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Effects of loading conditions on the fatigue failure characteristics in a polycarbonate

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Abstract. In this study, fatigue properties and crack growth characteristics of a polycarbonate (PC) were examined during cyclic loading at various mean stress (σ_{amp}) and stress amplitude (σ_{mean}) conditions. Different S vs. N and da/dN vs. ΔK relations were obtained depending on the loading condition. The higher fatigue strength and the higher resistance of crack growth are seen for the PC samples cyclically loaded at the higher mean stress and lower stress amplitude due to the low crack driving force. Non-linear $S-N$ relationship was detected in the examination of the fatigue properties with changing the mean stress. This is attributed to the different crack growth rate (longer fatigue life): the sample loaded at the high mean stress with lower stress amplitude. Even if the higher stress amplitude, the low fatigue properties are obtained for the sample loaded at the higher mean stress. This was due to the accumulated strain energy to the sample, where severe plastic deformation occurs instead of crack growth (plasticity-induced crack closure). Shear bands and discontinuous crack growth band (DGB) are observed clearly on the fracture surfaces of the sample cyclically loaded at the high stress amplitude, where the lower the σ_{mean}, the narrower the shear band and DGB. On the other hand, final fracture occurred instantly immediately after the short crack growth occurs in the PC sample loaded at the high mean with the low σ_{amp}, i.e., tear fracture, in which the shear bands and DGB are not seen clearly.

Keywords: polycarbonate; loading condition; fatigue strength; crack growth rate;failure characteristic

1. Introduction

Many engineering components made of polycarbonate (PC) have been employed dramatically in automotive and aerospace industries due to excellent transparency, high mechanical properties, high heatproof property and excellent flameproof property. Because failure in the components of the related polymer occurs, investigation of the mechanical properties would be important. The deformation characteristics in polycarbonate were studied by Krongauz *et al*. (2009), where the kinetics for the de-coloration reaction of photochromic spiropyran dissolved in the polymer are considered. Moreover, many researchers have examined the fatigue and crack growth characteristics until now. Fundamental experimental approaches have been carried out by Radon *et al*. (1976). In their conclusions, a linear relationship between crack length and cyclic number was

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found for PMMA and PC. A decrease in temperature resulted in a decrease of the cyclic crack growth rate; and an increase in frequency led to a decrease of the crack growth rate (Radon *et al*. 1976). The extensive associated researches have been devoted to this field by many investigators. Pruitt and Rondinone (1996) have examined the effect of sample thickness and stress ratio on the fatigue behavior of polycarbonate, and one of their conclusions is that the sample under plane stress exhibits enhanced crack saturation lengths. In addition, the crack growth rates for the thick specimens are slightly high level compared to the thin ones, due to the plane strain condition. Discontinuous fatigue crack growth in glassy polymers has been investigated by Skibo *et al*. (1977), and it appears that the crack front advanced discontinuously in increments equal to the band width after remaining stationary for hundreds of fatigue cycles. Fatigue crack growth characteristics of polycarbonate with different specimen thickness and molecular weight have been studied by Pitman and Ward (1980), and they estimated the relative contribution of the shear lips and the plane strain crazing mode to fatigue crack propagation. Moreover, the crack in the central region of the crack tip was examined in an optical microscope by measuring the width of the shear lips. The roles of crazes and shear bands in the initiation and crack growth were investigated under high strain fatigue tests by Mills and Walker (1980), and it appeared that a minimum surface strain of 2.7% is needed for crazes to from in polycarbonate within several hours, and that crack growth from these crazes is hindered by the shear bands. Existing criteria for craze initiation was reviewed on the basis of the active research on crazing of more than 50 years by Bucknall (2007 and 2012). In recent years, the crack growth characteristics have further studied by several researchers, where crack growth and craze-induced crack tip shielding in polycarbonate have been examined (James *et al*. 2012). In addition, the overload-induced retardation of fatigue crack growth for polycarbonate and acrylonitrile – butadience – styrene (PC/ABS) was investigated, and it appeared that the overload ratio has great effect on the crack growth retardation due to the formation of crack tip craze zone (Fang *et al*. 2007 and 2008).

