are restricted at lower temperature.

In this study, the laminated hybrid composites were developed for the Mg-based alloys, using the widely applied AZ31 sheets sandwiched with the high strength guasi-isotropic CF/PEEK prepregs. The PEEK polymer can sustain its mechanical properties up to 423K [24-25], thus it is postulated that the current Mg/CF/PEEK notched composite laminates might be utilized at higher temperatures. Herein, the mechanical properties subjected to tensile and the cyclic tests at elevated temperature were obtained. The failure mechanisms were observed. The response of mechanical behavior was highlighted.

2 Experimental

The prepregs of Carbon/PEEK (ICI Fiberite Co., USA) unidirectional plies were cut and stacked into guasi-isotropic [0/45/90/-45] laminates. The AZ31 (Al: 2.5-3%, Zn: 0.6-1.4%, Mn: 0.15-0.7%, Mg: balance) Mg sheets was supplied by Magnesium Elektron, England. The thickness of a alloy sheet is 0.5 mm after rolled, heated and weight flattened with scratch brushing. The density of AZ31 is 1.78 Mg/m^3 (approximately equal to polymer), melting point temperature is 627°C, ultimate strength is 260MPa, and stiffness is 2.07 GPa.

Prior to lamination, the slimmed AZ31 sheets were subjected to pretreatment by special chemicals in order to create the rough surface for better bonding with the APC-2 prepregs. The first trial was to mechanically polish the sheet surface use #200 SiC abrasive papers without chemical etching. After a series of tests, CrO_3-base etchant was the best and adopted.

The APC-2 guasi-isotropic prepregs were sandwiched with the AZ31 sheet to produce Mg/CF/PEEK laminated composites, expressed as AZ31/APC-2/AZ31/APC-2/AZ31. The modified diaphragm curing process as shown in Figure1 was adopted. The high speed drill with counterclockwise tungsten head was used to make a hole of 4mm diameter at the center in each specimen. The geometry and dimensions of a centrally notched hybrid composite specimen were shown in Figure 2.

An MTS-810 servohydraulic computer-controlled dynamic material testing machine was used to conduct the tensile test and constant stress amplitude T-T cyclic test with stress ratio = 0.1, frequency = 5Hz, sinusoidal wave form under load-controlled mode at elevated temperatures, such as 25°C (RT), 75, 100, 125, 150°C (slightly above APC-2 PEEK Tg = 143°C). An MTS 651 hot chamber was also installed to keep and control the specific temperature of a specimen inside for cyclic testing. A 25.4-mm MTS-634.11F-25 extensometer was used to monitor the strain continuously during the tests.

3 Results

The hybrid composite laminates were fabricated successfully. The mechanical properties of Mg/APC-2 hybrid five-layered composite laminates with and without notch of both lay-ups were listed in Table 1. The addition of mechanical properties in notched and unnotched cross-ply laminates at elevated temperature is for contrast and comparison with those of quasi-isotropic laminates. Generally, the ultimate strength decreases with the increasing of temperature. However, the longitudinal stiffness does not follow the trend. Mostly, it even becomes higher as the temperature rising. For simplicity, the ultimate load is adopted, instead of nominal stress, to avoid the complexity due to stress concentration in expressing the fatigue data. The applied load vs. cycles (P-N) curves of hybrid composite quasi-isotropic laminates at elevated temperature were presented in Figure 3. Needless to say all the loads normalized by the ultimate load at RT, the P-N curves are in the same trend. However, the normalized P-N curves by their own ultimate load at the corresponding temperature of hybrid composite quasi-isotropic laminates were described in Figure 4, it is found that the normalized P-N curves were reverse in sequence from top to bottom as the rising of temperature and also closely together less than 500 cycles.

4. Discussion

In unnotched specimens the strength of both lay-ups generally decreases as the rising of temperature, except a jump of strength in cross-ply laminates at 75°C due to the precipitation of Mg sheets. However, their stiffnesses even increase at high temperature. That is an evidence of sustaining stiffness of PEEK matrix at temperature below Tg. Next, in notched specimens the nominal stress is adopted, i.e., $\sigma_{ult} = P_{ult}/(W-d)t$. The ultimate strength, $\sigma_{ult,}$ of cross-ply laminates drops almost 50% of the unnotched, and σ_{ult} of guasi-isotropic notched laminates decreases to 65% of the unnotched. However, the longitudinal stiffness of both lay-ups decreases slightly of the notched, and it is irregular in the unnotched at elevated temperature.

In structural elements and connections notches cannot be avoided. To eliminate the complexity of stress concentration effect in notched laminates the fatigue date were treated by applied load vs. cycles (P-N) curves instead of conventional S-N curves. It is reasonable to expect the P-N curves go downwards as the temperature rising as shown in Fig.3, and the similar trend happens when normalized by the ultimate load at RT. However, the P-N curves become reverse in positions as shown in Fig.4, if normalized by the respective ultimate load at the corresponding temperature. That obviously tells us the fatigue resistance of notched hybrid composite laminates does not degrade even at elevated temperature. Thus, APC-2 and Mg/APC-2 composite laminates are one of the best candidate composite laminates in aerospace and defense industries. The theoretical and numerical analyses on the prediction of ultimate strength, stiffness and life incorporated with the finite element method and cumulative damage theories are still going on.

