Influence of Edge-Distance Ratio and Hole-Size Ratio on Bearing Strength of Poly(ether ether ketone) and Its Composites

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ABSTRACT: The influence of edge-distance ratio (E/D) and hole-size ratio (S/D) on the bearing strength and failure modes of three kinds of poly(ether ether ketone) were investigated using the pin-type test method (ASTM E238). The results showed that bearing strength increased with increasing E/D and with increasing S/D. In addition, the bearing strength and failure mode depended on the polymer molecular weight and carbon fiber content. The study also showed that there is a transition region for S/D or E/D between 2 and 3 where the tension and a combination failure mode are mutually changed. © 1997 John Wiley & Sons, Inc. J Appl Polym Sci **66:** 1847–1853, 1997

Key words: bearing strength; PEEK; edge-distance ratio; hole-size ratio

INTRODUCTION

Poly(ether ether ketone) (PEEK) is a semicrystalline material with high strength, heat resistance, and chemical resistance. Therefore, PEEK can be applied in many fields involving aerospace, coating, and insulation.[1,2] Its composites, made with carbon or glass fiber, can also be used in many situations where joints are made by bolts or rivets. For application where joints are made in this way, the mechanical properties of fiber-reinforced as well as pure PEEK have been investigated.[3–5] Bearing strength, the load at which bearing deformation does not damage the structural integrity of a part, is generally the mechanical property of concern. However, although it does not often appear in papers, bearing strength is a strength index which is dependent on the joint device and only indirectly characterizes the mechanical properties of the material. Fundamentally, bearing deformation in composites can be considered to be a combination of four failure modes: bearing, tension, shear-out, and cleavage, which are shown in Figure 1. The stress for each of the first three failure modes is mathematically written as follows:

$$\text{Bearing strength: } \sigma_b = \frac{P_{\max}}{tD} \tag{1}$$

$$\text{Tension strength: } \sigma_t = \frac{P_{\max}}{(W-D)t} \tag{2}$$

$$\text{Shear strength: } \tau_{xy} = \frac{P_{\max}}{2Et} \tag{3}$$

where $P_{\max}$ is the maximum load during bearing test; D is the diameter of the bearing hole; t is the thickness of specimen; W is the width of the specimen; and E is the distance from the center of the bearing hole to the center of the closer edge of the specimen in the direction of the principle

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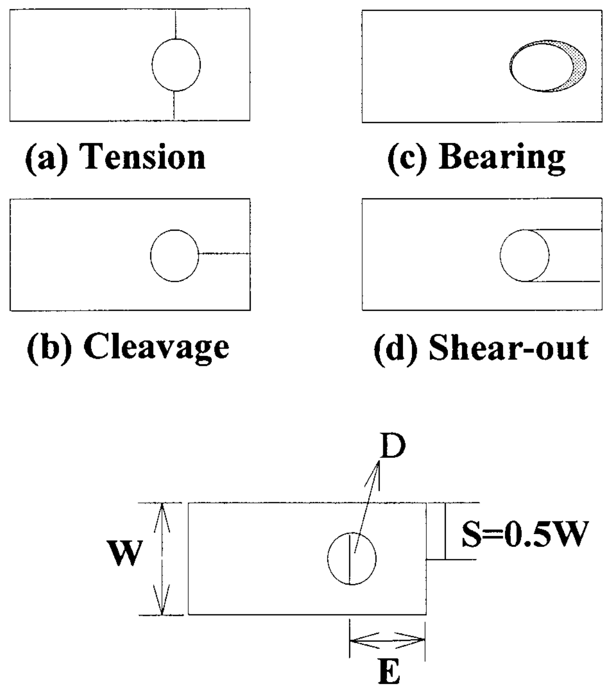


Figure 1 Failure modes and defined dimensional parameters for bearing test specimen of polymeric composites.

stress. The parameters above are also illustrated in Figure 1.

Determination of the bearing strength in any application depends on many parameters, including material parameters, fastener parameters, and design parameters.[6] In addition, the test method is an important factor. Reports[7,8] on the bearing strength of polymer composites are few. Among the more detailed, Walsh and colleagues[9] reported on PEEK and epoxy composites with different laminate configurations of graphite fiber. They used various test configurations for their bolted joints and concluded that the bearing strength of thermoplastic composites is superior to thermoset composites. Their study, however, left some questions, including the effects of edge distance and width, unresolved.

