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FRACTURE TOUGHNESS OF STRETCHED ACRYLIC PLASTIC,(U)

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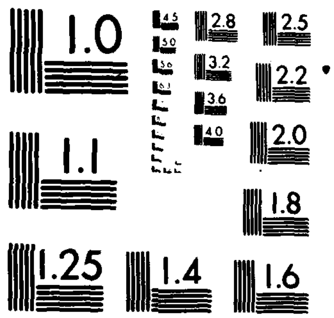

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FRACTURE TOUGHNESS OF STRETCHED ACRYLIC PLASTIC

by

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ABSTRACT

This paper presents the method and result of a parametric study of instability toughness, as measured by the critical stress intensity factor, K_c, of a multiaxially stretched acrylic plastic. A large number of computer controlled tests were conducted on the compact tension specimen under high compliance loading/load control. These tests reveal the significant effects upon K_c of a wide range of loading rates and specimen thickness, and specimen geometry. A direct and immediate application of the results is the recommendation of a new fracture toughness acceptance test for these materials.

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Presents the method and result of a parametric study of instability toughness, as measured by the critical stress intensity factor, K_c, of a multiaxially stretched acrylic plastic. A large number of computer controlled tests were conducted on the compact tension specimen under high compliance loading/load control. These tests reveal the significant effects upon K_c of a wide range of loading rates and specimen thickness, and specimen geometry. A direct and immediate application of the results is the recommendation of a new fracture toughness acceptance test for these materials.

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INTRODUCTION AND BACKGROUND

Since the emergence of stretched acrylic about 20 years ago it has beome a dominant material in aircraft transparency applications. The multiaxial or biaxial hot-stretching process produces a material with a much higher resistance to thru-crack propagation. The fracture mechanics characterization of this toughness has unfortunately not been used to any extent in design of these structures, but is a widely used and vital determinant of material quality which can vary appreciably due to the many variables involved in the stretching process.

The technique currently used for determining the fracture toughness of stretched acrylic is described in the military specification MIL-P-25690 A (1). The test method was established during the relatively early stages of development of fracture mechanics stemming from a set of pioneering papers in the field by Kies, et al (2,3). The method has not been modified to reflect the progress that has been made in this rapidly advancing field.

The testing method involved using a displacement controlled (primarily screw type) testing machine to pull a center cracked specimen (CCS) to failure (Fig. 1). The critical stress intensity factor K_c, was calculated from the load and crack length at instability using a relation from early calibration results (2,3). This relation agrees well with later analytical stress analyses of the CCS geometry (4). The range of loading rates allowed is broad and thickness effects were not considered.

This paper describes a fundamental application of fracture mechanics to develop an improved technique for characterizing the instability fracture toughness of this material. Points of prime interest and concern include specimen geometry, size, thickness, type of loading and loading rate, and convenience of the technique for toughness characterization of plastic materials.

MATERIAL AND SPECIMENS

The compact tension specimen (CTS) shown in Figure 3 was selected for the characterization program. This geometry is widely accepted and has been analyzed by Srawley and Gross (5). The CTS offers several advantages over the currently used CCS specimen including smaller size, lower loads to failure, simplified pin loading and alignment, and ease of pre-cracking. In addition the presence of two crack tips in the CCS geometry leads to a low estimate of toughness since the weaker of the two crack tips determines failure. The CTS has no such problem.

The choice of half-height to width ratio (H/W) for the CTS is somewhat arbitrary but the accepted ASTM value of 0.6 was chosen. The specimens had a length (L) of 2 in (5 cm) and 2.4 in (6 cm) and ranged in nominal thickness from 1/8 inch (.32 cm) to 7/8 inch (2.2 cm) which encompass the more widely used thickness.

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A V-tipped notch was machined in the specimen and a natural crack initiated at the notch using the procedure outlines in the current specification (1). This technique produced a sharp, natural crack extending .1 inch (2 mm) or more beyond the machined notch. This depth was found adequate to remove the crack tip from the effects of the machined notch which include stress field irregularities and change in material structure induced by the machining heat.