Up to data, a number of investigators have examined the fatigue properties of polycarbonate, and many useful experimental data has been reported (Mishnaevsky Jr. and Brøndsted 2007, Singh *et al*. 2011, Rae *et al*. 2007). In this instance, Li *et al*. (1995) have investigated influence of cyclic fatigue on the mechanical properties of amorphous polycarbonate, and changes in the mechanical properties of the polycarbonate during the initial failure stage lead to embrittlement of the material. Wang *et al*. (2003) have conducted the fatigue tests to construct the stress amplitude versus the fatigue life curve. With their study, damage variable for PC was measured after cyclic loading was conducted by pulling damaged samples to fracture under monotonic loading. Even though many related researches have been conducted, the authors believe that relevant experimental evidence is apparently incomplete especially for the effects of stress amplitude and mean stress on fatigue properties. Those approaches are specifically important for design of the engineering component. This is especially true, as more than 90% of component is fractured caused by fatigue. The aim of this study was hence to investigate the fatigue failure characteristics of polycarbonate via examination of the fatigue strength (S/N approach) and crack growth characteristics ($\mathrm{d}a/\mathrm{d}N - \Delta K$ approach).

2. Experimental procedures

The material employed in the present work is commercial polycarbonate (PC-1600) supplied by Takiron Co. LTD. To remove the residual stress after machining the specimens, the specimens were heated at 413K for 5 hours before furnace cooling. Fatigue tests were carried out at room

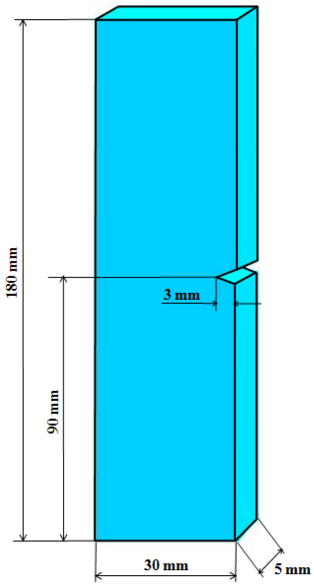


Fig. 1 Schematic illustration showing the specimen with a single notch

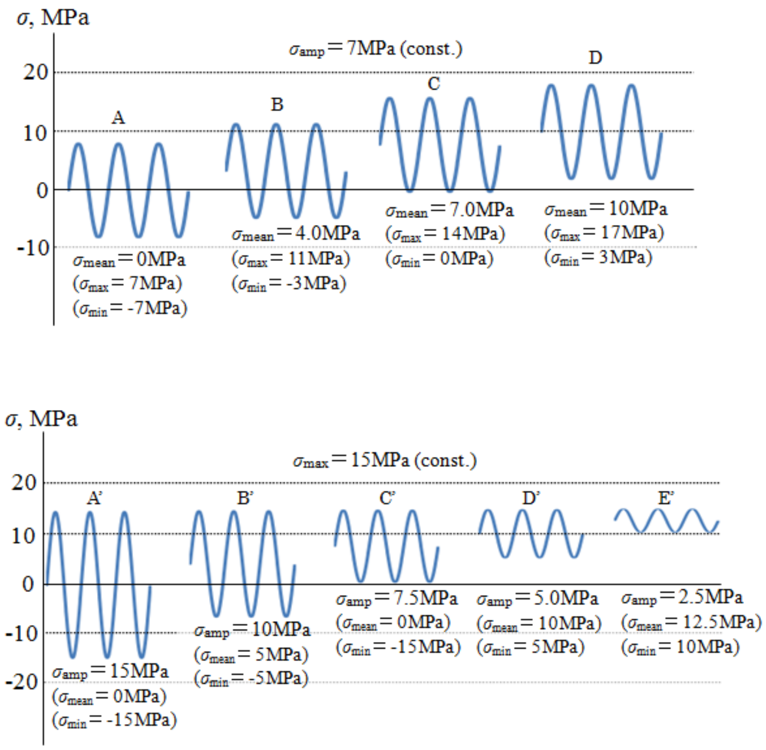


Fig. 2 Cyclic loading conditions for the crack growth tests under (a) different σ_{mean} and (b) different σ_{amp}

