Fatigue Fracture and Damage of Engineering Polymers

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Abstract.

Polymers are very interesting as structural materials in future. The high specific strength is attractive for the reduction of the mechanical systems. We carried out the fatigue tests on the several kinds of polymers to investigate the fracture behavior and the degradation process in the fatigue life. The tested polymers were ABS, PET and PEEK. The fatigue facture was evaluated in the inert and ambient atmosphere and fracture surface was observed through the SEM. The polymers were insensitive to the humidity. The whole fatigue tests were conducted in the condition, where the temperature increase was suppressed within 1 K. The fracture surfaces showed the characteristic features. The dimple patter was observed for the fatigue ruptured PET. The fatigue degradation was evaluated by the measurement of the change in the density and viscoelastic properties. The reduction in the density was observed for PET before the macroscopic fracture. The voids would be generated interior of the specimen and induce the fatigue crack nucleation. Furthermore, the viscoelastic properties changed prior to the fracture. The reduction in fatigue strength can be associated with the increase of the relaxation time. It would suggest that the change of the microstructure would take place during the cyclic loading. The cyclic applied stress would produce the radicals through the breaking of the molecular chains. Then new chemical reaction would bring more complex molecules, which could increase the relaxation time. The increment is proportional to the degradation of the fatigue strength.

Introduction

Polymers are much interesting materials for future precise machines. However, the mechanical properties have not been scrutinized to make the most of the characteristics of the polymers. Although the fatigue fracture of metallic materials has been examined and the details of fatigue crack behavior were discussed extensively [1], the study on fatigue of polymers was very little and the fundamental discussion was required for the wider application [2].

Polymers have excellent mechanical properties as new structural materials. Especially, high specific strength, high corrosive resistance, good workability, soft feeling and looking and so on are expected. So, astonishingly kinds of polymers have been developed and provided for the wide applications [3]. Furthermore, the complexity of the micro structures will result in the uncertainty on the performances. The mechanical properties would be associated with the history, molecular characteristics, treatment and environment. Our interest is in the reliability of polymers. Hence, we carried out the fatigue tests of the typical polymers, which are ABS (acrylonitrile-butadiene-styrene), PET (poly ethylene terephthalate) and PEEK (poly ether ether keton). The first polymer is one of typical engineering plastics with the high impact strength. The second is a typical polymer alloy with the medium tensile strength. The last is the highest strength polymer among them [4].

The fatigue life was evaluated to 10^7 cycles. The examination of the fracture surfaces could bring the information on the fatigue crack behavior to understand the fatigue crack nucleation and propagation of the polymers. In addition, the viscoelastic properties were evaluated to investigate the microscopic damage in the fatigued polymers, since it has scarcely been discussed [5].

Experimental procedure

The materials used for the experiments have the following molecule structures shown in Fig. 1.

