PREDICTION OF DAMAGE ENERGY UNDER CREEP-FATIGUE INTERACTION IN POLYMER MATRIX COMPOSITES

تخمين طاقة الدمار الناتجة من تداخل تأثير الزحف-الكلال في المواد المركبة ذات الأساس اللدائني

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ABSTRACT

In this investigation, the effect of creep-fatigue interaction on the carbon fiber reinforced polymer, UT500/135 material, was studied, using resulted damage energy and its relation to the hysteresis loop energy. By testing many of specimens under fatigue test with different hold times at 50^{o}C. The results showed that the occupation ratio of the damaging energy is very small compare to that for other materials as ferrous materials, and that most of the dissipated energy is transformed into heat.

On the other hand, the relation between cracked area per cycle with the damage energy was determined, so the results showed that this relation can be used as a useful tool to estimate the life of the material

Key words; creep-fatigue interaction, UT500/135, damage energy, hysteresis loop energy, Cracked Area.

الخلاصة:

في هذا البحث تمت دراسة تاثير تداخل الزحف مع الكلال على مادة لدائنية مقوّاة بألياف الكربون, و هي مادة (UT500/135), و قد تم دراسة طاقة الدمار الناتجة من ذلك التداخل بشكل خاص, و علاقتها بحلقة الطاقة الهستيرية الناتجة عن التداخل المشترك للزحف و الكلال على المادة, و ذلك من خلال مجموعة من العينات التي تم تعريضها الى اختبار الكلال مع فترات مسك مختلفة عند درجة حرارة 50 مئوية. و قد اظهرت النتائج ان النسبة المحسوبة من طاقة الدمار صغيرة جدا مقارنة بتلك التي تنتج في مواد اخى كالمواد الحديدية, و ان اغلب تلك الطاقة تتبدد الى حرارة.

من جهة اخرى, تم ايجاد العلاقة بين مساحة الشق الناتج عن الكلال مع طاقة الدمار الناتجة عن تداخل تأثير الزحف مع الكلال, حيث تبين ان هذه النسبة ممكن ان تكون اداة دقيقة لتخمين عمر المادة.

1. Introduction

At present, due to the energy saving concerns, there is an increase demand for lightweight structures for transportation industry, electric power wind generators among others. So the needs for real long-time mechanical performance prediction become quite important. For instance, the standards for buried GFRP (Glass Fiber Reinforced Polymer Composites) pipes demand more than 10,000 hr of creep tests in order to extrapolate data for two decades (in the time log scale) with a high level of confidence[1].

John Montesano et al. [2] investigated the fatigue behavior of a braided carbon fiber polymeric composite plate. The method yielded a fatigue threshold value that was in excellent agreement with that obtained through a conventional experimental test program. The damage mechanisms responsible for the increased heat dissipation and ultimately failure were identified, which provides support for the existence of a fatigue threshold for this material. Energy dissipation was also used as an indicator to determine the high cycle fatigue strength, providing support for the thermographic

approach. A relationship between the dissipated heat, the intrinsic energy dissipation and the number of cycles to failure has been clearly established.
The accelerated methodology proposed by **Miyano et al**. [3] on carbon and glass fiber reinforced polymers (CFRP and GFRP) laminates, rests on the fact that the time-superposition principle is the same for static, creep and fatigue strengths. Although not universally verified, it has been used successfully to predict fatigue lifetimes of many typical composites. In that context time-dependent failure criteria for viscoelastic materials is reviewed.
Since many components are subjected to complex loading cycles at high temperatures, high temperature low-cycle fatigue (LCF) experiments with hold time can be very meaningful tests for understanding the creep-fatigue interaction phenomenon under complex loading conditions. Therefore, in the study of creep-fatigue interaction, a damage formation mechanism is important in understanding a prediction for fatigue lives [4].
In LCF tests it had been reported that, as the hold time is increased, the fatigue life is decreased at a fixed test temperature (1–3), and the reason for life reduction is reported to be due to the creep effect of stress relaxation, which makes an additional plastic strain enlarging the hysteresis loop during hold time. In LCF, the evolution of hysteresis results in the degradation of materials, most of the hysteresis loop energy or the dissipated energy during one fatigue cycling is known to be transformed into heat, and only a small portion of the energy, i.e., damaging energy is accumulated in the specimen to bring about a material fracture. So an estimation of the amount of damaging energy coming out of the loop energy has an important meaning because some accumulated critical amount of damaging energy during fatigue causes the final fracture [5].
In this study, an estimation of the damaging energy is attempted by using the power law relation between the fatigue life and the hysteresis loop energy, and the quantitative values of it were compared with the fractured area per cycle.