temperature using an electro-servo-hydraulic system with 50 kN capacity. In the fatigue tests, rectangular specimens (180 × 30 × 5 mm) with and without single sharp notch (3 mm length) were used. The notches were created by a sharp knife made of a hardened steel on the center of the specimen as shown in Fig. 1. The specimen surfaces were polished carefully by sand papers so as to reduce the stress concentration arising from the tool marks. Note the reason for the use of the specimen without notch is to investigate the tensile properties. The tensile properties of this polycarbonate examined in the present work are as follows: ultimate tensile strength 63 MPa and fracture strain 90%.

The fatigue properties were evaluated by two different methods: *S*/*N* approach (fatigue life) and $da/dN - \Delta K$ approach (crack growth rate). Those tests were carried out under cyclic loading with a sinusoidal waveform at a frequency of 10Hz, and the maximum applied stress was determined with less than 35% of the ultimate tensile strength. In this examination, the fatigue tests were carried out at different cyclic loading conditions: various stress amplitudes and mean stresses. Fig. 2 shows the cyclic loading conditions for the crack growth tests (da/dN vs. ΔK). The mean stress (σ_{mean}) was changed under the same stress amplitude (σ_{amp} = 7.0 MPa): σ_{mean} = 0, 4.0, 7.0 and 10.0 MPa. On the other hand, the stress amplitude was altered under the same maximum stress (σ_{max} = 15.0 MPa): σ_{amp} = 2.5, 5.0, 7.5, 10.0 and 15.0 MPa. It should be pointed out that, in this case, the cyclic loadings at various σ_{amp} uncer the same σ_{mean} have not been conducted. In general, the stress amplitude could make significant factor to determine the fatigue strength, as the σ_{amp} value is attributed to the crack driving force. In this approach, the ΔK value was estimated by the following equations:

$$\Delta K = \Delta\sigma\sqrt{\pi a}\cdot \mathrm{F}(\zeta) \tag{1}$$

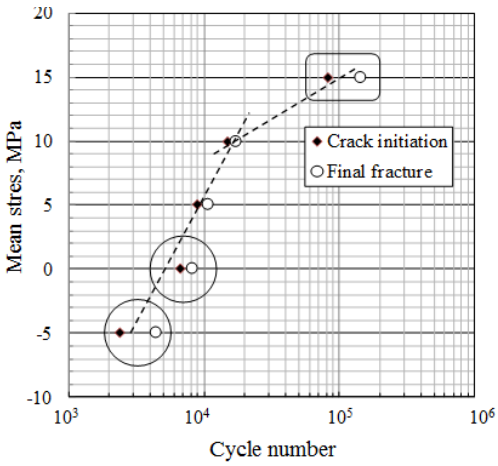
$$\mathrm{F}(\zeta) = \sqrt{\frac{25}{20-13\zeta-7\zeta^2}} \tag{1a}$$

$$\zeta = \frac{a}{W} \tag{1b}$$

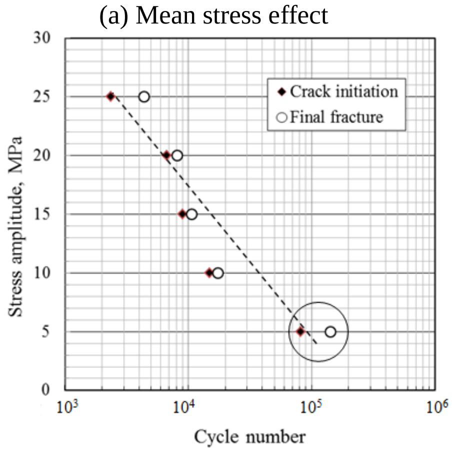
where a is fatigue crack length and W is the width of the specimen. The crack length was measured using a traveling light microscope with a resolution of 0.01 mm, and the applied load and strain values were measured using a standard load cell and a commercial strain gauge. In this case, the strain gauge was attached on the center of the specimen far away about 20 mm from the crack. A fracture characteristic after the fatigue tests was investigated by using an optical microscope and a scanning electron microscope (JSM-5310, SEM). The SEM observations were performed on the fracture surfaces at acceleration voltage of 15 kV after gold coating is conducted.