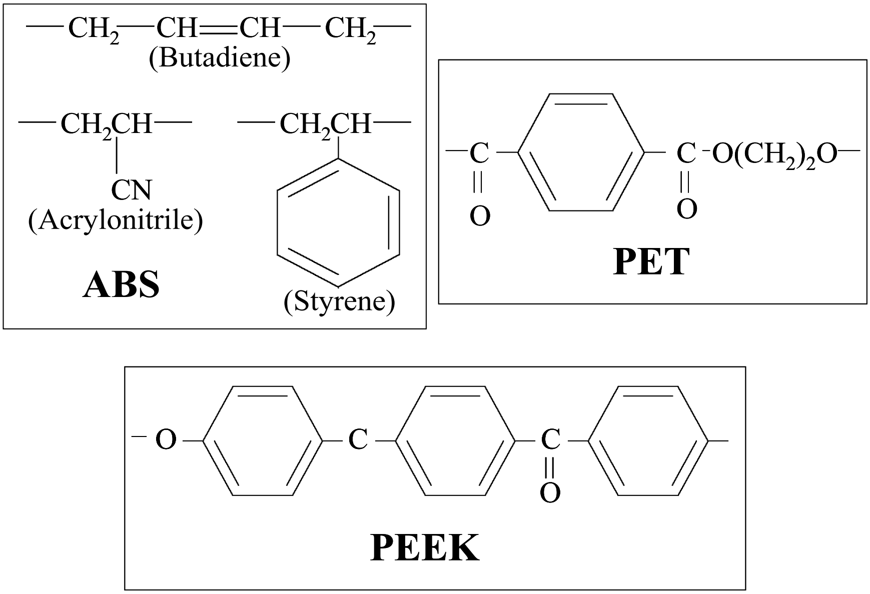


Fig.1 Molecule structures of polymers for fatigue tests

ABS is one of the typical polymer alloys. The high toughness is due to the soft phase of butadiene. The difference between PET and PEEK is in the number of benzene rings. They are single phase polymers. The number of benzene ring is proportional to the tensile and impact strength. The strength of the molecule chain is increased by the benzene ring [6].
The main mechanical and physical properties are also shown in Table 1 [4].

Table 1 Mechanical and physical properties of ABS, PET and PEEK

Material	Tensile stress [MPa]	Tensile modulus [GPa]	Impact strength [J]	Specific gravity
ABS	42	2.5	120	1.08
PET	80	3.1	37	1.38
PEEK	110	4.0	51	1.30

The whole fatigue tests were carried under the condition of the sine wave loading, of which the frequency was constant of 5 Hz. The stress ratio was 0.01. The experimental atmosphere was open air and the temperature was around 296 K. The primary experiment presented no effect of the humidity on the fatigue properties of these polymers at room temperature. The temperature rise of the specimen cyclically loaded was measured to check the effect on the fatigue properties [7].
The dimension of the test specimen has the gauge length of 5 mm and the diameter of 4 mm. The notched specimen was used to evaluate the effect of the stress concentration on the fatigue strength. The notch shape was V type, of which the stress concentration factor was 5.3.
The surfaces of the ruptured specimens were observed with the scanning electron microscope. The surfaces free from the coating were examined at the lower acceleration voltage of 10 kV.

Experimental results

The whole fatigue tests were carried out to the rupture of the specimens over the numbers of 10^7 cycles. The important problem is the temperature increase of the specimen, because of the low thermal conductivity and high specific heat. The temperature measurement revealed that the temperature increment for these polymers was null. The temperature change was below the fluctuation of the room temperature, less than 2 K. Hence, we did not take account of the effect on the fatigue properties. The stress amplitude vs. the numbers of cycle to failure was shown in Fig. 2. The stress level was proportional to the tensile strength of the polymers.