Hence, in this study we focus on the influence of edge-distance ratio (E/D) and hole size ratio (S/D) on the bearing strength of PEEK/carbon fiber composites. We also studied the effects of polymer molecular weight and carbon fiber reinforcement.

EXPERIMENTAL

Sample Preparation and Mold Injection Condition

Three types of PEEK pellets were obtained from ICI and RTP Company (USA). Their matrix designation and fiber contents are listed in Table I. For sample preparation, the pellets were dried in an oven at 120°C for 4 h to remove residual water before their use. Specimens were molded according to ASTM E238 code. Injections were made using a FANUC Autoshot Teris model 225D, with oil-circulating mold temperature controller, at 210°C. Mold temperatures of 360, 370, 380, and 390°C were examined. Injection speed and pressure were 12 cm/s and 1700 kg/cm^2, respectively. Hold pressure and back pressure were equal to 1100 and 50 kg/cm^2, respectively.

Bearing Strength Test

The bearing strength of PEEK and its composites were tested according to ASTM E238. A pin-type bearing fixture without lateral constraint, as shown in Figure 2, was used. Various steel pins were used as the load transfer pin. The specimens were tested in an Instron MTS-810 at a speed of 1 mm/min.

RESULTS AND DISCUSSIONS

Effect of Edge Distance Ratio

The relationship between maximum bearing strength and E/D are shown in Figure 3. For

Table I Description of Content for PEEK and Its Composites

Symbol	Content	M_v[a]
PEEK450G	100% PEEK450G neat	31,000
PEEK450C	70% PEEK450G neat + 30% carbon fiber[b]	31,000
PEEK2285	70% PEEK150P neat + 30% carbon fiber[b]	17,000

[a] Molecular weights of PEEKs were determined by viscometer.
[b] Short carbon fibers with an averaged diameter of 6 μm and a mean length of 65 μm were randomly blended in PEEK thermpolastic resins matrix.

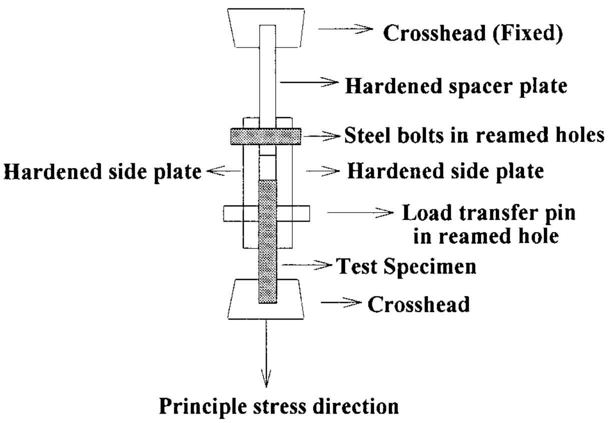


Figure 2 Schematic representation of pin-type bearing testing procedures.

three samples with S/D equal to 2, the bearing strength of all three samples increased with an increase in the E/D until an E/D of 2.5–3 was reached. Above this value, bearing strength began to decrease. When the E/D was increased, the fracture surface position was farther from the sample edge. As indicated above, this suggests that with an increase of E/D, [i.e., increase of E, "shear-out" force becomes less important, as shown in eq. (3)].

Figure 4 shows photographs of the failure mode of each sample type at different E/Ds. Failure occurred in tension when the E/D was greater than 2.5. When the E/D was less than 2, failure occurred in a combination of tension and shear-out for PEEK450C and PEEK2285, however PEEK450G failed due to shear and bearing.

In sequence, the maximum bearing strength of the three kinds of PEEK is PEEK450C > PEEK450G > PEEK2285. This sequence is due to both the molecular weight of the PEEK and the chopped carbon fiber content, as listed in Table I. Figure 5 shows the difference in the bearing strengths of PEEK450C and PEEK450G, the effect induced by carbon fiber, and the difference in the bearing strengths of PEEK450C and PEEK2285, the effect induced by molecular weight. Each difference is plotted as a function of E/D. With an increase in E/D, the bearing strength induced by molecular weight increased and the bearing strength induced by carbon fiber decreased. As we know, the mechanical strength of polymer with higher molecular weight is usually superior to that with lower molecular weight. Hence the bearing strength of PEEK450C is better than PEEK2285. As for the fiber effect on the bearing strength of samples PEEK450C and PEEK2285, Figure 5 indicates that the fiber reinforcement effect on the bearing strength is gradually decreased with increasing E/D. This is mainly due to the fact that fiber orientation on the core layer of the specimen is mostly perpendicular to the load direction,[10] therefore the fiber reinforcement effect on the tension failure mode is not profound at large E/D but the reinforcement becomes obvious at small E/D in which failure turns in a combination mode. Note that the upward or downward trend are both interrupted when the E/D becomes equal to 2.5. This suggests that a transition from combination failure mode to tension mode occurs at E/D of 2 to 3.

