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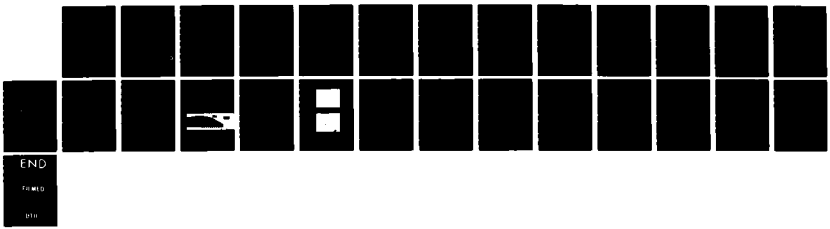

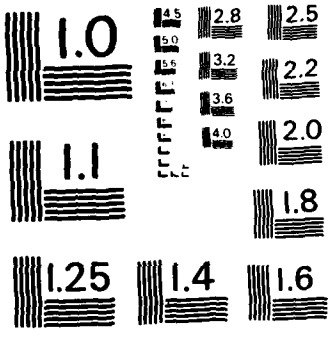

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Technical Report No. UWA/DME/TR-85/53

DYNAMIC FRACTURE TOUGHNESS

by

A. S. Kobayashi, M. Ramulu, M. S. Dadkhah, K.-H. Yang and B. S.-J. Kang

August 1985

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Dynamic Fracture Toughness

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ABSTRACT

Dynamic fracture toughness versus crack velocity relations of Homalite-100, polycarbonate, hardened 4340 steel and reaction bonded silicon nitride are reviewed and discrepancies with published data and their probable causes are discussed. Data scatter in published data are attributed in part to the observed fluctuations in crack velocities. The results reaffirmed our previous conclusion that the dynamic fracture toughness versus crack velocity relation is specimen dependent and that the dynamic crack arrest stress intensity factor is not a unique material property.

INTRODUCTION

Since Wells and Post [1], with the help of Irwin [2], determined the crack driving force, i.e. the dynamic stress intensity factor, and the crack velocity in fracturing photoelastic plates, numerous attempts have been made to relate these two quantities. The dynamic fracture community's interest in this relation is demonstrated by the fact that six out of the seven review papers dealing with the experimental aspects of dynamic fracture mechanics in the recent issue of the International Journal of Fracture [3] refer to the uniqueness or lack thereof in the dynamic stress intensity factor versus crack velocity relation and/or in the dynamic crack arrest stress intensity factor. The survey paper by Dally et al [4] describes the major findings to date and

indicates possible sources of experimental errors which may have lead to the current controversies on this subject.

The purpose of this paper is to present additional experimental results, some of which were obtained by the authors and their colleagues over the past decade, on dynamic stress intensity factor versus crack velocity relations in the context of the current controversy. Throughout this paper, the measured/computed dynamic stress intensity factors are referred to as the dynamic fracture toughness. Thus the driving force, i.e. the dynamic stress intensity factor, is tacitly equated to the material resistance to dynamic crack growth, i.e. dynamic fracture toughness.

DYNAMIC PHOTOELASTIC RESULTS

Although photoelastic polymers, such as Homalite-100 and epoxy, are not primary structural material, dynamic photoelasticity and caustics have been used in the past decade and half to uncover the basic principles which govern dynamic fracture mechanics. The dynamic fracture toughness, K_{ID}, versus crack velocity, $\dot{a}$, relations, which have been obtained through extensive fracture testing of polymers, showed that the the terminal crack velocity is test specimen dependent while the "near vertical stem" of these relations is either a unique [5] or a nonunique [6,7] material property. The latter is in agreement with the conclusion derived by one of the authors several years ago [8.9]. The dynamic photoelastic data used to support this conclusion has been reevaluated in this paper by an updated data processing procedure which incorporates higher order terms of the dynamic crack tip stress field.

Figures 1 and 2 show the K_{ID} versus $\dot{a}$ relations for Homalite-100 and polycarbonate fracture specimens. No attempt was made to fit an average K_{ID} versus $\dot{a}$ curve through the wide scatter of data generated from various batches of Homalite-100 and polycarbonate sheets tested over a period of ten years.