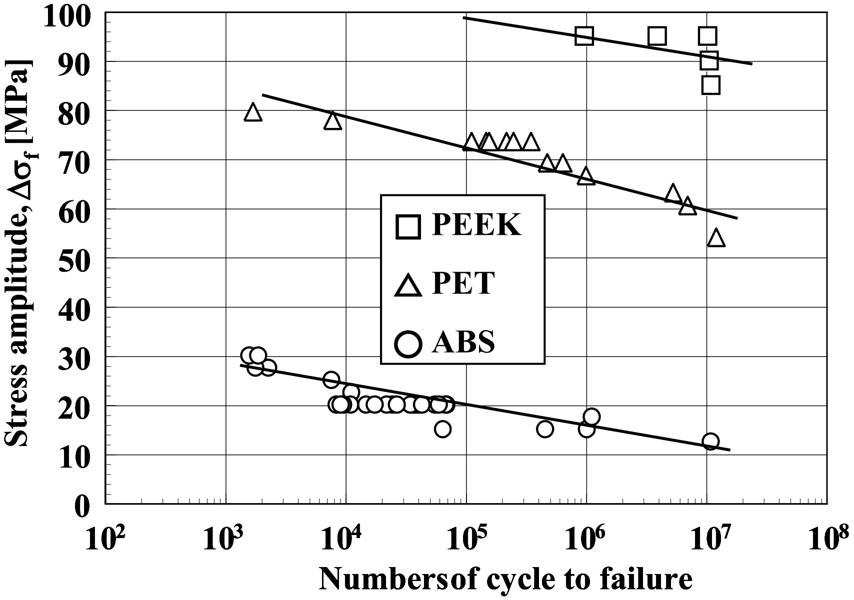
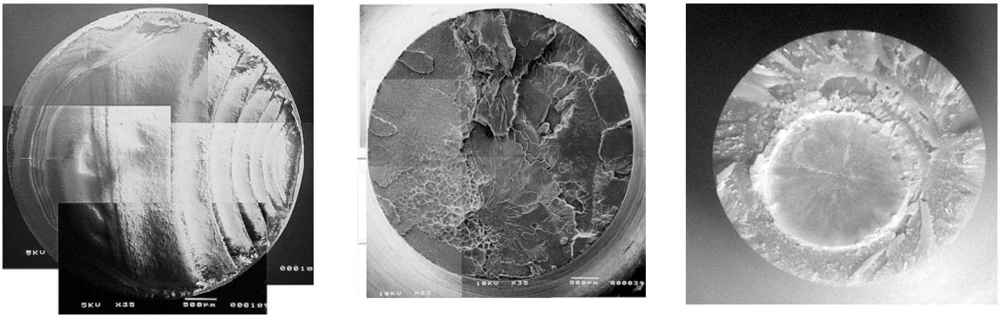


Fig. 2 S-N curves of ABS, PET and PEEK at ambient atmosphere.

The fatigue ratio of each polymer at 10^7 cycles was 0.82 for PEEK, 0.75 for PET and 0.29 for ABS. The SEM pictures of the specimens ruptured to about 10^7 cycles are shown in Fig. 3. The quite different features are observed for them. ABS showed the striation pattern, which was usually recognized for metallic materials. But the spacing of the striation was very large.



ABS **PET** **PEEK**

Fig. 3 SEM of ABS, PET and PEEK fatigued to the failure of about 10^7 cycles.

For PET the fracture surface was composed of the mixture pattern of dimple and cleavage. PET was ductile for cyclic loading and brittle for final rapid fracture. PEEK showed internal brittle cracking with the final brittle fracture. They had quite characteristic patterns for the fatigue rupture.

The fatigue crack nucleation mechanism is interesting each other. Furthermore, the nucleation mode changed under the applied stress level [7].

The measurement of the density change of the fatigued specimen suggested that little change in the density was observed for the fatigued ABS specimen but the density for PET specimen decreased with increasing in the number of cyclic loading [7]. The density decrease would be resulted from the void formation caused by the separation of the molecules and/or the break of the molecule chains. The PET is a single polymer and the applied stress is distributed homogenously in the whole molecules. When the applied stress is higher, the hydrostatic stress is also higher in the center of the specimen. Then the void formation would take place easily.

Discussion

The mechanism of the fatigue damage and crack nucleation of polymer is complex and can not have been explained on the simply analogy of those of metallic materials [8]. Three polymers exerted quite different patterns in fatigue fractured surfaces. Several kinds of experiments were conducted for polymers, but no experimental result revealed dimple pattern in the fatigue fracture [9]. The polymer is conventionally modeled by the viscoelastic models to describe the mechanical behavior [10]. So polymers normally have the soft region assumed to liquid. Hence, voids can be easily created in liquid phase under a tri-axial stress field [11]. The liquid-like phase could be assigned to the free volume of polymer [6]. PET and PEEK polymers are composed of gigantic chains of polymers as shown in Fig. 1. The chain is so strong, since the covalent bonding is formed between the atoms. But the van der Walls force is between the chains. Hence, each chain can be easily separated by the lower stress. The axial stress can accelerate the void formation, which nucleates the fatigue crack in PET and PEEK. On the other hand, ABS has three components of polymers as shown in Fig. 1. The weakest region among them is damaged by cyclic loading and plays a role of the trigger of the fatigue crack nucleation. The molecule is butadiene, which improves the toughness of ABS.