The material used was a commercially prepared bi-axially stretched acrylic conforming to MIL-P-25690 A.

LOADING PARAMETERS.

The loading parameters can play a very important role in the crack propagation behavior particularly in polymeric materials where viscoelastic effects are significant. In essence, the method for performing the test or loading machine type and compliance can affect the results. Precautions must be taken to separate material behavior from such effects.

The most fundamental loading parameter in these fracture toughness tests is the stress intensity factor, K, since it characterizes the stress state in the fracture process zone at the crack tip (within the constraints of linear elastic fracture mechanics). If there is little stable crack growth during the course of loading, K is proportional to the applied load so that using load control effectively controls the stress intensity factor. The use of load control has the advantage of accentuating instability as opposed to displacement control which tends to foster stable crack growth. From a statics point of view, there is no load relaxation with increasing crack length as in the displacement control (quasi-fixed grip) and from an energy point of view there is a large reservoir of readily available energy for crack propagation when a high-response load control is used.

Since one of the purposes of this research is a toughness characterization technique that is easy to implement, a means of accomplishing load control on a displacement (screw type) testing machine was developed and used in all tests. The loading scheme is to place a highly compliant member in series with the specimen as shown in Figure 2. Since the compliance of the member is much greater than that of the specimen, the load transmitted by the member is very nearly proportional to the crosshead displacement. A constant crosshead rate therefore produces a proportionally constant rate of force application, which produces a proportionally constant rate of increase in the stress intensity factor. In addition, the compliance of the testing machine (grips, crosshead, and frame) is rendered insignificant as that the use of the compliant member tends to isolate the specimen from the testing machine. Load control can also be used in conjunction with the compliant member where the effect of the member is to standardize the dynamic response characteristics of the system. The

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compliant member used in these tests was a fiberglass laminated beam configuration chosen for its strength, light weight, and reasonably high stiffness. Pulling was accomplished using a displacement controlled hydraulic actuator.

EXPERIMENTAL CONTROL

The tests and data evaluation were conducted using a computer based system for experimental control and data acquisition, and data analysis which includes processing, associative storage and retrieval, data base searching, and display. The system is shown schematically in Figure 4 and will be described in detail in a forthcoming report (6). Basically, a computer program inputs the test parameters, i.e., loading rate expressed as K-rate, initial crack length, and specimen geometry and size. The program conducts the test measuring appropriate information then processes and stores the data. Force, displacement, and time (see Figure 2) are monitored during the test and the crack length at failure was determined visually after failure. From these values the critically stress intensity factor K_{Ic} is computed using the Srawley and Gross relationship (5), and the actual loading rate K-rate is determined. The principle advantage of the computer based system is the ease and speed for running the nearly 300 tests and evaluating their results.

RESULTS AND DISCUSSION

The results can be considered to accomplish two basic purposes. The first is to show the effects on toughness of the various experimental parameters, and the second is to demonstrate whether linearly elastic fracture mechanics (K_{Ic}) is applicable to these materials. A total of nearly 300 tests were conducted and the parameters of greatest interest are the loading rate (K-rate), thickness, specimen size, and initial crack length. In all tests a small amount of stable crack growth preceeded instability ranging up to approximately .04 in (1 mm) for the low loading rates in thin specimens. This growth is considered beneficial in that it moves the fracture process zone in which the instability initiates away from the initial precrack tending to smooth any precrack irregularities.

The fracture surfaces observed were typical of those for stretched acrylic. A zone of pre-instability crack growth displays much tearing which reflects the energy dissipation mechanisms. The fracture surfaces indicate no large scale plastic yielding which enhances the use of linearly elastic fracture mechanics (K_{Ic}) as a fracture criterion.

