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INTRODUCTION

The purpose of this note is to report some observations on the pop-in mode of fracture made during a recent study of the fracture toughness of glassy plastics.[1] The pop-in mode, first discussed by Boyle et al.,[2] is applied to the tensile fracture characteristic of notched specimens in which crack extension begins with a distinct burst accompanied frequently by an audible click and is followed by slow crack growth under increasing loading. The load during this sudden initial extension of the crack or "pop-in" either remains constant or decreases depending upon the stiffness of the testing machine; since the pop-in corresponds to an increase in specimen compliance at constant extension, a decrease in load is expected provided the testing machine has sufficient stiffness. The importance of the pop-in mode is that it has been associated with the plane strain fracture toughness of the material[2] and thus offers a way to measure this toughness level in thinner specimens than are usually required. This note comments on pop-in extension, arrest of the pop-in extension, and on the toughness associated with pop-in. Some general observations on the use of plastics to study fracture phenomena are also presented.

DISCUSSION

The two types of tensile fracture characteristics observed during testing of several glassy plastics[1] were the pop-in mode and the flat or square fracture mode. One of the plastics, polycarbonate, apparently was near a transition between these two fracture modes for the test conditions used since both types of behavior were observed. The specimens were 1 × 2 inch single edge notch specimens, 0.250 inches thick; conditioned in accordance with Procedure A of ASTM D618 at 73°F and 50 percent relative humidity; and tested at room temperature and 0.2 cm/min. Figure 1 shows the load-displacement record for a pop-in mode while Fig. 2 gives the record for a flat fracture mode obtained with the same test conditions. From these figures, the first observation about the pop-in mode is that the load at pop-in is the same as the load causing catastrophic flat fracture in the other specimen. This behavior provides a direct demonstration that the fracture toughness at pop-in corresponds to the plane strain fracture toughness of the material.

The transparency of polycarbonate allowed observation of crack extension during loading; because of the high reflectivity of internal surfaces, very small crack extensions could be observed. The indication of pop-in on the load-displacement curve (decrease in load) visually correlated with a rapid extension of the crack in a semi-circular front as shown in insert 1 of Fig. 1 and 1(b) of Fig. 3. Increasing the load beyond the pop-in value produces two effects shown in 2a,b and 3a,b of Fig. 3. First, additional crack growth occurs by extension of the pop-in fracture surface through the center section of the specimen. Second, plastic zones develop in the unfractured regions bordering the central flat crack showing that deformation by shear is the important mechanism in these regions. Careful examination of the specimen at pop-in (1a of Fig. 3) did not reveal any visible plastic zone indicating that extensive plastic deformation does not occur during the rapid propagation of the pop-in.

A description of the pop-in extension and arrest consistent with these observations can be obtained by considering the stress state near the crack tip. Specifically, as shown by Dixon,[3] the stresses in the thickness direction increase rapidly from zero at the outer surfaces toward a maximum value dependent upon the notch geometry in the center portion of the specimen. For thin specimens, the thickness direction stresses cannot fully develop but, for thicker specimens, a region of constant stress develops in the central section of the specimen. This central region is associated with a condition of plane strain and triaxial stress, whereas the surface regions are in a condition of plane stress and biaxial stress. For polycarbonate and for many other materials as well, fractures under the condition of plane strain are associated with a low toughness while plane stress fractures have a high toughness. Thus, the local environment of a crack is like a laminate of two thin high toughness regions surrounding a low toughness central section.