3. Results and discussion

Fig. 3 depicts the relationship between the applied mean stress and cyclic number to the crack initiation (N_i) and final failure (N_f), i.e., *S* vs. *N* relations: (a) σ_{mean} vs. N (σ_{amp} = const.) and (b) σ_{amp} vs. N (σ_{max} = const.). It is seen that different trends of $S - N$ relationship are obtained. With decrement of the stress amplitude, the longer cyclic numbers to crack initiation and fatigue life were obtained (Fig. 3(b)), which is related with conventional $S - N$ curve. However, the inverse

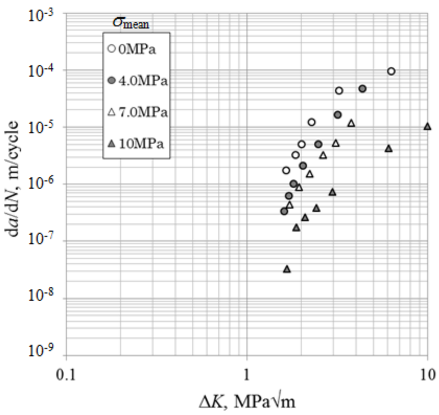


(a) Mean stress effect



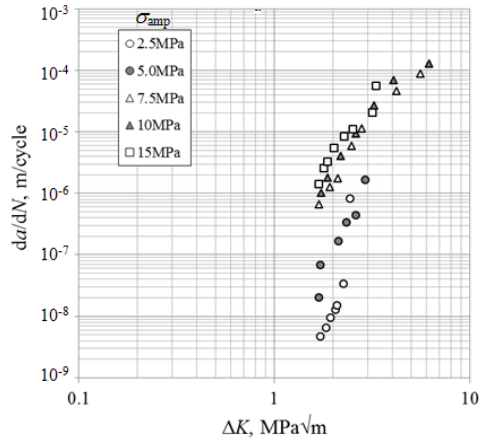
(b) Stress amplitude effect

Fig. 3 $S-N$ relations showing the crack initiation cycle and fatigue life: (a) mean stress effect and (b) stress amplitude effect

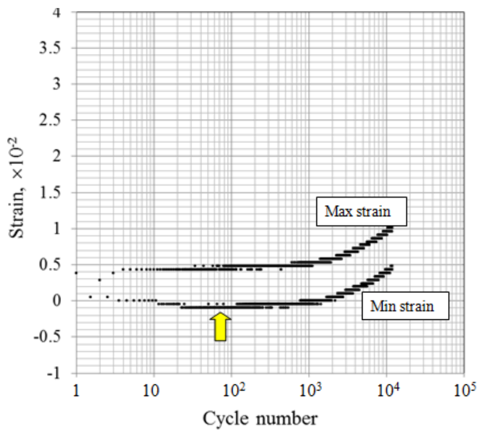


(a) Mean stress effect

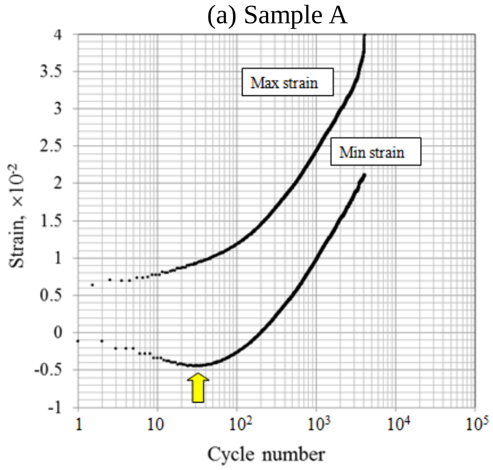
Fig. 4 $da/dN-\Delta K$ relations: (a) mean stress effect and (b) stress amplitude effect