Figure 5 is a master graph showing the results of nearly 300 tests and reveals the effects of loading rate and thickness on K_{Ic}. The graph shows the measured values of K_{Ic} for loading rates (K-rate) ranging from 22 psi$\sqrt{\text{in}}$/sec (25 N/cm$^{3/2}$-sec, failure occurs in approximately 3 minutes) to 450 psi$\sqrt{\text{in}}$/sec

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(500 $N/cm^{3/2}$-sec, failure in 5 seconds). Trend curves derived from averaging appropriate groups of data are shown in Figure 6. The most striking observation is the rapid decrease in toughness with increase in rate of loading. The increase is expected, however, and is typically the case in viscoelastic or rate sensitive materials. The lower loading rates allow more plastic flow which leads to the higher toughness values. At the lower rates the thinner specimens are tougher than the thicker whic is again expected since the thinner tend toward a state of plane stress. At the higher rates, all values tend to converge. The probable cause is that the higher rate allows less plastic deformation and the specimens tend more toward the plane strain condition so that the toughness values converge for the different thickness.

The two specimen sizes tested (H/W = .6) had widths (W) of 2 inches (5 cm) and 2.5 inches (6.2 cm). There appears to be no significant effect of size on K_c, although the size difference is not great. Different crack lengths, widths, and H/W ratios, within certain bounds, are of course accounted for in the linear elastic stress analysis. The analysis would be expected to apply unless the plastic zone size becomes large with respect to the dimensions of the specimen which is not the case in the current tests and the linearly elastic fracture mechanics approach is applicable. However, the stress analysis assumes plane strain conditions so will not be perfectly accurate for the plane strain tended toward the thin specimens at low loading rates. The error so induced in the K calculation is related to the Poisson ratio for the material and will be no greater than approximately 10%.

A striking feature in all tests is the large amount of scatter in the K_{Ic} values. Toughness testing, especially in the stretched acrylics, have always exhibited wide scatter due primarily to the unstable nature of the phenomenon. The two immediate suspected causes of the scatter are variations in crack geometry, and material variability. Careful comparison of the failed fracture surfaces revealed no correlation between crack tip geometry and toughness (for example, one might expect an eccentric crack front to produce a low toughness value). One does observe a larger slow growth region in specimens with higher toughness. This is expected since the high toughness reflects the greater energy dissipation which produces a large pre-instability damage zone. It appears that the most likely cause of the observed scatter is variability of the material (on the microscale) which is amplified by the unstable nature of the phenomenon.

RECOMMENDATIONS

A primary purpose of this investigation is to recommend an improved technique for characterizing toughness of stretched acrylic material. On the basis of the tests described above, the following recommendations seem justified:

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1. The compact tension specimen (CTS) with standard H/W ratio of 0.6 (see Figure 3) is a convenient specimen for all thicknesses examined (1/8 inch to 7/8 inch). A standard size (e.g., W = 2 in) should be specified. A standard but non-critical crack length (e.g., a/W = 0.5) should be chosen and current pre-cracking techniques continued.

2. Loading rate should be specified as a constant K-rate. The use of load control and/or displacement control with a compliant member greatly simplifies the K-rate control. The compliant member also serves to isolate the test from the testing machine and to accentuate instability.

3. It may be desirable to specify a much higher loading rate (K-rate) than the current specification (e.g., 200 psi $\sqrt{in}$/sec). The data (Figures 5 and 6) indicate that K_{Ic} is less dependent on thickness at this higher loading rate. In addition, the higher rates more closely indicate behavior under impact conditions which is a very important consideration in many applications.

The above recommendations and conclusions are intended to update and strengthen the fracture toughness acceptance test as well as render the test easier and less costly to run. In addition, the data described herein will hopefully provide insight into the fundamental fracture and failure behavior of these aircraft glazing materials.