2. Material:

The material is a carbon fiber reinforced polymer, UT500/135 which consists of twill-woven UT500 carbon fiber and 135 epoxy resin [6]. The mechanical properties of the material, as tested by Yasuo Hirose [7], are:
Young's Modulus is 54.9 GPa
Shear Modulus is 3.23 GPa, and
Poisson Ratio is 0.33.

3. Process:

Round-type specimens with a diameter of 4mm and a gauge length of 20mm were tested.. Strain-controlled LCF tests, with a strain rate of 2.02×10^{-4}/s, were carried out in a local heater with a capacity of (120°C) attached to a dynamic fatigue testing machine. The total strain range ($\Delta\varepsilon_t$) was from ±1.5% to ±2.5% and the testing temperature was 50°C. The variation was in the holding time of the specimens in tension or compression status at the testing temperature from 1 minute to 30 minutes.

4. Theoretical structure:

Under LCF conditions with or without hold time, the relation between the number of cycles to failure (N_f) and the plastic strain range ($\Delta\varepsilon_p$) [8]:

$$\Delta\varepsilon_p = CN_f^c \text{.................(1)}$$

where (C) is the material constant and (c) is Coffin-Manson exponent. Similarly, the power law relation between the number of cycles to failures (N_f) and the hysteresis loop energy per cycle (ΔU) is [9]:

$$\Delta U = CN_f^d \text{...................(2)}$$

where(C) is the material constant and (d) is the exponent.

The hysteresis loop energy which consists of both the peak stress and the plastic strain range may be a reasonable parameter to express the temperature dependence of fatigue lives. The concept of a hysteresis loop energy is the dissipated energy per cycle which considers both stress and strain. So the hysteresis loop energy is regarded as a reasonable parameter to identify the fatigue life related to temperature. Even though the energy dissipation through heat is actually dominant in LCF hysteresis, from the empirical relations of Eqs. (1) and (2), the damaging energy per cycle, which may be too small to be measured directly, can be estimated. If it is assumed that the failure occurs when the accumulated damage energy reaches a characteristic critical amount of energy i.e., either damaging energy for failure or
fatigue toughness [10], it leads to the following equation:

$$\Delta U_d N_f = U_{FT} \quad \text{..................(3)}$$

where (ΔU_d) is the damaging energy per cycle, and (U_{FT}) is either the accumulated damaging energy for failure or fatigue toughness. Therefore, combining Eqs. (2) and (3), one gets a relation for the ratio of the damaging energy per cycle to the hysteresis loop energy, which may be almost all heat[11].

$$\frac{\Delta U_d}{\Delta U} = \frac{U_{FT}}{C N_f^{1+d}} \quad \text{..................(4)}$$

In right part of Eq. (4), (C) and (d) can be obtained from the power law relation between fatigue life and the hysteresis loop energy in Eq. (2), The only unknown variable is (U_{FT}). So if the value of (U_{FT}) is determined, the ratio of the damaging energy per cycle to the hysteresis loop energy can be determined. Also the quantitative value of hysteresis loop energy yields the quantitative value of damaging energy per cycle.