(b) Street amplitude effect
Fig. 4 Continued

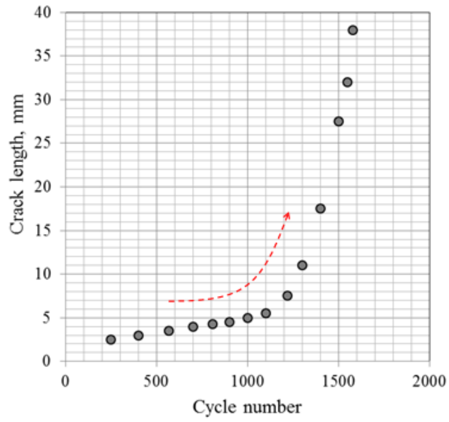


(a) Sample A

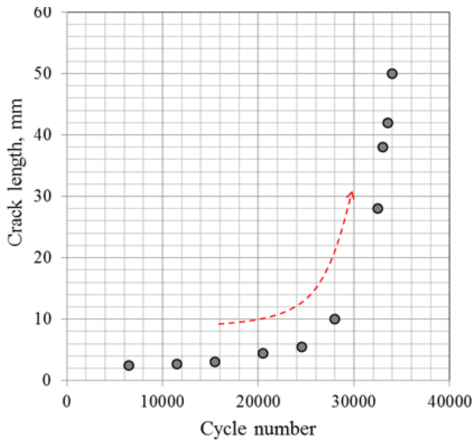


(b) Sample A’

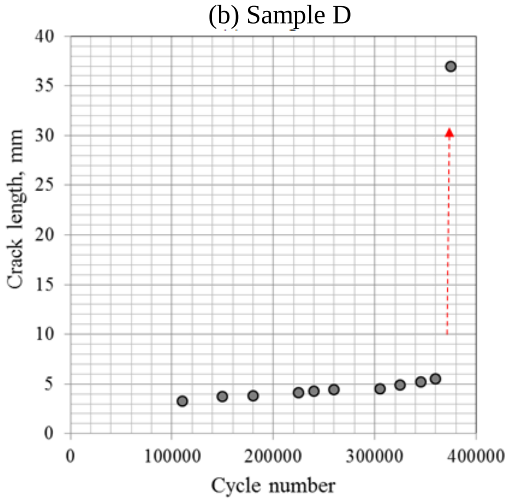
Fig. 5 Maximum and minimum strain variation as a function of cyclic number: (a) sample A and (b) sample A’



