FATIGUE DAMAGE PROGRESSION IN PLASTICS
DURING CYCLIC BALL INDENTATION

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Abstract

AE (acoustic emission) is utilized to monitor the progression of sub-surface damage in a
transparent PVC (poly-vinyl-chloride) plate subjected to contact fatigue by cyclic ball indenta-
tion. We monitored AEs from sub-surface damage by four small AE sensors mounted on the four
edges of a square plate, and estimated both the source location and fracture mode. The AE analy-
sis revealed that Mode-II lateral cracks initiated at cycle number, \(N = 8.9 \times 10^4\). AE sources of
corresponding events were located in front of progressing sub-surface lateral cracks at the depth
of 516 \(\mu\)m. We could not, however, monitor AE from Mode-I radial crack possibly due to small
crack opening. Finite element method (FEM) predicted lateral crack initiation at approximately
500 \(\mu\)m below the surface with the maximum shear stress.

Keywords: Cyclic ball indentation, Poly-Vinyl-Chloride plastics, Fatigue damage progression.

1. Introduction

Engineer Polymers or Plastics are widely used for contact components such as bearings and
gears in industrial fields due to their excellent performance at low cost. Understanding the
mechanism of cyclic contact damage is important for practical applications [1, 2]. No study on
cyclic contact for plastics has been performed so far and fatigue fracture process has remained to
be understood [3, 4].

In the present study, cyclic ball indentation tests were performed on PVC (poly-vinyl-
chloride) to study the mechanism of cyclic contact fatigue. The initiation and progression of
fatigue damage were monitored by AE (acoustic emission) technique. We studied the cyclic fa-
tigue mechanism by AE analysis, observed the indentation damage and analyzed using finite
element method (FEM).

2. Materials and Experimental Procedures

We used transparent PVC as samples of 20-mm square with 5-mm thickness. Cyclic ball in-
dentation tests were performed using an electro-hydraulic testing machine equipped with a ball
indenter and two eddy current sensors (displacement resolution: 0.4 \(\mu\)m). We prepared four types
of indenter balls with diameters \(d = 5, 10, 15\) and 20 mm. A software for controlling cyclic in-
dentation test was developed in house. The system measures the relationship between indentation
force \((F)\) and indentation depth \((h)\) at high resolution under various testing conditions, control-
ling the maximum indentation force \((F_{\text{max}})\) and the stress ratio \((F_{\text{min}}/F_{\text{max}})\), \(R = 0.05, 0.1\) and 0.5.

In these tests, the maximum number of cycle was set as $10^6$ cycles and cyclic frequency ($f$) as 5 Hz. All tests were performed at room temperature.

We monitored AE signals using four small AE sensors mounted on the side surfaces of a specimen. As shown in Fig. 1, the AE system consists of resonant-type sensors (Type PICO, PAC), 40-dB preamplifiers (9913, NF Circuit Block), A/D converter (Gage Applied Inc.) and a personal computer. Output of channel-1 sensor was branched into another circuit for triggering via a high-path filter. This eliminated low-frequency noise due to cyclic contact.

3. Results and Discussion

3.1 Determination of the Elastic Wave Velocity in Plate Specimen

We first studied the characteristics of AE waves using a laser system (Fig. 2). YAG laser pulses were point-focused at the center of specimen surface as shown in (a). Out-of-plane displacement was measured by a laser interferometer on the back-plane. In order to detect the shear
(S-) wave as well the longitudinal (P-) wave, the measurement point was changed from the epicenter to 1t-off \((t = \text{the specimen thickness})\) epicenter. The timing of pulse laser irradiation was monitored by a photodiode and used as trigger signal. Outputs of the interferometer were digitized by a two-channel digitizer (sampling interval 4 ns and sampling point 4096 points) and fed to a personal computer. Figure 2(b) shows a detected waveform at 1t-off epicenter. First pulse at 3.28 \(\mu\)s was the P-wave traveled at velocity \((V_p)\) of 2156 m/s. S-wave arrived at 6.96 \(\mu\)s traveled at velocity \((V_s)\) of 1016 m/s. Young’s modulus \((E)\) of PVC was calculated as 3.78 GPa, and Poisson’s ratio \((\nu)\) as 0.36. These values were found to be similar to those determined by indentation and compressive loading test. The static tests gave, \(E = 3.55\) GPa and \(\nu = 0.42\).

We next detected the elastic waves by a small AE sensor mounted on the side surface of the specimen. Velocity of the first arrival wave was measured as 2194 m/s and coincided with the velocity determined by laser system. Since the sheet velocity \((C_E)\) of symmetric \((S_0)\)-Lamb mode of PVC was slower and measured as 1794 m/s, we need to estimate the source location using the P-wave velocity.