For specimens thick enough for plane strain conditions to develop in the central region, a flat fracture is initiated at the notch in the plane strain region. The fracture moves forward most rapidly in the low toughness, central section forming a semi-circular crack front bounded by thin plane stress regions near the surfaces. This initial crack extension is arrested by the high energy, plane stress deformation of these boundary regions which must necessarily accompany crack extension in the central section. Also, as shown by Dixon, the development of a curved crack front modifies the stress distribution such that the maximum longitudinal stress is shifted to the boundary regions. The longitudinal stress in the central region is reduced thus aiding fracture arrest. Further crack extension takes place in the central plane strain region but increasing load is required in order to deform the boundary regions (see 2a,b of Fig. 3) to accomodate the crack extension. A maximum load point is reached when the strengthening effect of shear deformation of the boundary regions is overtaken by a combination of decreased specimen area due to the propagation of the central crack and by plastic instability in the shearing regions (see 3a,b of Fig. 3). Fracture of the boundary regions finally occurs by shear producing the familiar shear lips.

From this model, two critical thicknesses can be defined. A lower critical thickness, tc_1, is the smallest thickness in which a region of plane strain is developed in the central section; pop-in can only occur for thicknesses greater than tc_1. An upper critical thickness, tc_2, is reached when the pop-in extension is not arrested and produces complete fracture. This condition occurs because the area of the central plane strain region increases with thickness while the high toughness boundary regions do not increase in size. Thus, the boundary region becomes too thin relative to the pop-in size to arrest the crack.

For polycarbonate,[1] it is estimated that $tc_1 = 0.080$ inches, the minimum thickness for which a pop-in was observed and that $tc_2 = 0.250$ inches, the thickness corresponding to the observation of both pop-in and catastrophic fractures. These critical thicknesses can be expressed in a dimensionless form using the plastic zone size, r_y, since it is expected that the development of plane strain conditions depends on the extent of plastic deformation at the crack tip. Using the expression of Irwin and McClintock[4] for plane strain conditions:

$$r_y = \frac{1}{4\pi(2)^{1/2}} \left(\frac{K_{Ic}}{\sigma_y}\right)^2 , \qquad (1)$$

a value of $r_y = 0.008$ inches was estimated for polycarbonate which gives $(tc_1/r_y) = 10$ and $(tc_2/r_y) = 31$.

These values can be compared to the criteria proposed for assuring a specimen thickness is great enough to produce an acceptable plane strain fracture toughness test. Hahn and Rosenfield[7] estimated that the transition from plane strain to plane stress occurred for a thickness-to-plastic zone radius of 14 by observing the plastic deformation of steels in the thickness direction by means of etching. The value 14 corresponded to the start of a significant shift away from plane strain and agrees in magnitude with tc_1. Brown and Srawley[8] recommended a value of thickness-to-plastic zone radius of 44 based on experimental observation of the effect of thickness on measured fracture toughness. The value 44 corresponded to the attainment of a minimum value of toughness which did not significantly vary for increasing thicknesses; this value correlates best with the value for tc_2. It is noted that the above values of Hahn and

Rosenfield and Brown and Srawley have been modified from the original papers by using Eq. (1) for the plastic zone radius rather than other forms originally used so that a consistent comparison could be made.

These observations about the pop-in mode of fracture illustrate that the properties of glassy plastics make them especially useful materials for studying fracture phenomena in general. Other properties in addition to transparency which can be useful in fracture studies include birefringence and low elastic modulus. Birefringement plastics have been used frequently to investigate the stresses around cracks. The low modulus of plastics leads to larger and thus, more accurately measurable deflections. This is especially important in compliance analysis where, as noted by Srawley et al.,[9] accuracy of displacement measurements is the most critical factor. Similar to other experimental techniques of stress analysis such as photoelasticity, compliance analysis can be shown to be independent of the elastic properties of the media for simply connected regions and to require an equality of Poisson's ratio (usually a small correction) for multiply connected regions.[6] Thus, for a single edge notched specimen (a simply connected region), the results of a calibration using plastics should apply to any similar specimen independent of material. Figure 4 shows such a dimensionless curve including data from polystyrene, SAE 4340, and 7075-T6 specimens.