(a) Sample A

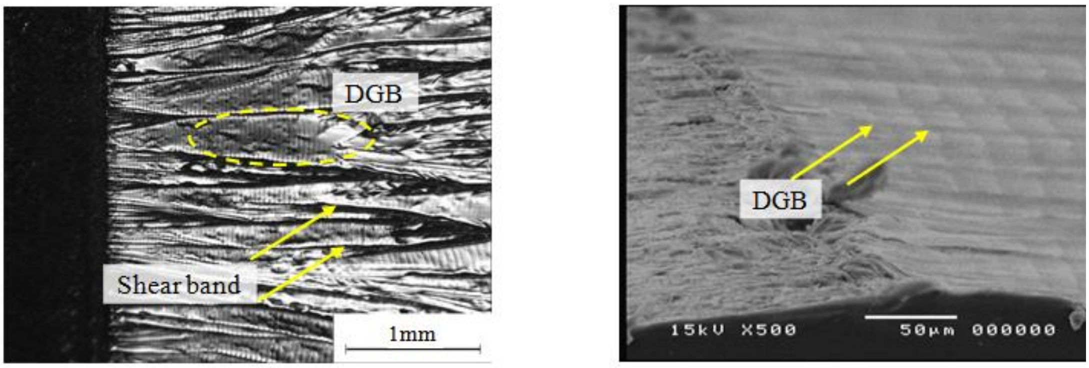


(b) Sample D

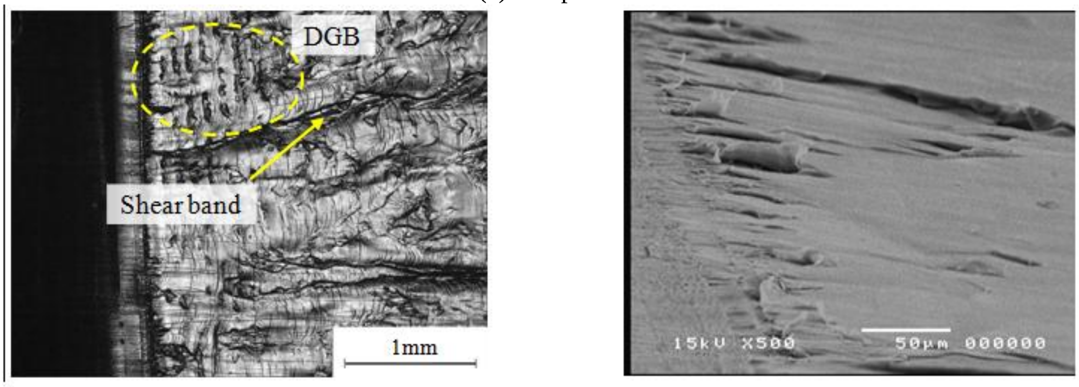


(c) Sample E'

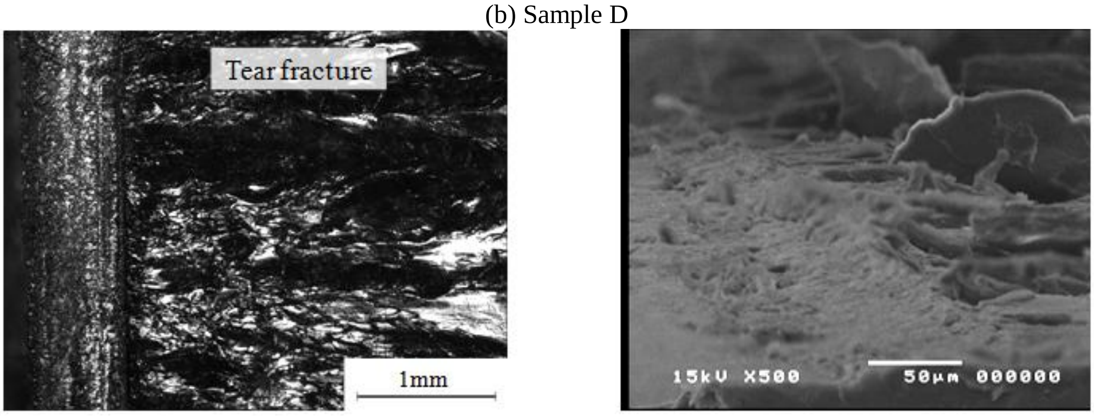
Fig. 6 Variation of fatigue crack length as a function of cyclic number: (a) sample A and (b) sample D and (c) sample E'



(a) Sample A



(b) Sample D



(c) Sample E’

Fig. 7 Optical and SEM images showing the fracture surfaces after crack growth tests: (a) sample A and (b) sample D and (c) sample E’

proportion is observed in σ_{mean} vs. N relationship, Fig. 3(a), where the high mean stress makes enhance of failure resistance at the same σ_{amp}. From this, the fatigue strength is especially influenced by both stress amplitude and mean stress. It should be pointed out first that the loading conditions at the lower σ_{mean} and lower σ_{amp} in Fig. 3(a) and (b), enclosed by circles, are related to the tension – compression loading test ($R < 0$) while other data plots are associated with the tension – tension loading test ($R > 0$). In spite of the different cyclic loading condition, their $S – N$ relations are almost clearly correlated. Moreover, non-linear $S – N$ relationship was detected in the examination of the fatigue properties with changing the mean stress (Fig. 3(a)), in which the sample loaded at the higher mean stress condition makes the longer fatigue life, as enclosed by the rectangular in Fig. 3(a). One of the reasons is attributed to the fact that the high mean stress under the same stress amplitude makes severe plastic deformation, leading to the slow crack growth rate. This crack growth characteristics (or different fracture mode) are further discussed in the later section of this paper.