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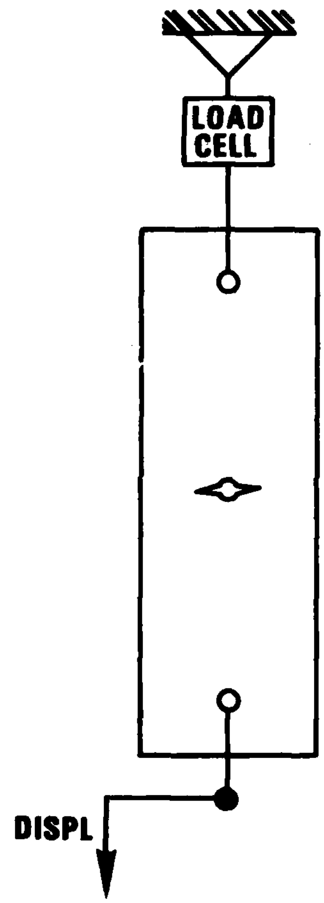

Figure 1. Center Crack Specimen Loading Scheme per Mil-P-25690.

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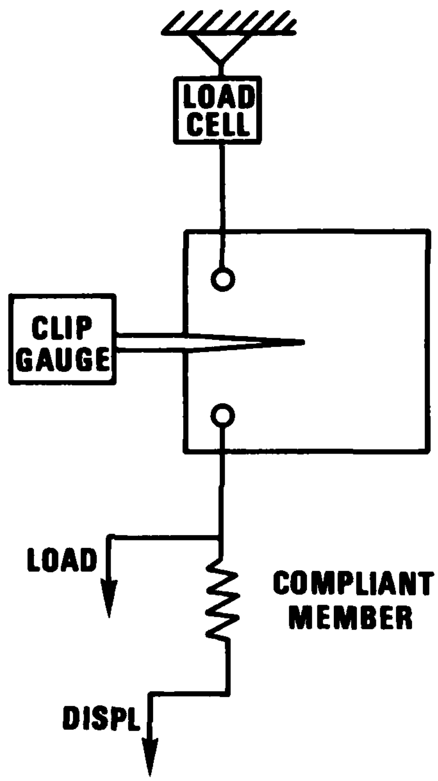

Figure 2. Compact Tension Specimen Loading Scheme.

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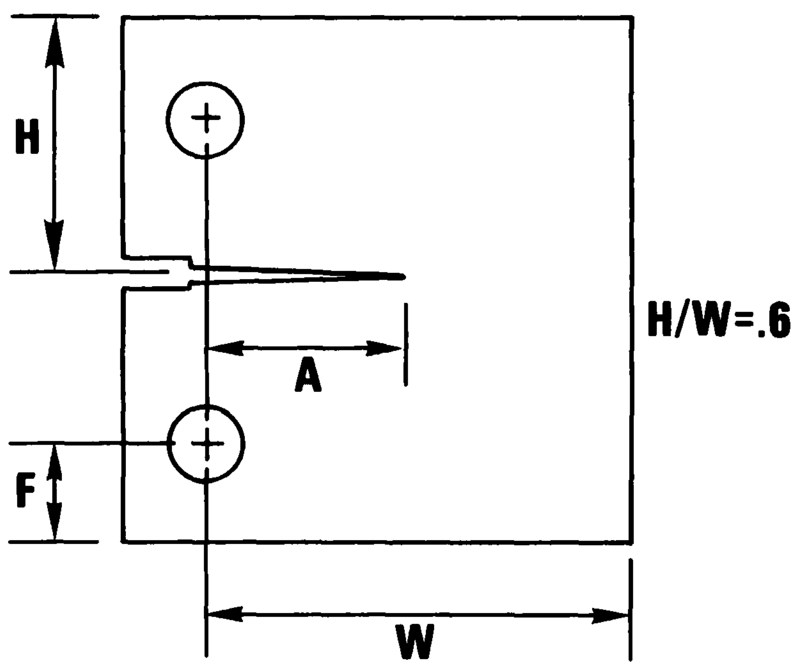

Figure 3. Compact Tension Specimen.