Plastics can be selected to model the macroscopic behavior of many metals. For example, polycarbonate has a behavior similar to a mild steel with a local deformation phenomena macroscopically similar to Lüders bands while acrylic plastics exhibit a brittle behavior with little plastic deformation. Some plastics such as polycarbonate and polyvinyl chloride show a sharp ductile-to-brittle transition behavior similar to many steels. Additional variation in tensile properties can be obtained by varying conditions of temperature, humidity and strain rate.

From a testing standpoint, plastics offer some obvious advantages including reduced loading requirements allowing investigations of size effects in testing machines of modest capacity and easy machinability to reduce specimen costs. For example, very sharp cracks which are difficult to machine in metal specimens can be readily introduced into a plastic specimen with a razor blade.

The above discussion has indicated that plastics can be used as a tool in fundamental studies of fracture in a manner similar to the frequent use of Fe-Si alloys. Future studies might include further investigations of the pop-in phenomena and its relation to specimen geometry using polycarbonate. A brittle plastic such as acrylic would be useful for studying specimen geometry and size effects with a minimum effect of plastic zones at the tip of the crack.

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REFERENCES

1. P. L. Key, Y. Katz, and E. R. Parker, An Application of Fracture Mechanics to Glassy Plastics, UCRL-17911, February 1968.
2. R. W. Boyle, A. M. Sullivan, and J. M. Krafft, Determination of Plane Strain Fracture Toughness with Sharply Notched Sheets, Welding Journal <u>41</u>, (9), 428s.(Sept. 1962).
3. J. R. Dixon, Effects of Crack-Front Geometry and Plate Thickness on the Stress Distribution in Cracked Plates, Conference Proceedings, Physical Basis of Yield and Fracture, Oxford, Sept. 1966.
4. F. A. McClintock and G. R. Irwin, Plasticity Aspects of Fracture Mechanics, <u>Fracture Toughness Testing and Its Application</u>, (ASTM, Philadelphia, 1965), p. 84.
5. A. M. Sullivan, New Specimen Design for Plane-Strain Fracture Toughness Tests, Materials Research and Standards <u>4</u>, (1), 20-24 (Jan. 1964).
6. Y. Katz, P. L. Key, and E. R. Parker, UCRL-17895, February 1968.
7. G. T. Hahn and A. R. Rosenfield, Sources of Fracture Toughness: The Relation Between K_{Ic} and the Ordinary Tensile Properties of Metals, Presented at ASTM Symposium on Applications Related Phenomena in Titanium and Its Alloys, Los Angeles, 1967.
8. W. F. Brown and J. E. Srawley, <u>Plane Strain Fracture Toughness Testing of High Strength Metallic Materials</u> (ASTM, Philadelphia, 1967).
9. J. E. Srawley, M. H. Jones, and B. Gross, Experimental Determination of the Dependence of Crack Extension Force on Crack Length for a Single Edge Notch Specimen, NASA Tech. Note D-2396 (1964).