5. Results and Discussion:

Figure (1) gives an experimental indication of the hysteresis loop energy of creep-fatigue for UT500/135 material, which is determined by means of spectroscopy. In this plot, the fatigue life with hold time, which is tested by fatigue test machine manufactured locally with attached electrical furnace at the Technical institute of Karbala, is observed to be reduced in about (45%) as the hold time increases from 1miniute to 30 minutes, and this phenomenon is coincident with many studies [5, 12] in that the fatigue life under creep-fatigue interaction conditions are decreased with increasing test temperatures and hold times. The power law relation between fatigue life and the hysteresis loop energy as shown in Figure (1) shows the general tendency toward decreasing fatigue lives in about (50%) with increasing hold times from 1miniute to 30 minutes.
In determining the characteristic damaging energy for failure or the fatigue toughness (U_{FT}), there are several methods for estimating the quantity of (U_{FT});
(a) The latent energy of cold working [13],
(b) The work required for tensile loading to failure [11],
(c) The extrapolation of fatigue data [14, 15], and
(d) Microscopic measurements of the damage [13, 16].
Among them, the method of [b] is used in this study, because it shows good reproducibility and a scattering of less than ±2.0% [10]. Tensile tests are conducted at two specimens at the test temperatures of 50^{o}C, to measure the total energy needed for tensile fracture. The average value of the total energy for the test temperature is 2.835MJ/m^3.

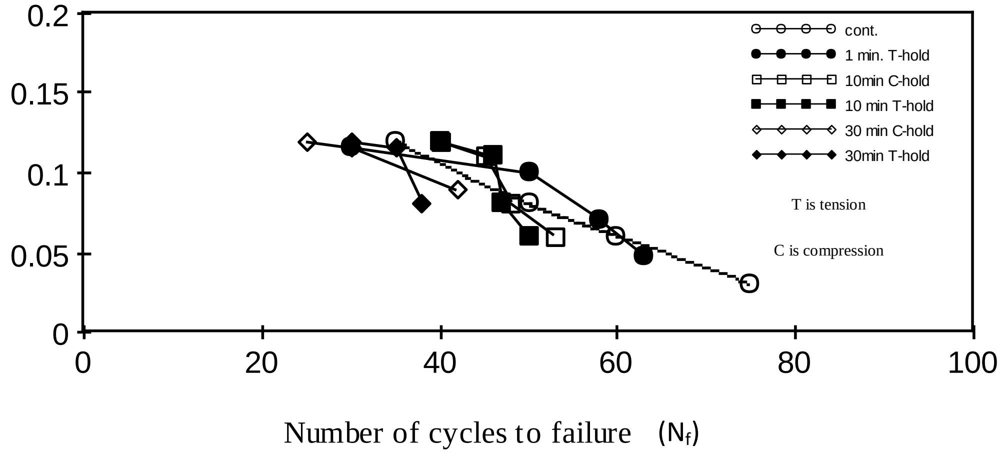

Figure (1). The empirical relations of the power law relations between the fatigue life and the hysteresis loop energy for UT500/135 at 50^oC.

The empirical equations that obtained from the test can be outlined as the following:

$\Delta U = 0.084 N_f^{-2.58\times10^{-4}}$ (cont.)……………….….(5)

$\Delta U = 0.094 N_f^{-2.85\times10^{-4}}$ (1 min. T-hold)……………(6)

$\Delta U = 0.108 N_f^{-4043\times10^{-4}}$ (10 min. C-hold)………..…(7)

$\Delta U = 0.111 N_f^{-4.006\times10^{-4}}$ (10 min. T-hold)………….(8)

$\Delta U = 0.132 N_f^{-7.822\times10^{-4}}$ (30 min. C-hold)…………..(9)

$\Delta U = 0.123 N_f^{-6.968\times10^{-4}}$ (30 min. T-hold)…...........(10)

Here, the concept of hysteresis loop energy is the dissipated energy per cycle which considers both stress and strain. So the hysteresis loop energy is regarded as a reasonable parameter to identify the fatigue life connected to hold times.