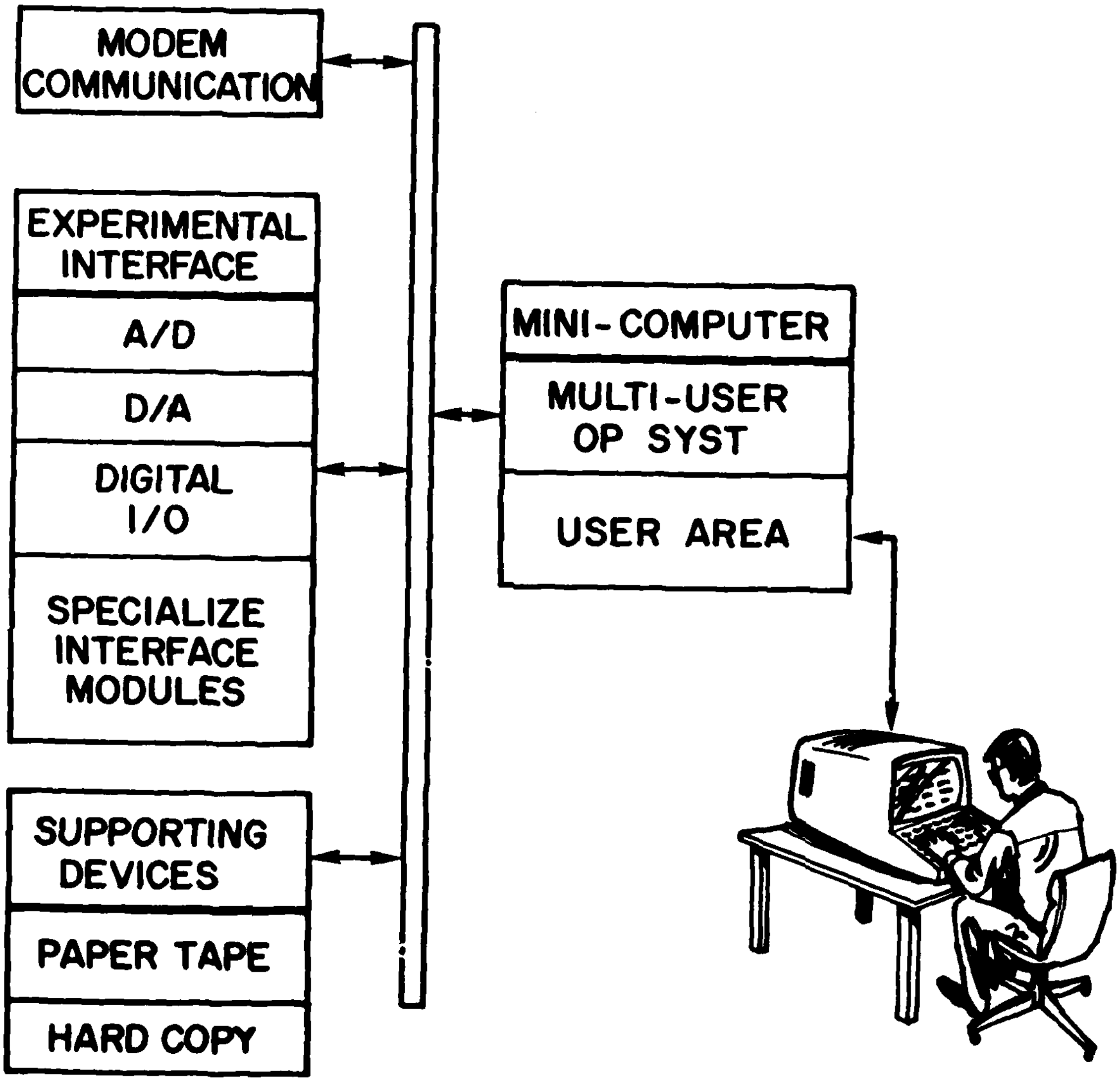

Figure 4. Computer Based Data Acquisition and Evaluation System

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