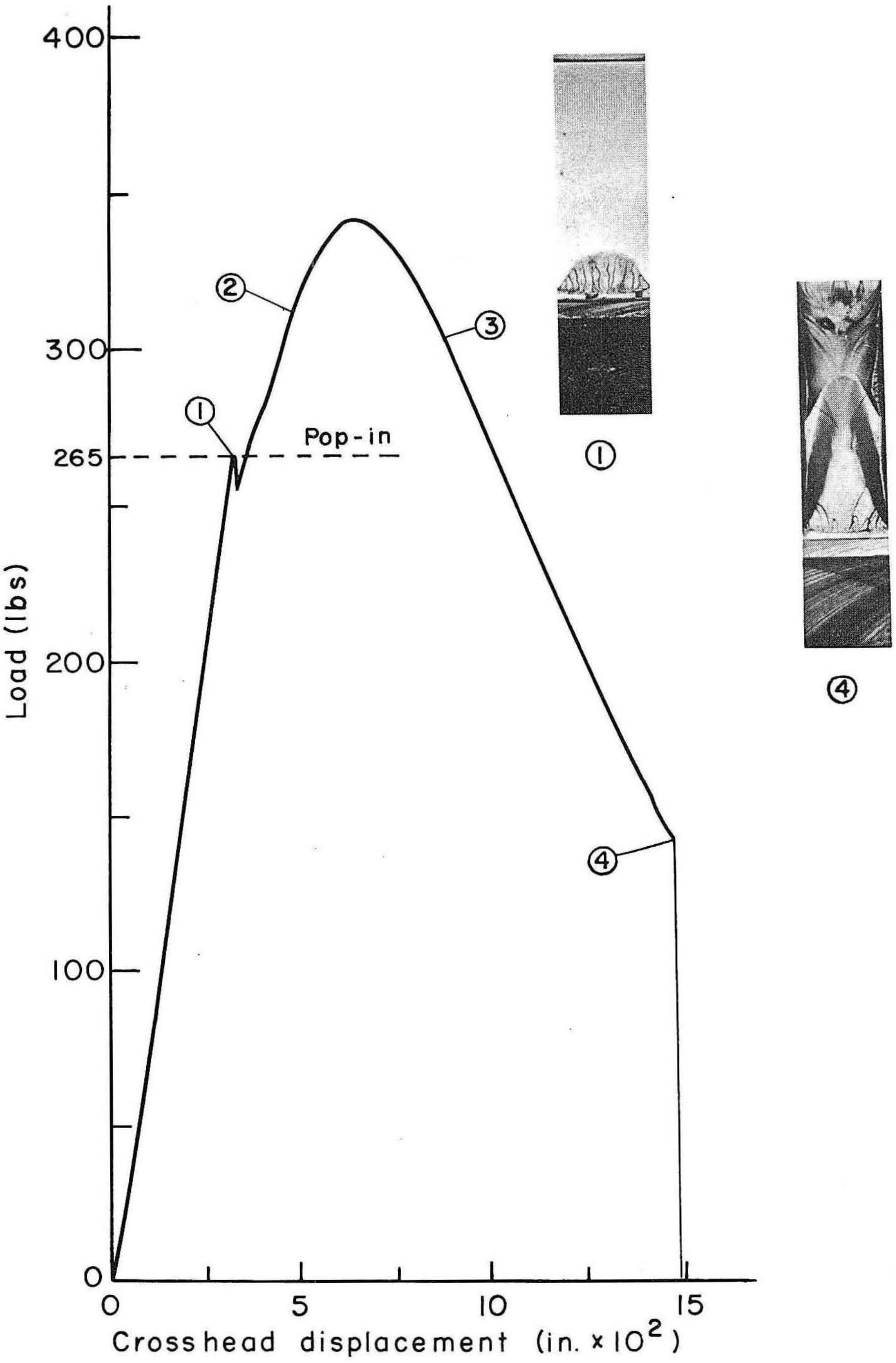

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Fig. 1 Load-displacement record for pop-in fracture with a polycarbonate SEN specimen. The plane of fracture just after pop-in as viewed through the specimen is shown in insert 1; the fracture surface after separation is shown in insert 4. Test conditions: room temperature and 0.2 cm/min. Numerals 2 and 3 refer to Fig. 3.