Effect of Hole-Size Ratio

Hole-size ratio (S/D) can be defined as the half-width of the specimen (S) divided by the diameter of the hole (D). The relationship between maximum bearing strength and S/D is shown in Figure 6, for a constant E/D equal to 2. The maximum bearing strength of the three types of PEEK increased with decreasing hole size (D) although there was an interruption in this trend at S/Ds of 2 to 3, depending on the sample.

As eqs. (1)–(3) show, as S/D is gradually de-

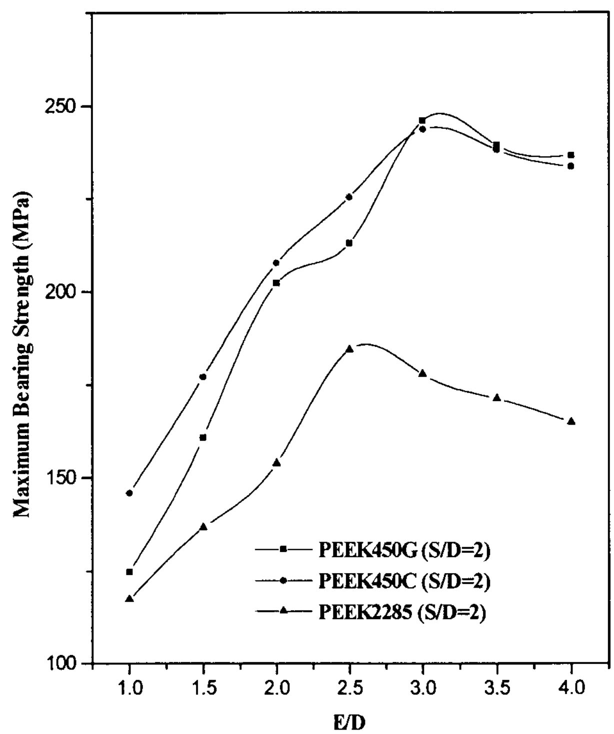
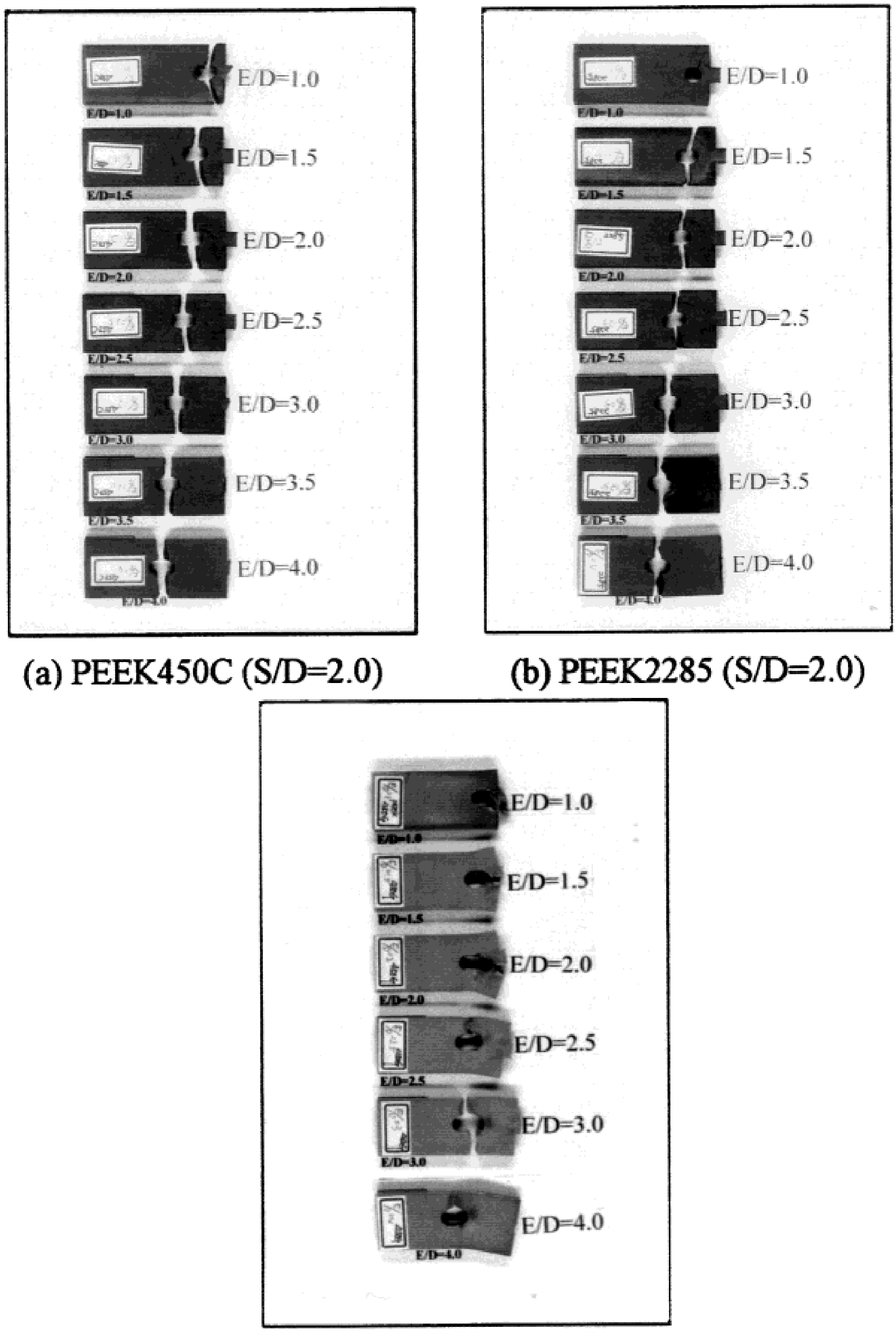


