FATIGUE STRENGTH OF STAMPABLE SHORT CARBON FIBER REINFORCED THERMOPLASTIC COMPOSITES

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Abstract

The static and fatigue behaviors of stampable discontinuous carbon fiber-reinforced polyamide (CF/PA) composite have been examined at different temperatures. The experimental results show that the static strengths in tension and compression are both decrease with increasing temperature. It is also found that the temperature dependence of the tensile and compressive strengths can be described by means of an exponential function of the Arrhenius type. Then, constant amplitude fatigue tests are carried out at different stress ratios and at different temperatures, respectively. The fatigue test results demonstrate that the S-N relationship of the discontinuous fiber composite significantly depends on stress ratio, and the fatigue degradation occurs most rapidly at the critical stress ratio in line with the observations made thus far for continuous fiber composites. The anisomorphic constant fatigue life diagram approach developed for continuous carbon fiber composites is applied to the stampable composite, and it is proved that this method can successfully be used to predict the fatigue life of the discontinuous carbon fiber composite at different temperatures as well as at different stress ratios.

1. Introduction

A strong demand for reducing the emissions of carbon dioxide pushes automotive industries to replace conventional materials for some components with composites of lower densities and to redesign vehicles accordingly [1]. Short fiber-reinforced thermoplastics are often chosen for this purpose because of their cost effectiveness and fast moulding to parts of complex shapes. For successful application of short fiber-reinforced thermoplastics to the components of structures, we need to overcome some difficulties involved and to establish an engineering method for predicting their mechanical properties, especially their fatigue life under complex loading during service.

Bernasconi et al. [2] have examined the fatigue behavior of short glass fiber reinforced polyamide 6 using the specimens that were cut out of injection moulded plates at different angles. They found that the in-plane anisotropies in the tensile static and fatigue strengths of injection moulded plates are approximately orthotropic and they can adequately be described by means of the Tsai-Hill static failure criterion [3] and its fatigue variant known as the Sims-Brogdon fatigue model [4], respectively. De Monte et al. [5] have observed similar features in the results for a similar short glass fiber-

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reinforced PA6 injection moulded composite at different stress ratios and temperatures. It was also observed by Bernasconi et al. [2] that the normalization by static strength approximately eliminates the effect of fiber orientation and thus allows identifying a master S-N curve. The existence of a master curve has been suggested early on by Mandell et al. [6] and Jia and Kagan [7] for the fatigue data obtained at different temperatures. These observations for short glass fiber-reinforced composite are similar to those for continuous carbon fiber-reinforced composites [8].

Injection moulded plates have a layered structure [9]. Typically, it consists of a skin layer of random distribution of fibers, a shell layer of longitudinal fiber distribution parallel to the mold flow direction and a core layer of transverse fiber distribution. The thickness of these layers determines the degree of in-plane anisotropy. In fact, De Monte et al. [5] have observed that the in-plane anisotropy of an injection moulded plate is higher in a thinner plate. Accordingly, Bernasconi et al. [2] have pointed out that the thickness of a core layer developed in real components that are fabricated by injection moulding depends on location and thus the transfer of the experimental results for a particular injection moulded plate specimens of constant thickness to the design of real components is not straightforward.

Recently, a different kind of short carbon fiber-reinforced thermoplastic composite, which is called a stampable short carbon fiber-reinforced thermoplastic composite, has been developed [10]. It is novel not only in allowing application to stamp forming to any shape but also in achieving enhanced strength owing to improved adhesion between short carbon fibers and matrix. The stampable short carbon fiber thermoplastic composite is very attractive not only because of its better formability, but also because of its in-plane isotropic and enhanced mechanical properties. In addition, the stampable short carbon fiber thermoplastic composites have no skin-core morphology across the thickness in contrast to the injection molded short fiber composites.

The present study aims to examine the static and fatigue behaviors of stampable short carbon fiber-reinforced polyamide composite. To this end, static tension and compression tests are first performed at different temperatures to quantify the temperature dependence of basic mechanical properties of the composite. Then, constant amplitude fatigue tests are carried out at different stress ratios and at different temperatures, respectively. Finally, the anisomorphic constant fatigue life diagram approach [11] with temperature as the parameter that was developed for continuous carbon fiber composites is applied to the stampable short carbon fiber-reinforced polyamide composite to evaluate the validity of this method to predict their S-N curves at different temperatures as well as at different stress ratios.