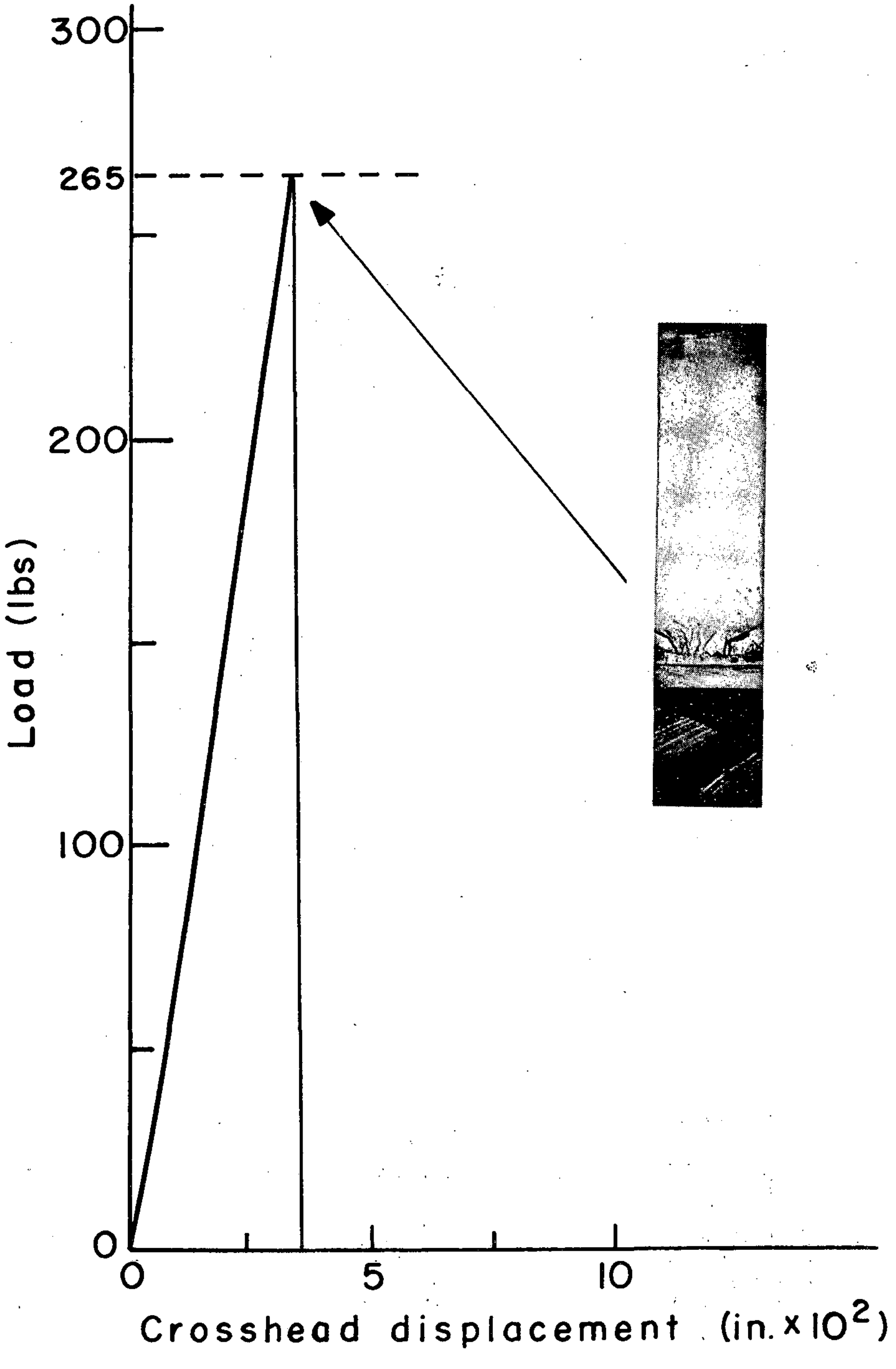

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Fig. 2 Load-displacement record for catastrophic fracture with a polycarbonate SEN specimen. Insert shows the fracture surface after separation. Test conditions: room temperature and 0.2 cm/min.