Nevertheless, polymers are generally stable against the environment. The property could prevent cracks from nucleating on the surface of the specimen. The break of polymer chain frequently takes place under a condition of cyclic loading and then radicals are generated. The radicals are accumulated with increasing the numbers of cyclic loading [12]. The radicals are so active that the strong interaction between the radicals and environment could take place. The chemical reaction could induce the brittleness of the polymer and then the crack would be easily nucleated on the surface.

Cyclic loading could accumulate several kinds of structural damage in the materials. In crystalline solid, the damages have geometrical structures, which are described by simple topological defects [13]. In polymers, the defects are complex and the structures are diverse. Furthermore, polymers naturally contain various kinds of disordered structures. The length of the polymer chain is also distributed around the mean value. So the properties of polymer depend upon the manufacturing processes. Cyclic loading would bring some kinds of effect through the change of the micro structure. The polymer chains are usually entangled by the interaction of each chain. Tensile loading extends and straightens the chains and causes the mutual displacements [13]. We expect there would be some relationship between the viscoelastic properties of polymers to estimate the fatigue damage from the microscopic viewpoint. Then, the elastic modulus and viscosity of these polymers were evaluated with applying the simple Maxwell model to the fatigued polymers [6]. The experimental results are showed in Figs. 4 and 5.

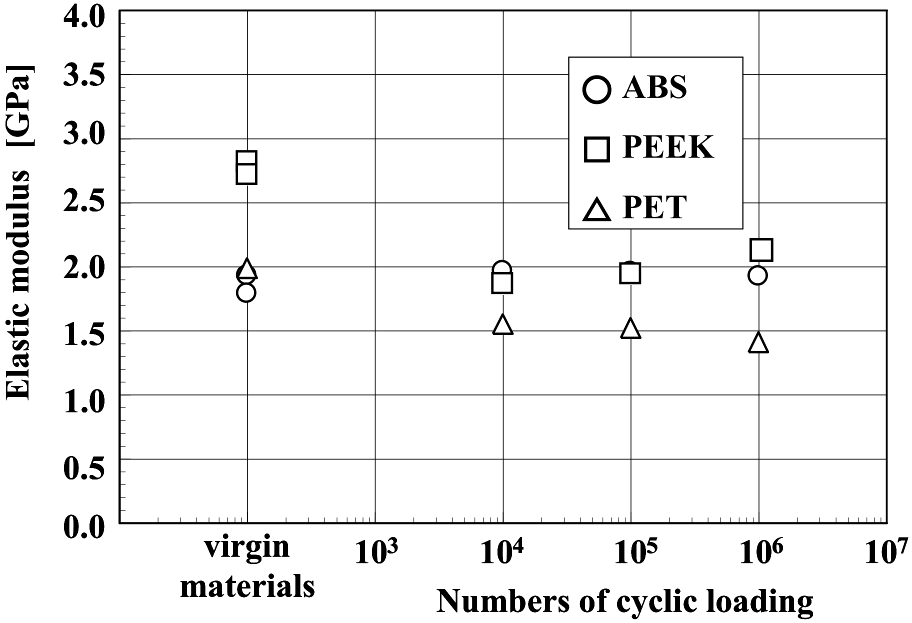


Fig. 4 Elastic modulus of ABS, PEEK and PET subjected to cyclic loading.

Fig. 4 shows the change of the elastic modulus for the specimen cyclically loaded under a condition of the applied stress, which is the rupture stress of 10^7 cycles. For ABS the elastic modulus does not show change. For PET it decreases with cyclic loading. On the other hand, PEEK shows decrease at lower cycles and then increases with cyclic loading. The respective behavior is so complex that it could not be understood simply. Fig. 5 shows the change of the each viscosity of the polymer. These show the different behavior from the elastic modulus.