2. Material And Experimental Procedure

2.1. Material And Specimens

The material used in this study was a discontinuous carbon fiber-reinforced thermoplastic composite plate with in-plane homogeneous and random distribution of fibers. It is a polyamide variant of the stampable thermoplastic composite [10]. The stampable composite plate was fabricated by molding dry mats of short carbon fibers and Polyamide 6 resin films, which were laid up alternately, under 250°C melt-pressing condition. The volume fraction of fibers was 20%. The thickness of the composite plate was about 2.5 mm.

Two kinds of coupon specimens with different nominal dimension were cut out of 300 mm by 300 mm in-plane isotropic press molded composite panels. For static tension and tension-tension (T-T) fatigue tests in which only tensile load is applied to specimens, long specimens were employed; the dimensions of the straight-sided gauge part were length L_G = 58.8 mm and width W = 15 mm. For static compression, and compression-compression (C-C) and tension-compression (T-C) fatigue tests, on the other hand, short specimens were used to reduce a risk of buckling of specimen due to applied compressive load; the dimensions were gauge length L_G = 15 mm and width W = 15 mm.

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2.2. Test Procedure

Constant amplitude fatigue tests were performed under load control at room temperature (RT ~ 23°C) and high temperatures (70°C, 130°C). Fatigue load was applied to specimens in a sinusoidal waveform with a constant frequency of 5 Hz; the fatigue loading condition is based on the testing standard JIS K7083. Most specimens were fatigue tested for up to 10^6 cycles, and fatigue tests that lasted over this limited were terminated prior to fracture. In this study, fatigue tests were performed at four different values of stress ratio: $R = 0.1$, 10, –1.0, χ to elucidate the effect of stress ratio on fatigue behavior. The particular value of stress ratio designated by χ is defined as the ratio of compressive strength σ_C (< 0) to tensile one σ_T (> 0); i.e. $\chi = \sigma_C / \sigma_T$. It is called the critical stress ratio [11].

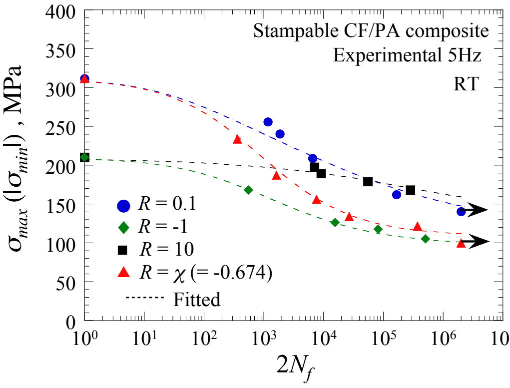

Figure 1. S-N curves for different stress ratios.

3. Fatigue Test Results and Discussion

3.1. Stress Ratio Dependence

The fatigue data for different stress ratios that were obtained from constant amplitude loading tests at room temperature (RT) are shown in Fig. 1 as plots of maximum fatigue stress *level* against the logarithm of number of reversals to failure. Note that while the values of $\sigma_{\max}$ are plotted for T-T loading and T-C loading at $R = \chi$, the absolute values of minimum fatigue stress $|\sigma_{\min}|$ are plotted for C-C loading and T-C loading at $R = -1$. The static tensile strength σ_T and compressive strength $|\sigma_C|$ that were obtained at the same test temperature are plotted at $2N_f$ = 1 as points of the ordinate in the S-N diagram. The dashed lines in Fig. 1 indicate the S-N curves fitted to the fatigue data.

In Fig. 1, it is seen that the S-N relationship for the stampable CFRTP greatly depends on stress ratio. The overall features of the sensitivity to mean stress in fatigue are similar to those reported so far for continuous carbon fiber composites. In particular, the sensitivity to fatigue becomes highest under T-C loading at $R = \chi$, suggesting that a larger value of alternating stress amplitude in fatigue loading has a more degrading effect on the fatigue of the composite. It is also seen in Fig. 1 that the S-N data for the stress ratios in the range $\chi < 0 \sigma R < 1$ can approximately be described by means of the smooth dashed curves that can be extrapolated back to the point indicating the tensile strength. By contrast, the S-N curves fitted to the fatigue data for T-C ($R = -1 < \chi$) and C-C ($R = 10$) loading can smoothly be connected to the compressive strength. Short specimens failed in a compressive mode under the completely reversed cyclic loading at $R = -1$, since $0 > \chi > -1$. Similar features were observed in the fatigue data obtained at high temperatures.