Figure 3 Relationship between maximum bearing strength and E/D at S/D equal to 2.



(c) PEEK450G (S/D=2.0)

Figure 4 Photograph of failure mode of bearing strength of three kinds of PEEK at different E/Ds: (a) PEEK450C, (b) PEEK2285, and (c) PEEK450G.

creased, mean tension strength is more important than bearing and shear-out. Figure 7 shows photographs of the failure mode of the three kinds of PEEK at different S/Ds. PEEK450C and PEEK2285 fail in a combination of tension and shear, although for S/D less than 2, only tension

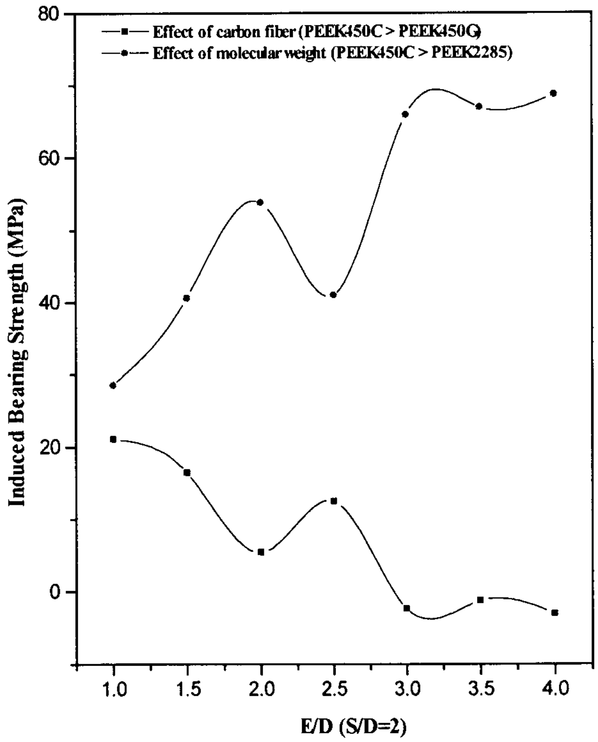


Figure 5 Influence of different molecular weights and effect of carbon fiber on the relationship between bearing strength and E/D at S/D equal to 2.

failure is obvious. For PEEK450G, tension failure dominated when S/D was smaller than 2 and a combination of shear and bearing failure occurred when S/D was greater than 2.5. Relating these failure mechanisms to the bearing strength graph, Figure 6, when S/Ds lie between 2 and 3 a transition region exists where tension force competes with other failure modes in the material.