Due to the proper surface treatments the bonding between Mg sheet and APC-2 prepregs is good enough that no delaminations were found in the notched samples during fabrication. However, delamination would be started from the free edges and around the hole when applied cycles over 500~1000. The failure mechanism is a combined modes of cracking of Mg sheet, delamination, fiber breakage of 0˚ fibers, matrix cracking in 90˚ fibers, and shearing of ±45˚ fibers.

5 Conclusion

The centrally notched hybrid guasi-isotropic composite laminates were successfully fabricated. The tensile and cyclic tests were performed at elevated temperature. The concluding remarks are summarized as follows.

- Ultimate load and ultimate strength were obtained. Generally, they decrease as the temperature rising. Notched specimens lost 35~50% ultimate strength of the unnotched.
- Longitudinal stiffness decreases slightly and changes irregularly.
- The P-N curves were established. The normalized P-N curves by the ultimate load at the corresponding temperature become reverse in the original positions at elevated temperature.

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Table 1. The mechanical properties of notched and unnotched hybrid composite laminates of both lay-ups

Unnotched — $A=25\times2.6=65mm^2$

	Cross-Ply				Quasi-isotropic			
	P_{ult} (KN)	σ_{ult} (MPa)	ε_{max}	E_{11}(GPa)	P_{ult} (KN)	σ_{ult}(MPa)	ε_{max}	E_{11}(GPa)
25°C	44.2	680.00	0.019	34.79	27.00	415.38	0.020	21.76
	39.1	601.54	0.017		30.17	464.15	0.020	
	40.1	616.92	0.018		28.93	445.08	0.019	
average	41.13	632.82	0.018		28.70	441.54	0.020	
75°C	43.09	662.92	0.015	42.16	28.15	433.08	0.015	26.79
	45.67	702.62	0.015		27.49	422.92	0.014	
	42.31	650.92	0.015		28.48	438.15	0.016	
average	43.69	672.15	0.015		28.15	431.38	0.015	
100°C	42.35	651.54	0.016	38.02	26.52	408.00	0.015	27
	40.55	623.85	0.016		27.47	422.62	0.013	
	38.43	591.23	0.015		29.13	448.15	0.016	
average	40.44	622.21	0.016		27.71	426.26	0.015	
125°C	38.80	596.92	0.015	39.20	26.32	404.92	0.013	29.6
	35.08	539.69	0.013		26.25	403.85	0.012	
	38.58	593.53	0.014		24.35	374.62	0.011	
average	37.49	576.72	0.014		25.64	394.46	0.012	
150°C	32.62	501.85	0.010	42.27	25.76	396.31	0.014	26.2
	36.12	555.69	0.012		24.44	376.00	0 .014	
	34.25	526.92	0.012		24.27	373.38	0.012	
average	34.33	528.15	0.011		24.82	381.90	0.013	

Centrally Notched — $A=(25-4)\times2.6=54.6\ mm^2$

	Cross-Ply				Quasi-isotropic			
	P_{ult} (KN)	σ_{ult} (MPa)	ε_{max}	E_{11}(GPa)	P_{ult} (KN)	σ_{ult}(MPa)	ε_{max}	E_{11}(GPa)
25°C	19.44	356.04	0.010	32.3	18.07	330.95	0.010	29.8
	20.74	379.86	0.011		18.73	343.04	0.013	
	19.88	364.10	0.010		18.64	341.39	0.011	
average	20.02	366.67	0.010		18.48	338.46	0.011	
75°C	18.33	335.71	0.010	34.27	18.12	331.87	0.012	27.85
	18.68	342.12	0.009		17.82	326.37	0.013	
	19.2	351.65	0.010		17.61	322.53	0.012	
average	18.74	343.16	0.010		17.66	323.44	0.012	
100°C	20.54	376.19	0.009	34.77	16.73	306.41	0.011	24.5
	19.41	355.49	0.010		16.22	297.07	0.011	
	20.16	369.23	0.010		17.86	327.11	0.012	
average	20.04	366.97	0.010		16.94	310.26	0.011	
125°C	18.34	335.90	0.009	30	15.59	285.53	0.012	25.7
	18.21	333.52	0.009		16.15	295.79	0.012	
	18.21	333.52	0.010		15.61	285.90	0.011	
average	18.25	334.31	0.009		15.78	289.01	0.012	
150°C	18.2	333.33	0.009	31.99	14.17	259.52	0.011	23.3
	17.62	322.71	0.011		14.47	265.02	0.011	
	18	329.67	0.010		14.61	267.58	0.011	
average	17.94	328.57	0.010		14.42	264.10	0.011	