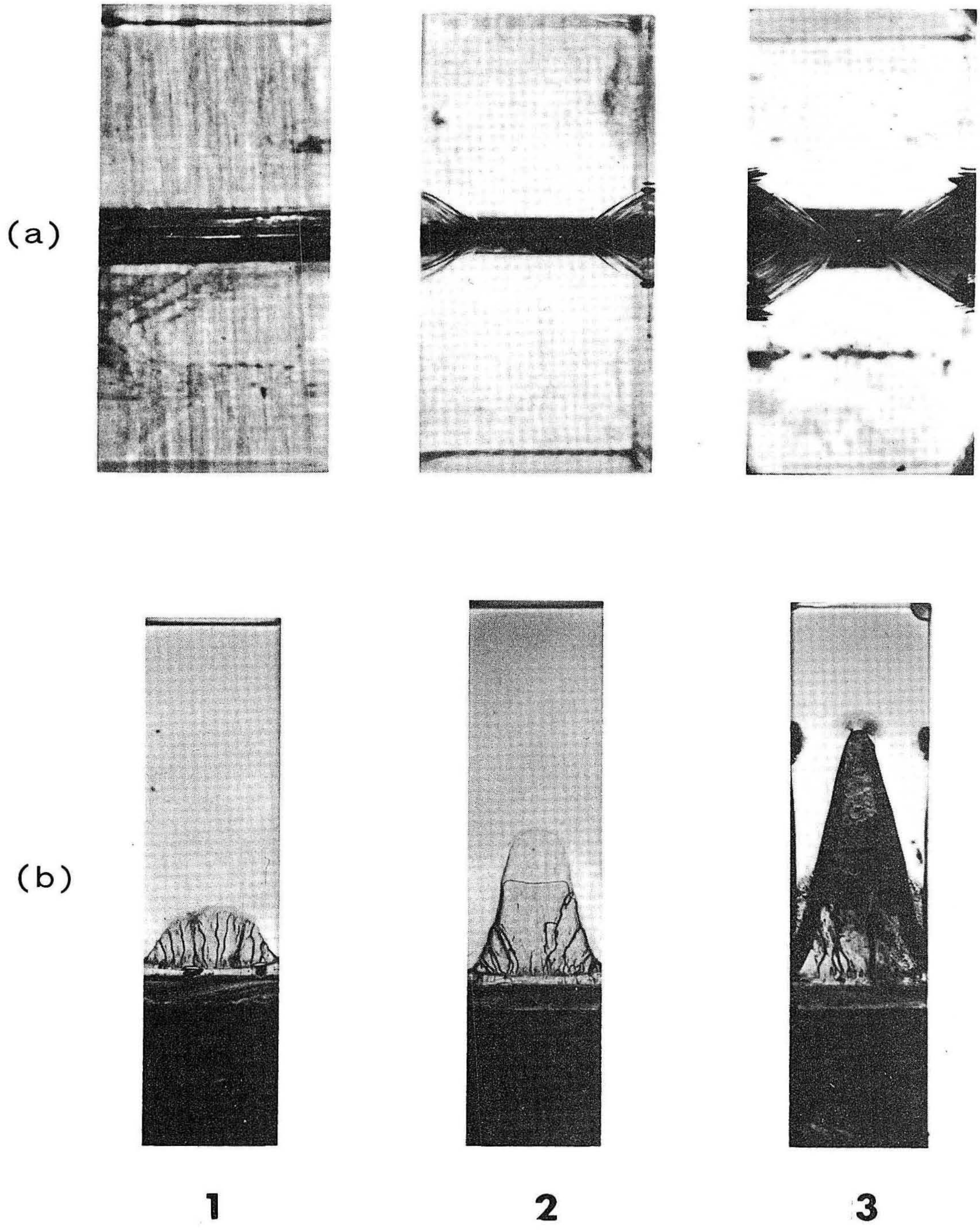

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Fig. 3 Development of plastic zones (a) and growth of the central flat region (b) in a pop-in fracture in a SEN polycarbonate specimen. Numerals 1, 2, and 3 refer to Fig. 1