The fatigue data in Fig. 1 were normalized using the tensile strength in the cases $R = 0.1$ and χ and using the compressive strength in the other cases $R = -1$ and 10, respectively, and they were plotted in Fig. 2. Comparison of the normalized S-N relationships for different stress ratios in Fig. 2 reveals that the stress ratio of fatigue loading has a marked influence on the slope of S-N relationship. A largest gradient of S-N relationship is accompanied by fatigue loading at the critical stress ratio $R = \chi$. This suggests that fatigue damage develops most rapidly under fatigue loading at the critical stress ratio [11].

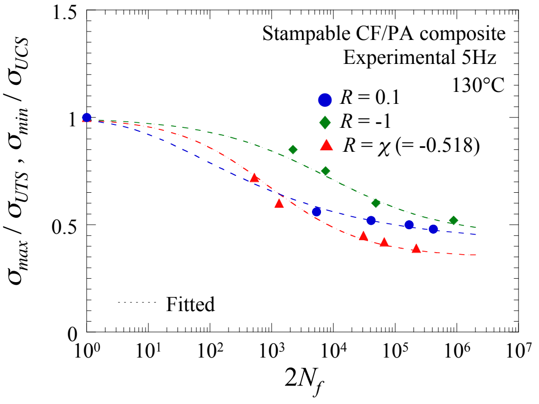

Figure 2. Effect of stress ratio on S-N curve.

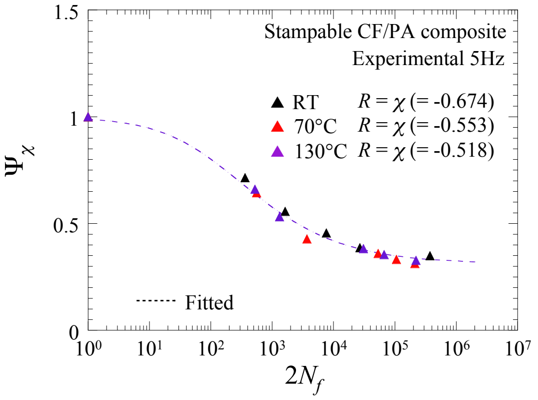

Figure 3. The master S-N curve for $R = \chi$.

3.2. Temperature Dependence of S-N Curve

The normalized S-N relationships at different temperatures almost agree to each other, regardless of stress ratio. This observantion seuggests that the effect of temperature on the S-N curve for the stampable short carbon fiber composite can approximately be eliminated by normalization of fatigue stress with respect to the associated static strength at the same temperature.

3.3. Normalized S-N Curve in Terms of the Modified Fatigue Strength Ratio

In general, the critical stress ratio of a composite depends on temperature. Accordingly, the reference S-N curve for the critical stress ratio depends on temperature, and thus it is affected by the difference between the values of critical stress ratio at different temperatures. A problem raised is that we need to deal with the stress ratio dependence of the referenced S-N relationship. To cope with this problem,

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we will use the modified fatigue strength ratio Ψ [8].

The S-N data for the different values of critical stress ratio at different temperatures that were normalized using the modified fatigue strength ratio are plotted in Fig. 3. From Fig. 3, it is seen that all the normalized fatigue data fall on a single S-N curve over the range of fatigue life, regardless of temperature. This observation suggests that the effect of temperature as well as the effect of stress ratio has substantially be removed by dealing with the fatigue data in terms of the modified fatigue strength ratio, and a master normalized S-N relationship can be identified for the stampable short carbon fiber polyamide composite with respect to fatigue loading at the critical stress ratio over a range of temperature.

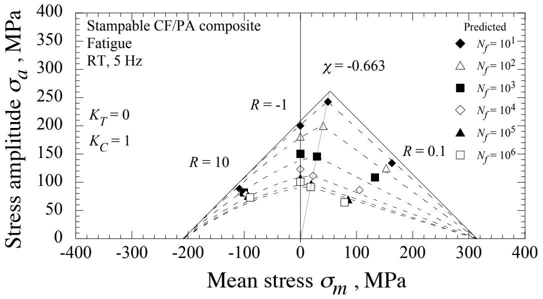

Figure 4. Anisomorphic constant fatigue life diagram at RT.