It is assumed that the fatigue toughness is regarded as the work of tensile loading to failure, i.e. heat transformed during monotonic loading is neglected in the damaging energy for failure, and the fatigue toughness is constant when the fracture mechanism is the same, regardless of the hold time at a fixed temperature.

From Eq. (4), ($\Delta U_d/\Delta U$) can be obtained by giving the corresponding values, and the results are shown in Table (1);

TABLE 1: The Determination of ($\Delta U_d/\Delta U$)for Various Test Conditions for UT500/135 at 50^oC.

Wave shape	Total strain range ($\Delta\varepsilon_t$)			
	±1.5%	±1.7%	±2.0%	±2.5%
continuous	0.021	0.023	0.026	0.028
1min T-hold	0.023	0.025	0.027	0.031
10min C-hold	0.035	0.031	0.030	0.027
10min T-hold	0.04	0.036	0.034	0.03
30min C-hold	0.068	0.042	0.040	0.037
30min T-hold	0.078	0.059	0.043	0.032

First, the ratio of damaging energy per cycle to the hysteresis loop energy is increased with an increase in the total strain range ($\Delta\varepsilon_t$)for continuous cycling and 1 minute tensile-hold cycling in about (30%), and this trend is coincident with the result that the fatigue life is reduced with an increase in the total strain range[4]. Also, the tendency, that the ratio increases with an increase in the hold time at a given total strain range, shows good agreement with that of fatigue life with hold time. This results that the ratios of damage to hold time have the range of 10^{-2}. It also implies that most of the dissipated energy is transformed into heat. On the other hand, when the hold time is longer or equal to 10 minutes, the ratio is decreased in about (70%) with an increase in the total strain range. This phenomenon can be explained in such a way that an increment in hold time causes increasing creep, and that the time dependent processes result in a decrease in the ratio[1]. That is, as referred to in Table (2), the absolute value of the damaging energy per cycle decreases with strain although the ratio of occupation increases.

On the basis of the above results, the absolute damaging energy per cycle (ΔU_d) is summarized in Table (2) by substituting the hysteresis loop energy (ΔU) in Eq. (4) with the results of Table (1). All the results of (ΔU_d) in Table (2) show the same tendency of ($\Delta U_d/\Delta U$) in Table (1), but the value of damaging energy is decreased in about (30%) with an increasing total strain range, even when the hold time is shorter than 10 minutes in which ($\Delta U_d/\Delta U$) is increased with the total strain range, so this result is the same that obtained by Guedes [1] . The explanation of this specific result could be interpreted by the role of time dependent processes which contribute to damage accumulation independent of the fatigue damage. In a smaller total strain range in which the total failure time is relatively longer because of the longer fatigue life with hold time, the accumulation of creep damage is dominant as well as that of fatigue. So the ($\Delta U_d/\Delta U$)is larger for a relatively small total strain range, but the variation of (ΔU_d) shows an inverse phenomenon. That is the value of damaging energy decreases with the increasing in total strain range, showing general fatigue properties, because the increase of hysteresis loop energy (ΔU), which causes the consequent decrease of (ΔU_d) with total strain range, overcomes the effects of the occupation ratio.

TABLE 2: The Determination of (ΔU_d) for Various Test Conditions for UT500/135 at 50^{o}C. (All in MJ/m^3)

Wave shape	Total strain range ($\Delta\varepsilon_t$)			
	±1.5%	±1.7%	±2.0%	±2.5%
continuous	0.0033	0.0003	0.0021	0.0011
1min T-hold	0.0043	0.0033	0.0027	0.0025
10min C-hold	0.0060	0.0041	0.0030	0.0019
10min T-hold	0.0068	0.0052	0.0036	0.0024
30min C-hold	0.0121	0.0061	0.0042	0.0029
30min T-hold	0.0129	0.0086	0.0052	0.0023