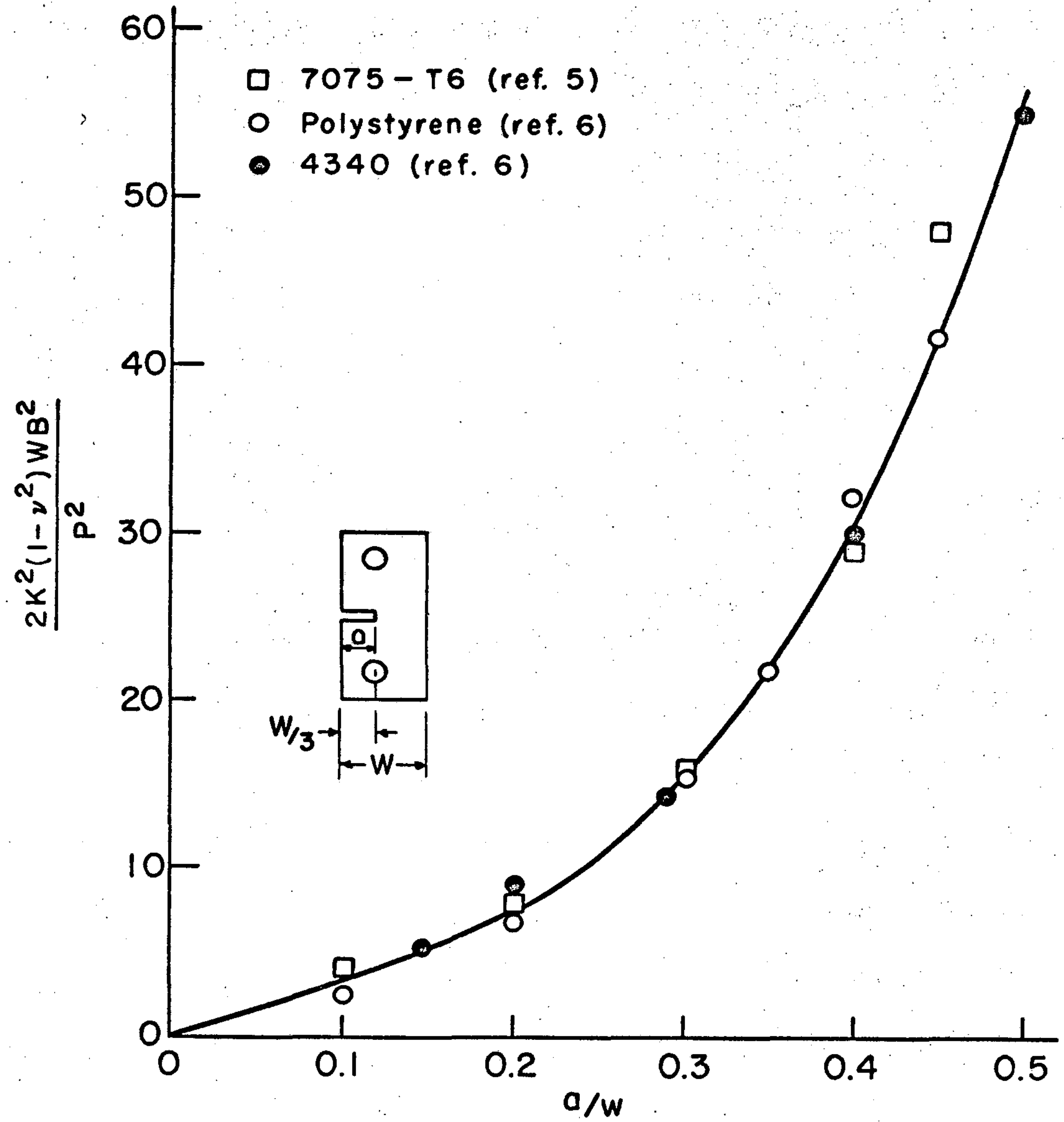

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Fig. 4 Dimensionless Fracture Toughness Parameter for Single Edge Notch Fracture Specimens.