In Figure 6, we again see that the sequence of maximum bearing strengths is PEEK450C > PEEK450G > PEEK2285. This order can be explained by the sample molecular weights and carbon fiber contents as listed in Table I. Figure 8 again plots the bearing strength difference between appropriate samples to isolate the effect due to the presence of carbon fiber and the effect due to the difference in molecular weight of the PEEKs. With an increase in S/D, the bearing strength induced by the difference in the molecular weight of the PEEKs increased and the induced effect due to carbon fiber also increased. The reason has been mentioned above, in discussing Figure 5. The higher molecular weight of PEEK450C in comparison with PEEK2285 results in its higher bearing strength. The fiber orientation and failure models explain the variation of bearing strength with S/D for samples of PEEK450C and PEEK450G. With small S/D, samples fail in tension mode and the fiber oriented perpendicularly to the load direction does not significantly contribute the bearing strength. However, at large S/D, failure shifts from tension to a combination mode; the fiber reinforcement is becoming profound. Figure 8 also suggests that the region where S/Ds go from 2 to 3 is a transition region where tension and combination mode are mutually changed.

CONCLUSIONS

From this study, several conclusions can be made:

1. The sequence of maximum bearing strength of the PEEKs is PEEK450C > PEEK450G > PEEK2285. This order depends on polymer molecular weight and carbon fiber content.
2. With increasing E/D, the failure mode changes from a combination of shear and tension to tension for PEEK450C and PEEK2285, whereas the failure mode

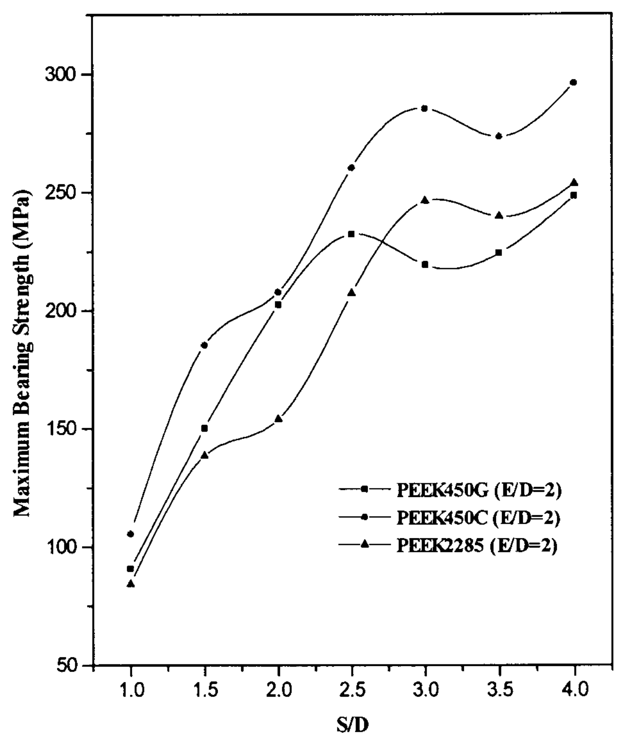


Figure 6 Relationship between maximum bearing strength and S/D at E/D equal to 2.