The σ_{amp} vs. N_f relationship for the stress amplitude test (Fig. 3(b)) is presented by a power law dependence of the applied stress and cyclic number to final fracture (Puchi-Cabrera *et al*. 2007).

$$\sigma_{amp} = \sigma_f N_f^b \tag{2}$$

where σ_f the fatigue strength coefficient and b the fatigue exponent. The values of σ_f and b for the samples in Fig. 3(b) examined are: σ_f = 1183 MPa and b = -0.467 (correlation rate = 0.95). In this case, increased fatigue life is associated with an increasing fatigue strength coefficient (σ_f) and a decreasing fatigue exponent (b). In the present sample, the σ_f value is much high compared to the high quality aluminum alloys (Okayasu and Yoshie 2010), while the tensile strength is much lower level. This may be due to the $S – N$ relationship obtained by the different cyclic loading conditions. In fact, the fatigue tests are generally conducted by changing the maximum stress under the same R-ratio.

Fig. 4 represents the da/dN vs. ΔK for the polycarbonate: (a) σ_{mean} effect and (b) σ_{amp} effect on the crack growth rate. Note that the data plot indicated in Fig. 4 are small number, but those are associated with the crack growth characteristics in region II (Paris law):

$$da/dN = C(\Delta K)^m \tag{3}$$

where C and m are material constants. As seen, different da/dN vs. ΔK relations were obtained depending on the loading condition. As seen, there is a linear variation of log da/dN versus log ΔK, defined on the basis of linear elastic fracture interpretations (Kumai *et al*. 1996). From the obtained da/dN vs. ΔK relations, the higher crack growth rate is observed for the PC samples cyclically loaded at the lower mean stress and the higher stress amplitude, as indicated in Fig. 4(a) and (b), respectively. The obtained crack growth characteristics show similar trend of their fatigue life shown in $S – N_f$ relations, Fig. 3(a) and (b). Similar approach was conducted by Pruitt and Rondinone (1996), in which the effects of R-ratio and specimen thickness on crack growth rates are investigated using the polycarbonate. The crack growth rate for the lower R-ratio makes high crack growth rate, which is related to our high crack growth rate under the following loading conditions: the low mean stress and the high stress amplitude. The overall fatigue crack growth rates for the previous studies (Pruitt and Rondinone 1996 and Skibo *et al*. 1977) are higher than those for our samples. The reason behind this is not clear at the moment, but this would be attributed to the different cyclic loading conditions, e.g., cyclic frequency. It should be pointed out that the ΔK_{eff} value is one of the significant parameters to understand their crack growth characteristics clearly. Even though there is lack of experimental data in Fig. 4, the authors believe that the ΔK_{eff} values for all samples can be approximated in-between 1 and 2 MPa$\sqrt{}$m.

To understand the different fatigue properties, the strain characteristics during cyclic loading were examined continuously. The representative results are shown in Fig. 5: sample C (tension – tension loading test) and sample A’ (tension – compression loading test), where the maximum and minimum strain values during the fatigue test were plotted. It is clear that the maximum strain level increases gradually during the cyclic loading to final fracture in both stains, while the minimum strain is decreased to the negative levels in the early fatigue stage for certain cyclic numbers in advance as indicated by the arrows, and then that increases to the failure. Such minus strains in the early stage are affected by the severe plastic deformation.