Figure 1 shows that the scatter bands about the imagined vertical stems of the dynamic tear test (DTT), single edge notched (SEN), modified compact (M-CT) and wedge-loaded rectangular double cantilever beam (WL-RDCB) Homalite-100 specimens are similar to those shown in [7]. However, differences in the minimum dynamic fracture toughness, K_{Im}, of the vertical stems of the DTT and SEN specimens are larger than that reported in [6]. The difference in K_{Im} for the more ductile WL-RDCB and DTT polycarbonate specimens is about 10 percent and is in agreeement with the general observation by Rosakis et al [10].

Figure 3 shows the K_{ID} versus crack extension relations of four SEN specimens subjected to different fixed grip loading condition [9]. Also shown are the corresponding static stress intensity factor. This figure, which is similar to the well-publicized results of Kalthoff et al [11], demonstrates that the dynamic crack arrest stress intensity factor, K_{Ia}^{dym}, is a constant for the same specimen while the static crack arrest intensity factor, K_{Ia}^{stat}, varies with the crack initiation condition.

SCATTER IN K_{ID} VERSUS $\dot{a}$ RELATION

Since the above photoelastic results are in general agreement with the caustic results, the published discrepancies in the K_{ID} versus $\dot{a}$ results cannot be attributed to the differences in the experimental procedures alone. However, the discrepancies could be attributed in part to the size of the crack tip region used for data reduction in the presence of stress wave effects [12]. The caustic method by definition and the authors' photoelastic method by choice had restricted the crack tip region to within 5 mm of the crack tip but outside of the nonlinear region of about 1 mm [13] surrounding the crack tip. The dynamic photoelastic results in [4] are derived from larger crack tip regions with the use of larger number of higher order terms in the crack tip stress

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field. Such data reduction procedure will yield accurate stress intensity factors under static loading. On the otherhand, the dynamic isochromatics in a larger crack tip region would be less sensitive to small perturbations in the dynamic stress intensity factor as shown in a previous numerical experiment [8]. The combined effect of the large crack tip region, in which measurements were made, and the large fracture specimens [4], which are shown in the right half of Figure 4, would minimize any oscillations in the K_{ID}. In contrast, the stress wave effect is more severe in the smaller fracture specimens, which is shown in the left half of Figure 4, and the resultant oscillations in K_{ID} is more readily detected when a smaller crack tip region is used in data reduction.

The experimental errors involved in crack velocity measurements have been discussed in [4,12,15] with [4] suggesting the use of ultrasonic fractography [16] for increased accuracy. Such crack velocity measurements [17] were made on CT, SEN, 3-point bend and Charpy polymethyl methacrylate (PMMA) specimens approximately one half the size of the smallest WL-RDCB specimen in Figure 4. The qualitative changes in the crack velocities with crack extension in the SEN, CT and 3-point bend specimens are similar to those reported in [18,19,20], respectively. Moreover, the crack velocities, which were determined from the discrete Cranz-Schardin photographs, ultrasonic fractography and streaking photography did not exhibit any unusual perturbation in the otherwise gradually varying crack velocities in these polymeric materials. Figure 5 shows the experimental setup and a typical streaking photograph [19] used to determine the continuous change in crack velocity in a fracturing polycarbonate modified compact (M-CT) specimen. While the crack velocity measurements, which were made directly from the Cranz-Schardin photographs may not be accurate, the results appear to be in qualitative agreements with those obtained by the more accurate ultrasonic fractography [17] and streaking photography [19].

The small but sharp changes in crack velocities, which are comparable to those reported in [12], were observed in the Charpy specimens [17] which were subjected to severe stress wave effects. As will be shown later, such discontinuous crack velocities was also observed in small hardened 4340 steel and ceramic specimens where the stress wave effect is pronounced.

Experimental-Numerical Procedure

The crack tip state of stress of a propagating crack in opaque or optically insensitive material has been determined by photoelastic coating method [21] and the more popular caustic method. An alternate procedure is to combine experimental and numerical techniques by using measured crack extension history interactively with a dynamic finite difference or finite element program in its generation or propagation phase [22]. The latter propagation analysis was used extensively by the Battelle group [23] to study the dynamic crack toughness and arrest charateristics of steel [24] and by one of the authors and his colleague to study the nonlinear fracture response of concrete [25]. The former generation analysis has been used to study the dynamic fracture response of glass [26] and reaction bonded silicon nitride [25].