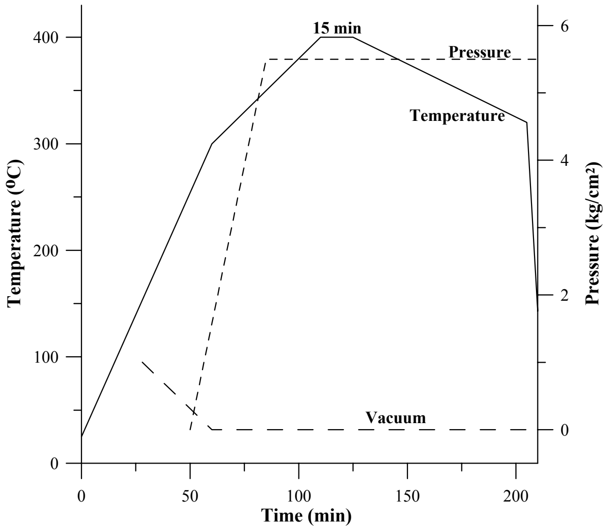


Fig. 1. Curing process for hybrid composite laminates

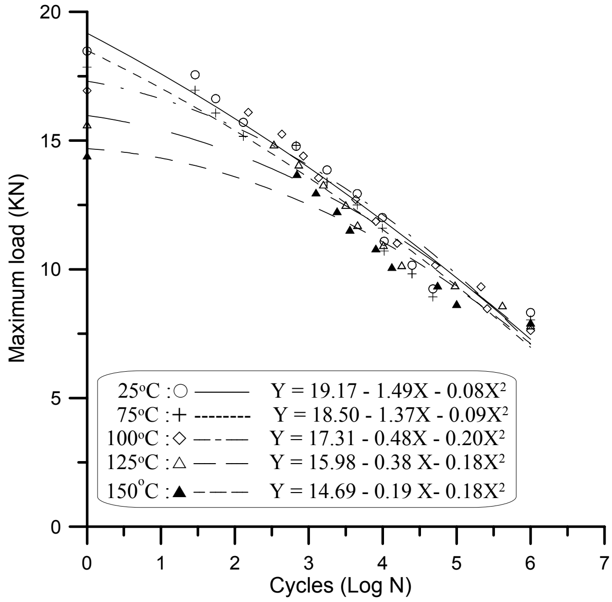
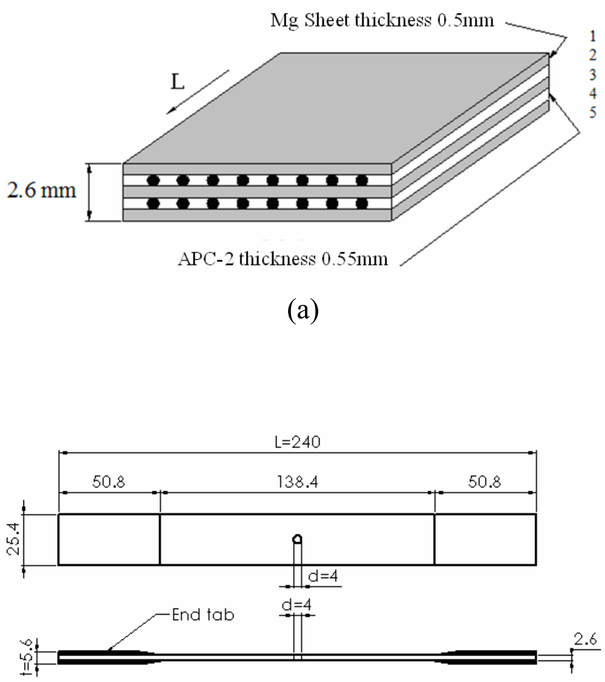


Fig. 3. The load vs. cycles (P-N) curves in centrally notched hybrid quasi-isotropic composite laminates at elevated temperature.



(a)

(b)

Fig. 2. The (a) geometry and (b) dimensions of a specimen

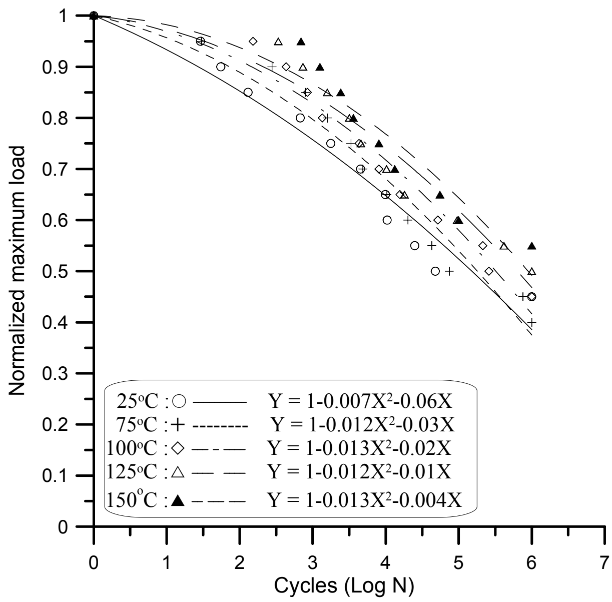


Fig. 4. The normalized load vs. cycles (P-N) curves in centrally notched hybrid quasi-isotropic composite laminates at elevated temperature.