The crack growth characteristics are further investigated. Fig. 6 shows variation of crack growth length as a function of cyclic number: (a) low mean stress 0 MPa at high σ_{amp} (sample A); (b) high mean stress 10 MPa at high σ_{amp} (sample D) and (c) high mean stress 12.5 MPa at low σ_{amp} (sample E'). As seen, the crack growth characteristics are altered depending on the loading condition. For sample A, crack growth occurs gradually to the final fracture in a short fatigue life. Similar crack growth occurs for sample D, although this case is a longer fatigue life. This is because of the different mean stress. On the other hand, for sample E', crack growth can't be seen clearly until just before the final fracture. The fatigue crack length before the final fracture is as short as 3 mm, which is less than 1/10 of the other ones (samples A and D). Such failure mode occurs because of the high strain energy, accumulated to the PC sample instead of the energy release by crack growth. In addition, this occurrence may be attributed to the greatly strained material, arising from the higher stress with the lower stress amplitude, i.e., cyclic creep like failure. Similar result has been reported in the study by Fang *et al*. (2007), where the PC/ABS alloy is overloaded before the fatigue test, and this overload makes the high resistance of the crack growth due to plasticity-induced crack closure. James *et al.* (2012) have reported the fracture surfaces of fatigue cracks in PC support closure arguments and this occurrence make the damage of fracture surface. In addition, they have analyzed the length of plastic zone ahead of crack tip using the Dugdale formula (James *et al*. 2012). It should also be considered that such different crack growth characteristics are attributed to the crack closure arising from the craze. In fact, it is reported that the overload-induced retardation of fatigue crack growth is affected by the formation of the crack tip craze zone (Fang *et al*. 2008).

Failure characteristics of their samples were further examined by direct observations. Fig. 7 depicts the fracture surfaces for samples A, D and E', observed by an optical microscope and a scanning electron micrograph. As seen, shear bands on the fatigue cracks were created clearly in the samples loaded at the higher stress amplitude (samples A and D), where the lower the mean stress, the narrower the shear band span. In addition, discontinuous fatigue crack growth behavior is detected obviously in samples A and D. Similar to the shear band, the width of DGB is narrower and clearer for the PC sample loaded at the lower mean stress. Note that the reason for the narrow shear bands created is not clear at the moment, so this will be further discussed in the future. In contrast, the shear bands and DGBs cannot be seen for sample E', in which the rough fracture surface is detected. This fracture mode would be created by the rapid crack growth to the final fracture, namely tear fracture. From the above experimental works, it is verified that both fatigue life (S vs. N) and crack growth rate (da/dN vs. ΔK) are sensitive to the cyclic loading condition. Different fracture mode is observed in the study by Fang *et al*. (2007), in which porous or dimple features were obtained on the fatigue crack surfaces. The reason behind this could be attributed to the different loading condition and material properties. Interesting study was carried out by Mills and Walker (1980), where the roles of crazes and shear bands in the initiation and crack growth were examined for polycarbonate and polyvinylchloride, and the craze density and the maximum craze length are interpreted by the strain level. Furthermore, the craze creation and crack growth mechanism ahead of crack tip were analyzed by the direct observation (James *et al*. 2012). It is considered that the craze initiation is treated as frustrated fracture process rather than a yield mechanism (Bucknall 2007). James *et al*. have developed the advanced experimental technique to provide insights into fractography, identification of the crazed region and location of the crack tip position (2012).

4. Conclusions

In the present work, fatigue properties and crack growth characteristics of the polycarbonate were examined under various stress amplitudes and mean stresses. The obtained results are given as follows:

1. Different S vs. N and da/dN vs. ΔK relations were obtained depending on the loading condition. With decrement of the stress amplitude, the longer cyclic numbers to crack initiation and fatigue life were obtained, which is similar trend to conventional S – N curve. However, the inverse proportion was detected in σ_{mean} vs. N relationship, in which the high mean stress makes enhance of failure resistance at the same σ_{amp}.

2. Non-linear S – N relationship was detected in the examination with changing the mean stress, which is attributed to the extreme lower fatigue life. Such result was obtained in the samples loaded by the high mean stress with the lower stress amplitude.

3. Because of the slow crack growth rate, the high fatigue strength was obtained for the PC samples loaded at the higher mean stress with the lower stress amplitude. Even if the same stress amplitude is applied to the PC sample, the high fatigue strength is obtained for the samples loaded at the high mean stress. This is attributed to the absorbed high strain energy caused by the severe plastic deformation instead of the energy release by crack growth.

4. Shear band and discontinuous fatigue crack growth were observed clearly specifically in the sample cyclically loaded at the high stress amplitude, where the lower the mean stress, the narrower the shear band as well as the DGB. On the other hand, the rapid crack growth occurs to the final fracture without shear band and DGB for the samples loaded at the higher mean stress with the lower stress amplitude, in which rough fracture surface, caused by tear fracture, was observed.

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