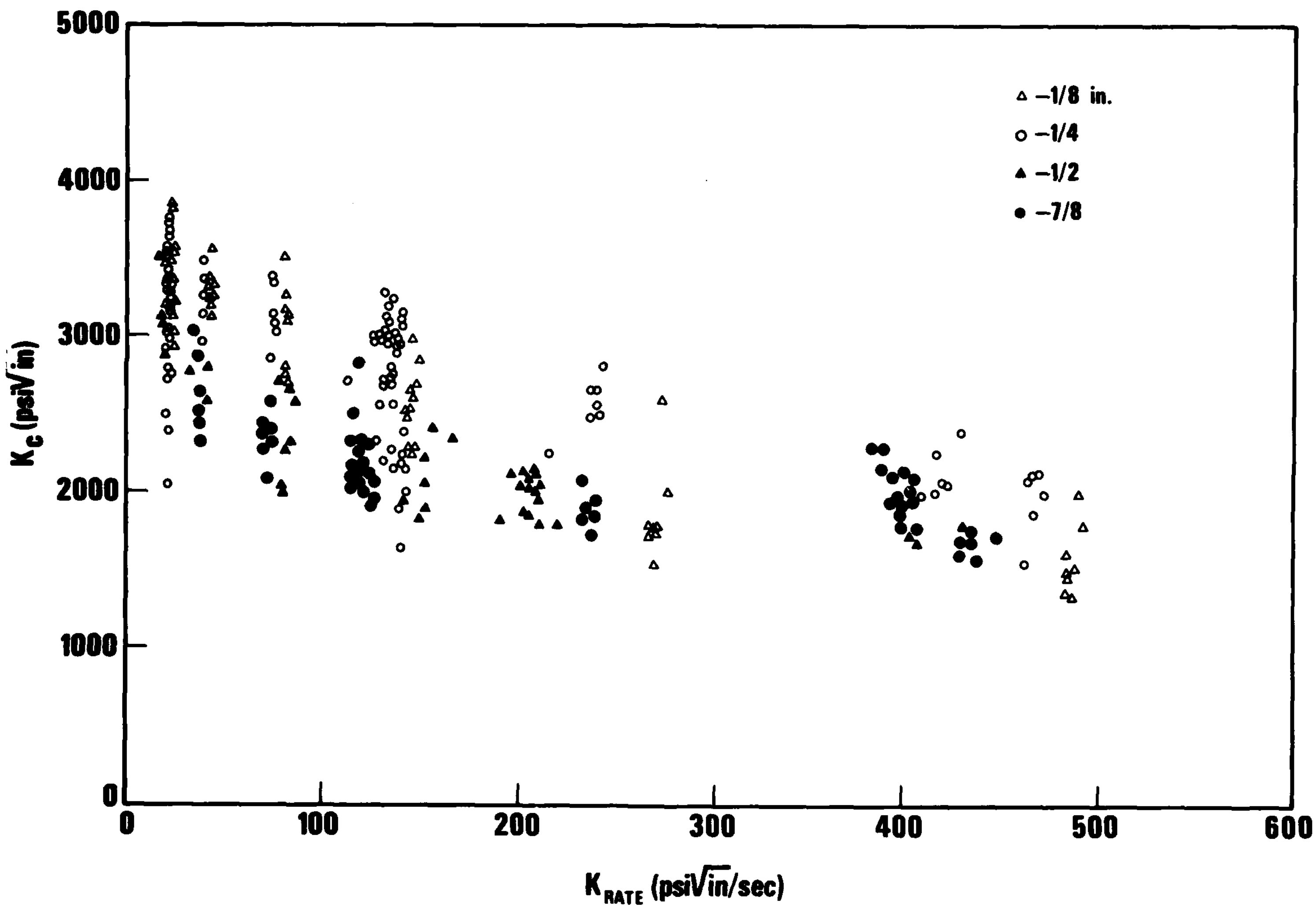

Figure 5. Fracture Toughness (K_{Ic}) for Varying Loading Rates (K_{rate}) and Thickness.