The above hybrid experimental-numerical procedure was used to determine the K_{ID} versus $\dot{a}$ relation for 4340 steel hardened to Rockwell C 44. The dynamic crack extension histories in four wedge-loaded modified double cantilever beam specimens (WL-MDCB), shown in Figure 6 (a), and with a chevron starter notch were measured by a KRAK-GAGE* and FRACTOMAT.* Figure 7 shows typical crack extension records of two fracturing 4340 WL-MDCB specimens. The initial and slower crack propagation in the chevron notch specimens is followed by rapid crack propagation and subsequent deceleration. The latter crack

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*TTI Division, Hartrum Corp, Chaska, MN.

deceleration is interrupted by a number of short intervals of crack arrest where the average time between each crack arrest coincides with the average transit time of shear wave from the crack tip to the lateral edge of the specimen and back.

Such intermittent crack propagation is more pronounced in the blunt notch 4340 WL-MTDCB specimen, which is heat treated to a hardness of Rockwell C 52. Figure 8 shows the crack extension history with crack arrest intervals indicated by arrow marks. Such intermittent crack arrests, as long as 20 microseconds, were reported by Van Elst [28] and de Graaf [29], who used streaking photography to record continuous crack extension in Robertson type low-carbon steel specimens. Ravi-Chandar et al [7] and Rosakis et al [10] also reported the presence of discontinuous crack velocities in their highly dynamically loaded specimens.

Returning to the hybrid experimental-numerical procedure, an average of the measured crack extension histories, which are shown in Figure 9, without crack arrest of four 4340 steel WL-MTDCB specimens was then used to drive a dynamic finite element code in its generation mode and the dynamic fracture parameters were determined.

Figure 10 shows the K_{ID} versus crack extension relation as well as the corresponding static stress intensity factor in this high strength 4340 steel WL-MTDCB specimen. Figure 11 shows the K_{ID} versus $\dot{a}$ relation for this study as well as that of Rosakis et al [10]. The remarkable agreement between the two independent results could be due in part to the similarities in specimen geometries.

Despite the differences in K_{ID} versus $\dot{a}$ relations, a vertical stem in the K_{ID} versus a relation always existed in the photoelastic polymers and 4340 steel specimens discussed so far. However, limited dynamic fracture studies of

extremely brittle materials, such as glass and structural ceramics [26,27,30], show that K_{Im} and hence the vertical stem in the K_{ID} versus $\dot{a}$ curve does not exits in some materials. Figure 12 shows the K_{ID} versus $\dot{a}$ relation of reaction bonded silicon nitride WL-MTDCB specimens loaded to fracture under both static and dynamic conditions. The specimen geometry is identical to that shown in Figure 6 (a) with Figure 6 (b) showing the dynamic loading arrangement. While the crack propagating under static loading had attempted to arrest, as shown in Figure 12, the same crack propagating under dynamic loading showed little tendency for arresting.

CONCLUSIONS

As profoundly stated by many authors in [3], the controversy regarding the uniqueness or lack thereof in the K_{ID} versus $\dot{a}$ relation is far from being settled. While available experimental results indicate that in the absence of stress wave effects, such as in infinitely large fracture specimen under benign loading, K_{ID} versus $\dot{a}$ relation may possess a unique K_{Im} or a vertical stem. Such unique vertical stem is not observed in dynamic fracture specimens of smaller size and/or under dynamic loading.

Comparative study of various experimental data shows that the consistency in data scatter cannot be totally attributed to experimental errors and that the intermittent crack arrest and the discrete changes in crack velocity are caused by the reflected stress wave.

DISCUSSION

In the pursuit of the above uniqueness controversy, we pose the question "for what reason?" The end use of the sought K_{ID} versus $\dot{a}$ relation is as the fourth constitutive equation for estimating the dynamic fracture response of an elastic solid. Limited numerical experiments show that the arrest crack length

of a propagating crack is obviuosly governed by K_{Im} [31-34]. For a dynamically loaded specimen or in the presence of severe stress wave effects, however, small differences in K_{Im} may not cause large differences in the arrest crack length while the same difference in K_{Im} may cause large differences in arrest crack length in the absence of stress wave effects.