6.The Cracked Area per Cycle

From the basic assumption that the damaging energy per cycle is consumed to the crack growth during fatigue cycling, the cracked area per cycle is closely related to the damaging energy within the hysteresis loop energy. In a typical LCF crack growth, an empirical growth law [17] is given by Eq. (11),

$$\frac{da}{dN} = Qa \quad \textbf{...........(11)}$$

where (Q) is the constant, which can be determined by measuring the slop of the curve drated by crack length verses crack growth rate, and (a) is the crack length. Crack growth rates during LCF may be determined by several methods, but the general approach is known to be striation counting [18]. In this study, the relationship between the crack length and the striation spacing is discussed by a SEM fractograph analysis, to satisfy the linear relationship of Eq. (11). The striation spacing is increased at a fixed crack length when the fatigue life is decreased as shown in Figure (2), where the slope in Figure (3) is the same as (Q) in Eq. (11). Therefore, from the assumption that the shape of a crack is semicircular [19], the cracked area per cycle may be proportional to the crack length and the crack growth rate, and that is given by Eq. (12).

$$Cracked\ area\ per\ cycle \propto \frac{da}{dN}\left(= Qa\right) \times a = Qa^2 \quad ....(12)$$

From the above results, it is clear that the damaging energy per cycle depends on the empirical constant (*Q*), although the comparison of each absolute value is impossible because the damage accumulation results in not only the formation of a crack surface but also the formation of a 3-dimensional plastic deformation. However, it is considered that the cracked area may give apparent information about the damaging energy. The comparison between damaging energy and (*Q*) is done from this approach based on the above concept, and each value of damaging energy and Q show almost the same tendency, so this fact it the same that appeared by Jeong and Nam [4] . It reflects the dependence of the damaging energy on the crack growth area, as shown in Figure (3).