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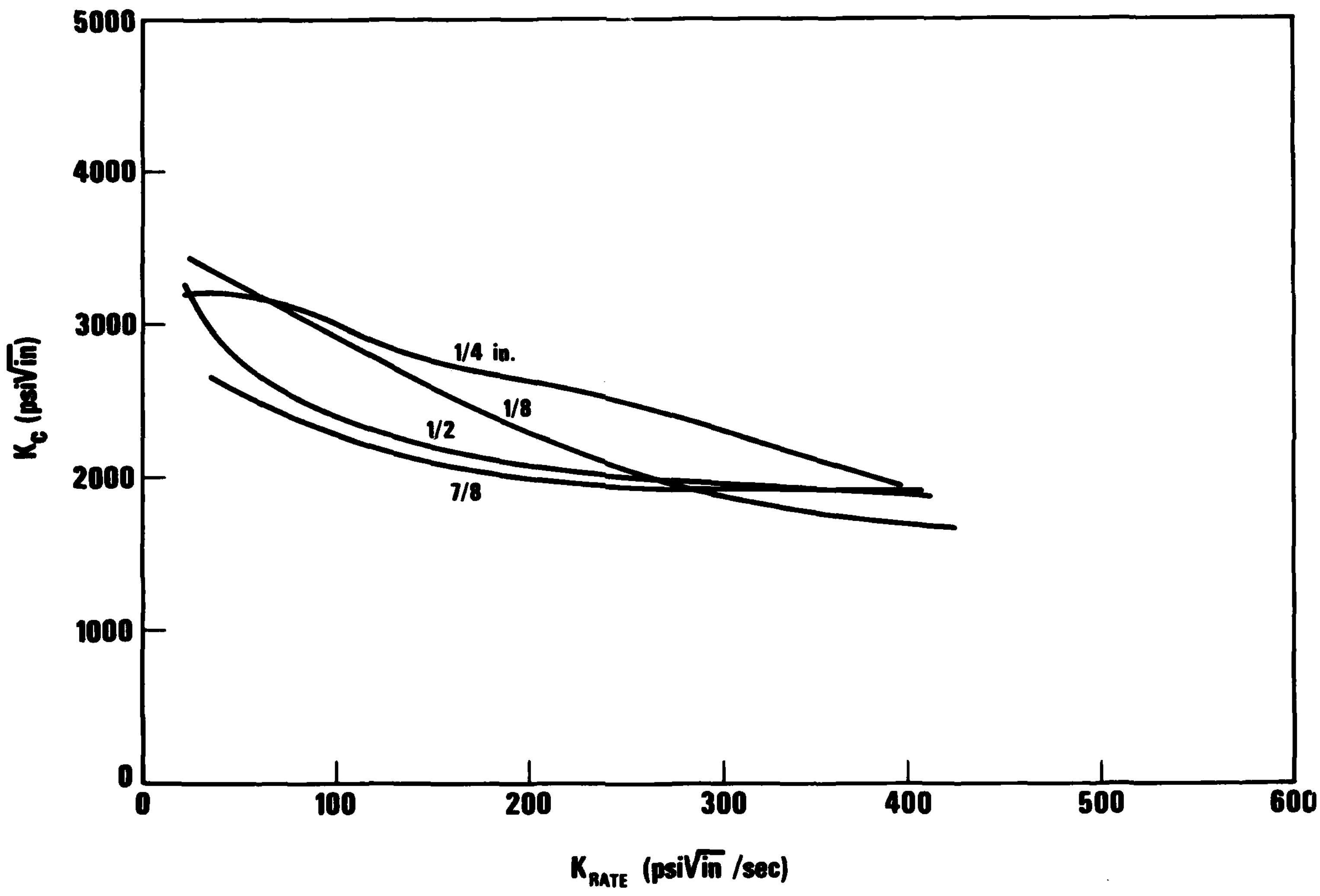

Figure 6. Fracture Toughness (K_{Ic}) for Varying Loading Rates (K_{rate}) and Thickness Trend Curves.

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