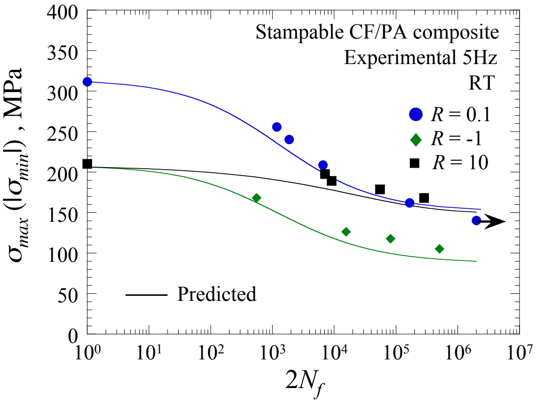

Figure 5. Predicted S-N curves for different stress ratios.

4. Fatigue Life Prediction for Constant Amplitude Loading

The anisomorphic constant fatigue life (CFL) diagram approach, which was recently developed by Kawai [11] with a view to developing an efficient engineering tool for fatigue life analysis of composites, enables us to take into account all the characteristics of the CFL diagrams for carbon fiber composites. In this engineering methodology, it is assumed that all the detail of the growth of damage is lumped together into the degradation of strength. Nevertheless, it was shown to be valid not only for the fiber-dominated fatigue but also for the matrix-dominated fatigue in continuous carbon fiber-reinforced thermoset composite. In this study, the anisomorphic CFL diagram approach is tested on the stampable discontinuous carbon fiber-reinforced thermoplastic composite at different temperatures.

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The anisomorphic CFL diagram for the stampable CFRTP composite at RT is shown in Fig. 4 by dashed lines, together with the experimental CFL data that are indicated by symbols. From Fig. 4, it is seen that the anisomorphic CFL diagram agrees well with the experimental CFL diagram in the tested range of fatigue life. Therefore, this observation proves that the anisomorphic CDL diagram approach can be applied to the stampable CFRTP composite at RT.

The experimental results obtained from this study elucidate that the CFL diagram for the stampable CFRTP composite at RT is asymmetric about the alternating stress axis, and the peaks of the CFL envelopes for different constant values of life appear under fatigue loading at a stress ratio close to the critical stress ratio $\chi = -0.66$. These features observed in the stampable discontinuous carbon fiber-reonforced polyamide composite are similar to those for continuous carbon fiber-reinforced epoxy composites [11].

The S-N relationships predicted using the anisomorphic CFL diagram are compared with the experimental results in Fig. 5. This figure shows comparisons between the predicted and experimental S-N relationships for different stress ratios at room temperature; in these figures, predictions are indicated in solid lines. Except for the slightly conservative predictions of the fatigue lives for $R = 10$, the predicted S-N curves agree well with the observed S-N relationships. Note that the calculations for $R = 0.1$, 10, and –1 give pure predictions using the anisomorphic CFL diagram, since the fatigue data for these stress ratios were not used when constructing the anisomorphic CFL diagram. Therefore, we can evaluate the predictive accuracy of the anisomorphic CFL diagram approach by comparing the predictions with the fatigue data for these stress ratios.

5. Conclusions

The effects of stress ratio and temperature on fatigue life of a stampable short carbon fiber-reinforced polyamide composite were examined. To this end, static tension and compression tests were first performed at different temperatures (RT, 70°C and 130°C) to quantify the temperature dependence of basic mechanical properties of the composite. Then, constant amplitude fatigue tests were carried out at different stress ratios (0.1, χ, and 10) and at different temperatures (RT and 70°C), respectively. Finally, the anisomorphic constant fatigue life diagram approach with temperature as the parameter that was developed for continuous carbon fiber composites was applied to the stampable short carbon fiber composite. The results obtained from this study may be summarized as follows.

(1) The S-N relationship for the discontinuous carbon fiber composite significantly depends on stress ratio, and fatigue degradation occurs most rapidly at the critical stress ratio $R = \chi$ in line with that for continuous carbon fiber composites, regardless of temperature.

(2) The effect of temperature on the S-N curve for the stampable short carbon fibe composite can approximately be eliminated by normalization of fatigue stress with respect to the static strength at the same temperature. The S-N curves for the critical stress ratios at different temperatures are associated with different values of stress ratio. The effect of stress ratio as well as the effect of temperature on the S-N curve for the critical stress ratio can be removed by means of the modified fatigue strength ratio.

(3) The anisomorphic constant fatigue life diagram approach with temperature as the parameter that was developed for continuous carbon fiber composites can successfully be used to predict the S-N curves for the stampable discontinuous carbon fiber-reinforced thermoplastic composite at different temperatures as well as at different stress ratios.

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