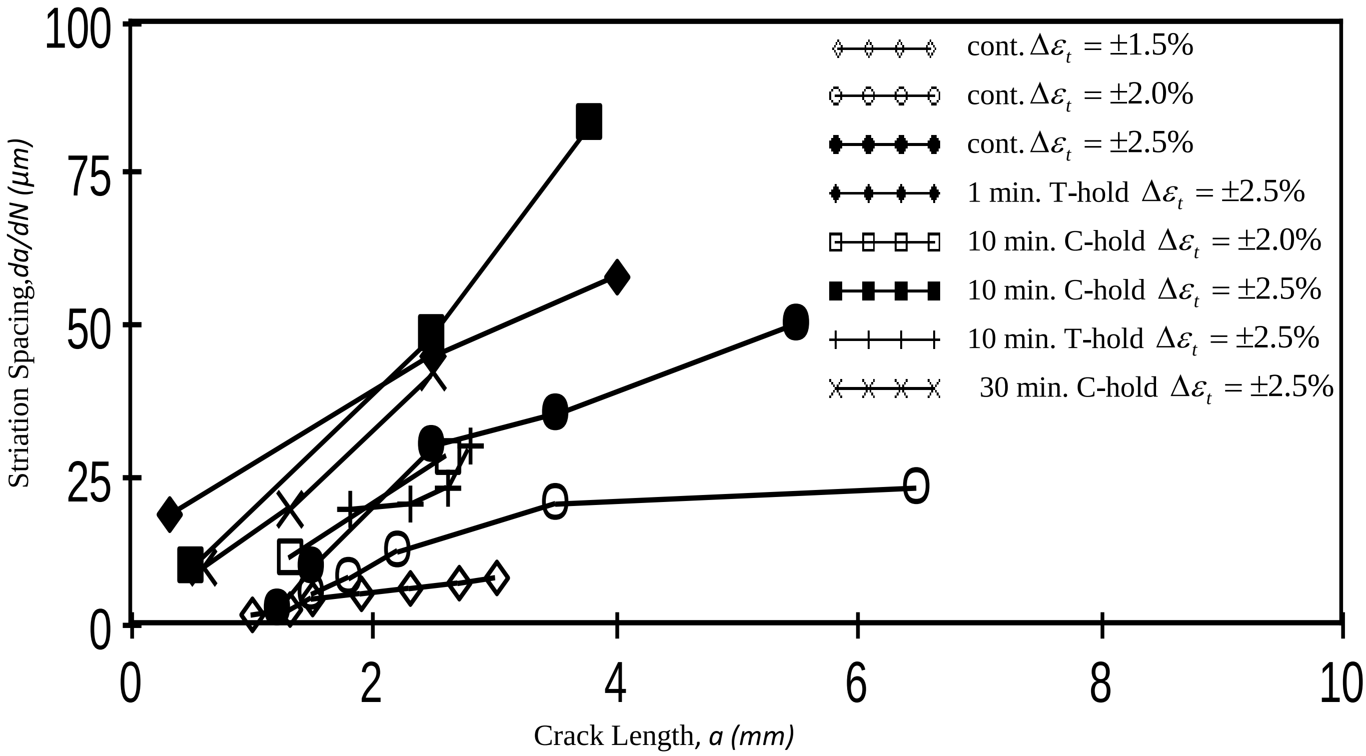

Figure (2). The variations of a crack growth rate with a crack length in UT500/135.

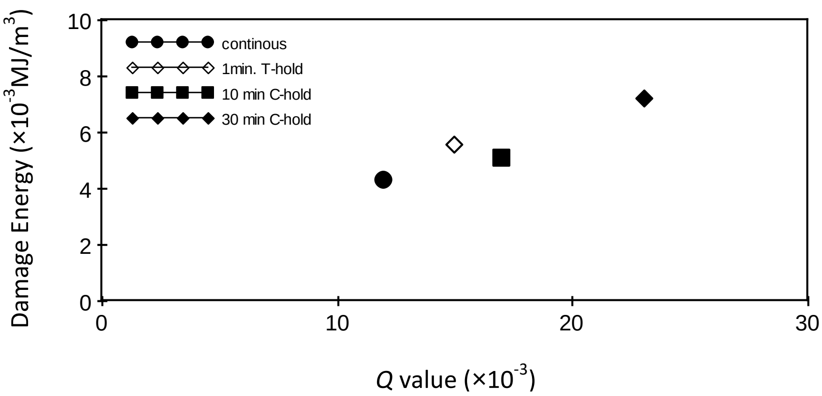

Figure (3).A comparison between damaging energy and Q value.

It appears that when the holding time increases from 1 minute to 30 minutes, the *Q* value increases in about (65%), so the crack length increases in relation to the crack growth rate until failure happen with a large amount of damage energy.
The problem of measuring and adequately defining the damaging energy in the hysteresis loop energy can be developed by making correlations between relevant experimental parameters and calculated values. In case of fracture toughness, the damaging energy has been regarded as dislocation storage energy. It has been considered that the energy retained is dependent on the dislocation density in the plastically deformed which remains at both fractured surfaces and the bulk after failure [16]. So on the basis of this argument, a certain concept of energy extending from the area to volume is introduced in the LCF condition, the comparison of absolute energy values may be possible, and it leads to a precise life estimation method from the relationship to Eq. (3).

7. Conclusions:

As a fact, fatigue life analysis with hysteresis loop energy, which is the dissipated energy during one cycling, can express the general tendency of a decreasing fatigue life with an increasing temperature. But, another conclusions was obtained from this investigation as the following:

1. An estimation of the damaging energy per cycle in the hysteresis loop energy shows that the occupation ratio of the damaging energy is very small, and that most of the dissipated energy is transformed into heat.
2. The cracked area per cycle is a tool of the experimental approach, comparing the calculated damaging energy, and it shows the same trend as in the dependence of damaging energy.
3. The crack growth rate increases when the *Q* value increases, which is related to the amount of resulted damage energy.

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