Cyclic loading could produce the rearrangement of the molecule structures. As a result, the void formation takes place or the separation of the polymer chains occurs. The break of the molecule could generate radicals. The break could result from the week bond of the polymers.

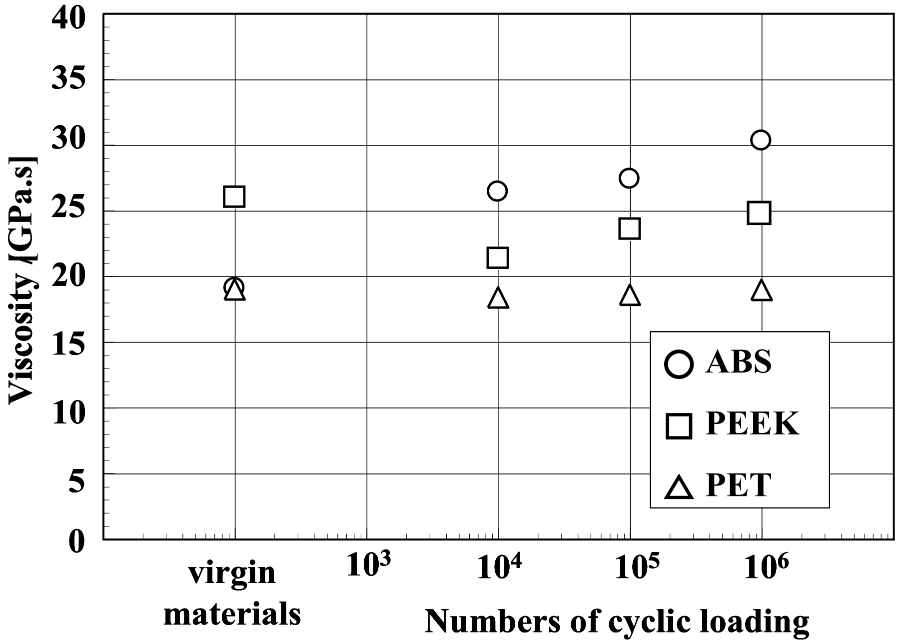


Fig. 5 Viscosity of ABS, PEEK and PET subjected with cyclic loading.

In ABS, the week site is due to the double bond in butadiene. So radicals are easily generated in ABS. Radical is more easily generated by cyclic loading than one directional loading [6]. The cyclic accumulation of the external work could accelerate the formation of the radical in the extended polymer chains.

However, the changes of elastic modulus and viscosity were not simple. It is difficult to relate these values to the fatigue properties of the fatigue polymers.

Hence, we introduce another parameter, which is rewritten by both of parameters, elastic modulus and viscosity. It is named as relaxation time $\tau = \eta / E$. Since relaxation time is a measure of the stiffness of the material, it would be associated with the strength of the material. Then we would expect the relationship between the relaxation time and the fatigue degradation of the polymers. The degradation in the fatigue strength of the polymers are defined as the reduction from the tensile strength, $\sigma_B - \Delta\sigma_f$. σ_B is the tensile stress of the specimen. The experimental result is showed in Fig. 6. The degradation of fatigue strength is proportional to the relaxation time. The accumulation of fatigue damage would increases the relaxation time for these polymers. The increase of the radicals in the polymer loaded statically and cyclically is showed in Fig. 7 [12].

Under static loading the radicals is proportional to the strain. Cyclic loading can accelerate the generation of the radicals. The difference would result in the characteristic behavior of the fatigue damage of polymers. The increase of the radials would be resulted from the break of molecule chains. In addition, the radicals would produce another chemical reaction between them. Hence, the complex behavior of elastic modulus and viscosity would be observed in Figs. 4 and 5. Nevertheless, the relaxation time increases with fatigue and the damage is accumulated. The fatigue damage of polymer could be evaluated by the relaxation time. The conclusion would suggest that the stiffness of polymer