3.2 Fatigue Damage Progression during Cyclic Ball Indentation Testing

We performed the cyclic ball indentation testing with the maximum indentation force, \(F_{\max} = 981\) N, stress ratio, \(R = 0.1\), and indenter diameter, \(d = 10\) mm. Figure 3 shows the variation of the maximum and minimum indentation depth \((h_{\max} \text{ and } h_{\min})\) with the number of cycles, \(N\). This figure also shows cumulative AE counts. We detected first AE at \(N = 8.9 \times 10^4\) cycles and AE counts increased rapidly with cycle numbers. This test was terminated at \(N = 1.01 \times 10^5\) cycles when total AE event counts reached 4097. Figure 4(a) shows the post-test micrograph of the indentation damage. White semi-elliptical cracks near the contact area (not clear due to transparency of PVC) in the photograph is sub-surface cracks induced by cyclic contact. A large crack near the top and a smaller one at the bottom can be seen. Figure 4(b) shows a magnified view of (b) on the periphery of contact area. It shows a fine radial crack in the radial direction. Cross section along the line A-A’ in Fig. 4(a) is shown in Fig. 5. We observed sub-surface cracks at the depth of 516 \(\mu\)m. This is the white semi-elliptical lateral crack observed in Fig. 4(a).

Fig. 3 Indentation depth and cumulative AE counts as a function of indentation cycles.
Fig. 4 (a) Surface photograph of indentation damage, (b) magnified view of area marked (b).

Fig. 5 Cross sectional view of indentation damage (A-A’ line of Fig. 4(a)).

Fig. 6 AE source locations during cyclic ball indentation.
We analyzed AE waveforms to study the progression of fatigue damage. Figure 6 shows change of AE source locations estimated for AE events detected between \( N = 8.9 \times 10^4 \) and 10.1 \( \times 10^4 \) cycles. It is noted that AE sources are located slightly ahead of the periphery of the white crack. Location of source moves away from the contact area with increasing \( N \).

Next, we examined the fracture types based on the radiation pattern of longitudinal waves [5]. Figure 7 shows a set of AE waveforms. The polarity of the first arrival waves (marked by an arrow) from channel 1 and 3, mounted on the adjoining side surfaces, were negative while those from channel 2 and 4 are positive. This polarity distribution indicates shear or Mode-II type fracture [5]. The first-peak amplitudes of channel 1 and channel 2 were much larger than those of channel 3 and channel 4. This implies that the sliding vector of the lateral crack is in the direction connecting channels 1 and 2 (vertical in Fig. 1). This polarity distribution was observed for all AE events during the test. It is concluded that the AEs were produced by Mode-II lateral cracks. In contrast, we could not detect any AEs from Mode-I radial cracks, even though some of them were clearly visible. This is possibly due to small crack volumes of the radial cracks.

### 3.3 Mechanism of Lateral Cracks

We examine next lateral crack mechanisms, based on the experimental data and FEM for different size balls. Figure 8 shows the depth of the lateral crack initiation site, \( h_{\text{lateral}} \) as a function of \( \Delta F \). The \( h_{\text{lateral}} \) were determined by cross sectional observation. Symbols with downward arrows indicate no lateral crack initiation. All lateral cracks developed at 550 \( \mu \text{m} \) below the surface. This depth is independent of \( \Delta F \).
Figure 9 shows typical $F$ vs. $h$ curves of the specimen at pre-determined $N$ values. Test condition is the same with that of Fig. 3. This revealed that the $F$ vs. $h$ curve differences between loading (upper curve) and unloading (lower curve) decreased with increasing $N$. The area surrounded by two curves represents the stored deformation energy ($E_d$) in a single loading cycle [6]. The $E_d$ decreased with increasing $N$, as shown in Fig. 10, and decreased to a low, constant value beyond $N = 4.5 \times 10^4$ cycles. PVC produced permanent dent and deformed elastically after a large number of cyclic contacts.

Two-dimensional stress distribution under the contact area in the transverse section was calculated to study the driving force and depth of lateral cracks using finite element method (FEM)
with MARC (K7-2) and MENTAT II (V3.2.0). Two-dimensional FEM model with 1588 elements and 1645 nodes for a permanent dent is shown in Fig. 11. Diameter $d$ of the permanent dent was given by the measured value after the test, and the permanent depth $h$ was determined from $F-h$ curve in Fig. 11. Young’s modulus $E = 3.78$ GPa and Poisson’s ratio, $\nu = 0.36$ were used. We calculated the stress distribution using elastic contact analysis with $F_{\text{max}} = 981$ N and $d = 10$ mm.

![Fig. 10 F-h curve during the cyclic ball indentation test.](image)

![Fig. 11 FEM model for ball indentation test with $d = 10$ mm diameter.](image)

![Fig. 12 Shear stress $\tau_{rz}$ with contours at $F_{\text{max}} = 981$ N with $d = 10$ mm diameter.](image)

Figure 12 represents the contour map of shear stress $\tau_{rz}$ at $F_{\text{max}}$ of 981 N during ball indentation test with $d = 10$ mm diameter. Maximum $\tau_{rz,\text{max}}$ of 94.3 MPa is generated at the depth of 512
µm from the surface. This depth agrees quite well with the experimental depth of 516 µm in Fig. 8. It indicates that the lateral crack is produced at the depth of maximum shear stress.

6. Conclusions

Utilizing AE technique, we studied damage progressing in PVC (poly-vinyl-chloride) plastics subjected to cyclic ball indentation test. Results are summarized below.

1. In the test with maximum indentation force of 981 N and indenter diameter of 10 mm, sub-surface lateral crack initiated and grew with cyclic ball indentations. This crack was Mode II fracture and produced AE signals. Sources of these events were located ahead of growing lateral cracks. The lateral crack developed at 516 µm from the surface where the maximum shear stress is generated.

2. The depth of lateral crack initiation was observed to be about 500 µm and independent of indentation force, stress ratio and indenter diameter.

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References