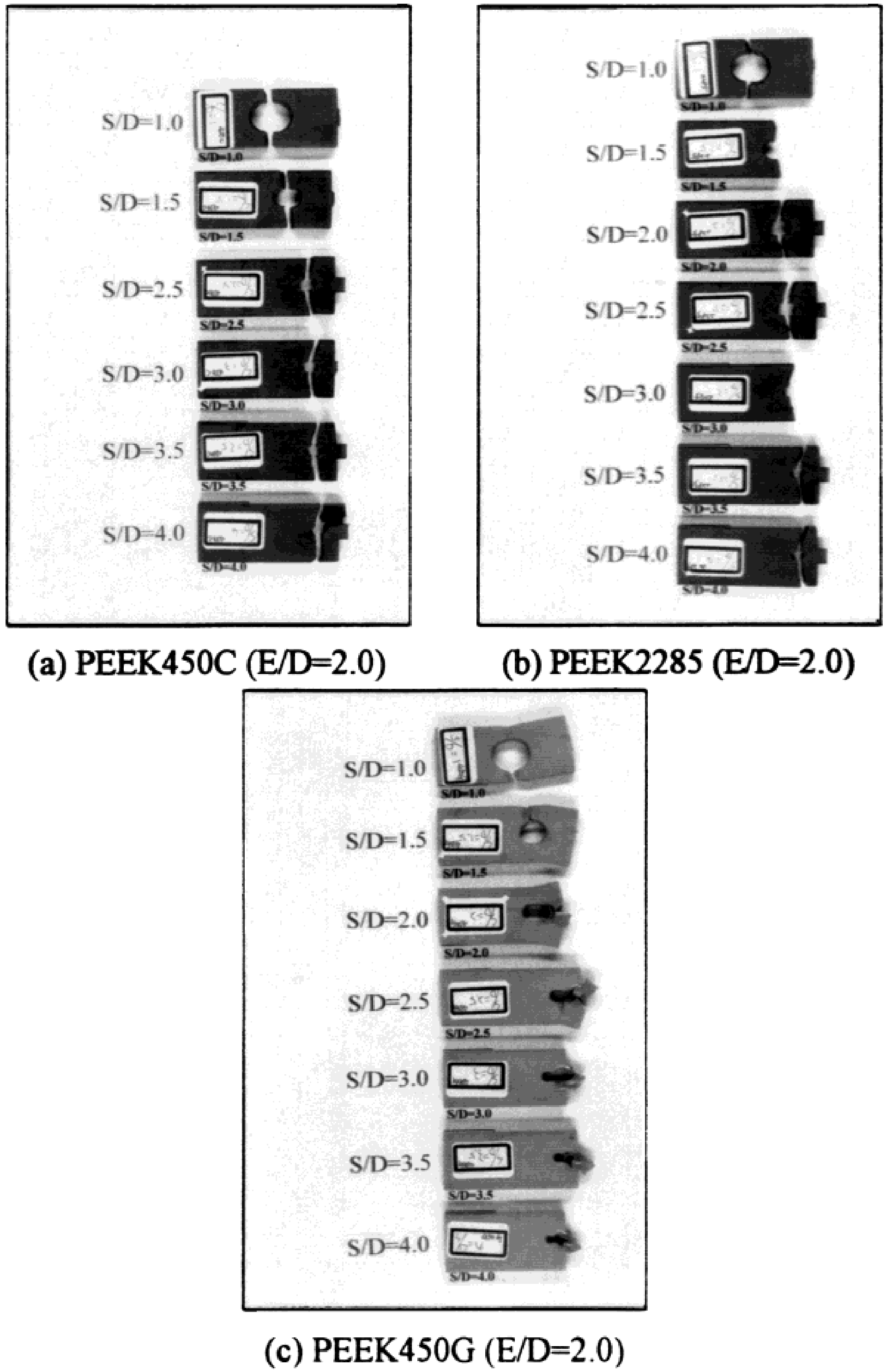


Figure 7 Photograph of failure mode of bearing strength of three kinds of PEEK at different S/Ds: (a) PEEK450C, (b) PEEK2285, and (c) PEEK450G.

changes from a combination of shear and bearing to tension for PEEK450G.

3. With increasing S/D, the failure mode changes from tension to a combination of tension and shear for PEEK450C and PEEK2285, whereas the failure mode

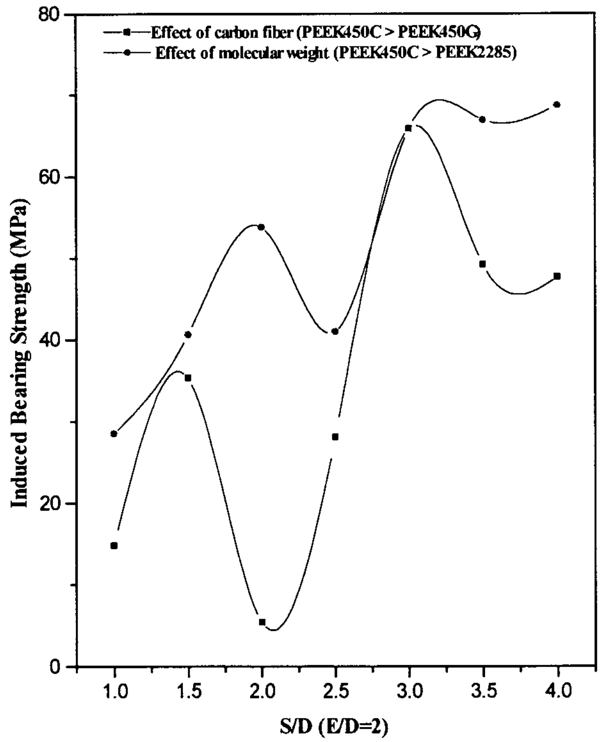


Figure 8 Influence of different molecular weights and effect of carbon fiber on the relationship between bearing strength and S/D ratio at E/D equal to 2.

changes from tension to a combination of shear and bearing for PEEK450G.

4. The transition region where the failure mode changes occurs for either E/D or S/D between 2 and 3.

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