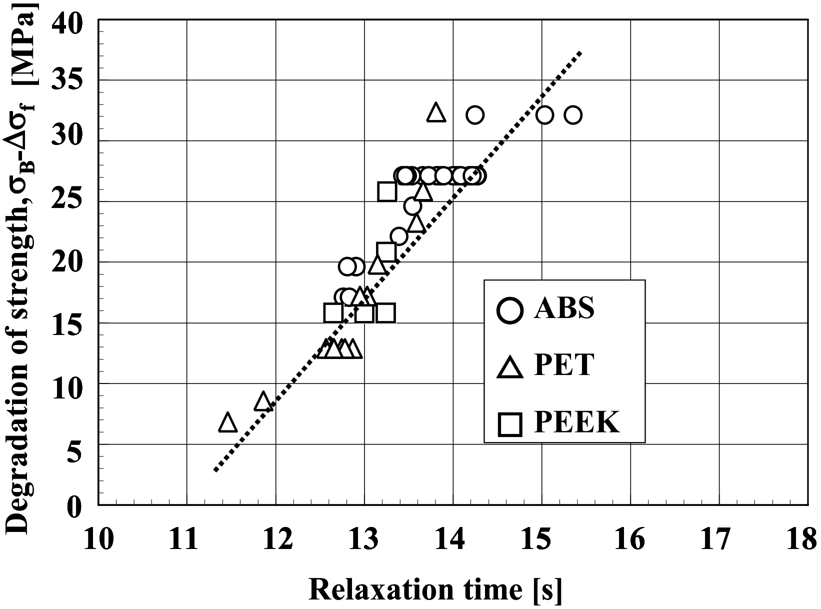


Fig. 6 Relationship between degradation of fatigue strength and relaxation time of polymers.

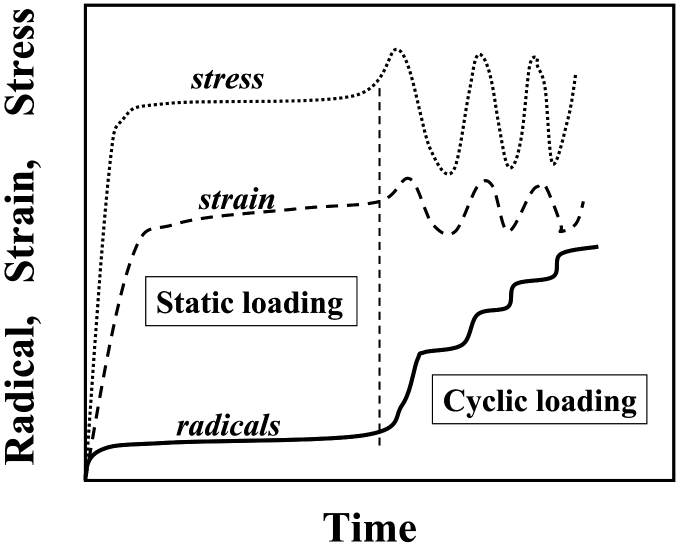


Fig. 7 Schematic illustration of increases of numbers of radicals in polymer under static and cyclic loading [12].

was reduced by fatigue loading. The intrinsic fatigue strength of polymer is associated with the micro structure of molecules, which is macroscopically estimated by the relaxation time.

Summary

(1) Three kinds of polymers, ABS, PET and PEEK were fatigued to the rupture of over 10^7 cycles.
(2) Fatigue fracture behavior of polymer strongly depends upon the molecular structure.
(3) Fracture surfaces were quite different each other. Striation pattern was observed for ABS, dimple and cleavage patterns for PET and cleavage pattern for PEEK.
(4) The viscoelastic behavior, elastic modulus and viscosity of polymers fatigued showed the complex manners.
(5) The degradation of fatigue strength of the polymer is proportional to the relaxation of the polymers loaded cyclically.
(6) The increase of the relaxation time can be associated with the increase of the numbers of the radicals in the fatigued polymers.
(7) The radicals would be easily generated in the polymers loaded cyclically.
(8) The increase in the numbers of radicals would reduce the stiffness of polymer.

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