ACKNOWLEDGEMENTS

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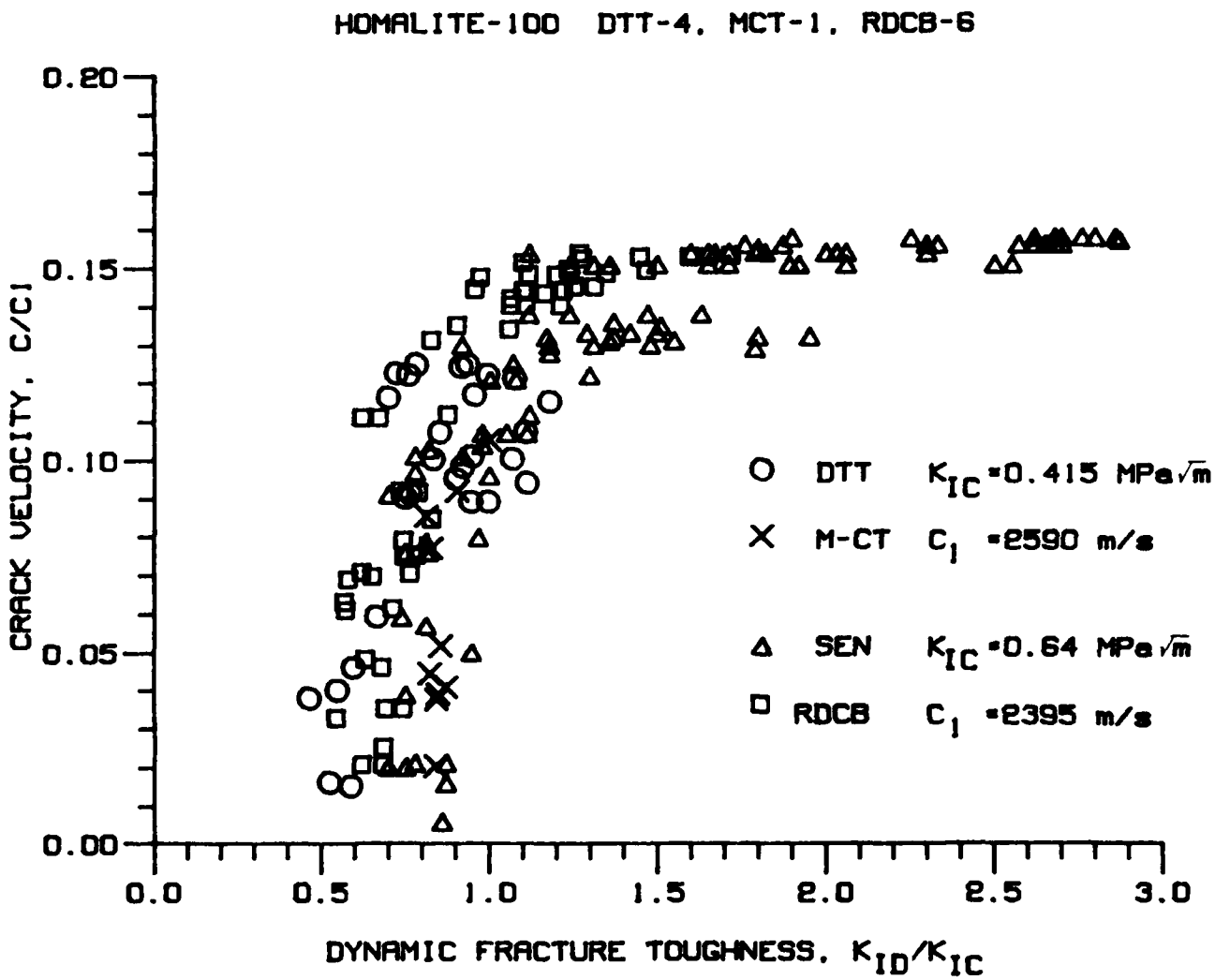


FIGURE 1. DYNAMIC FRACTURE TOUGHNESS VERSUS CRACK VELOCITY RELATION. HOMALITE-100

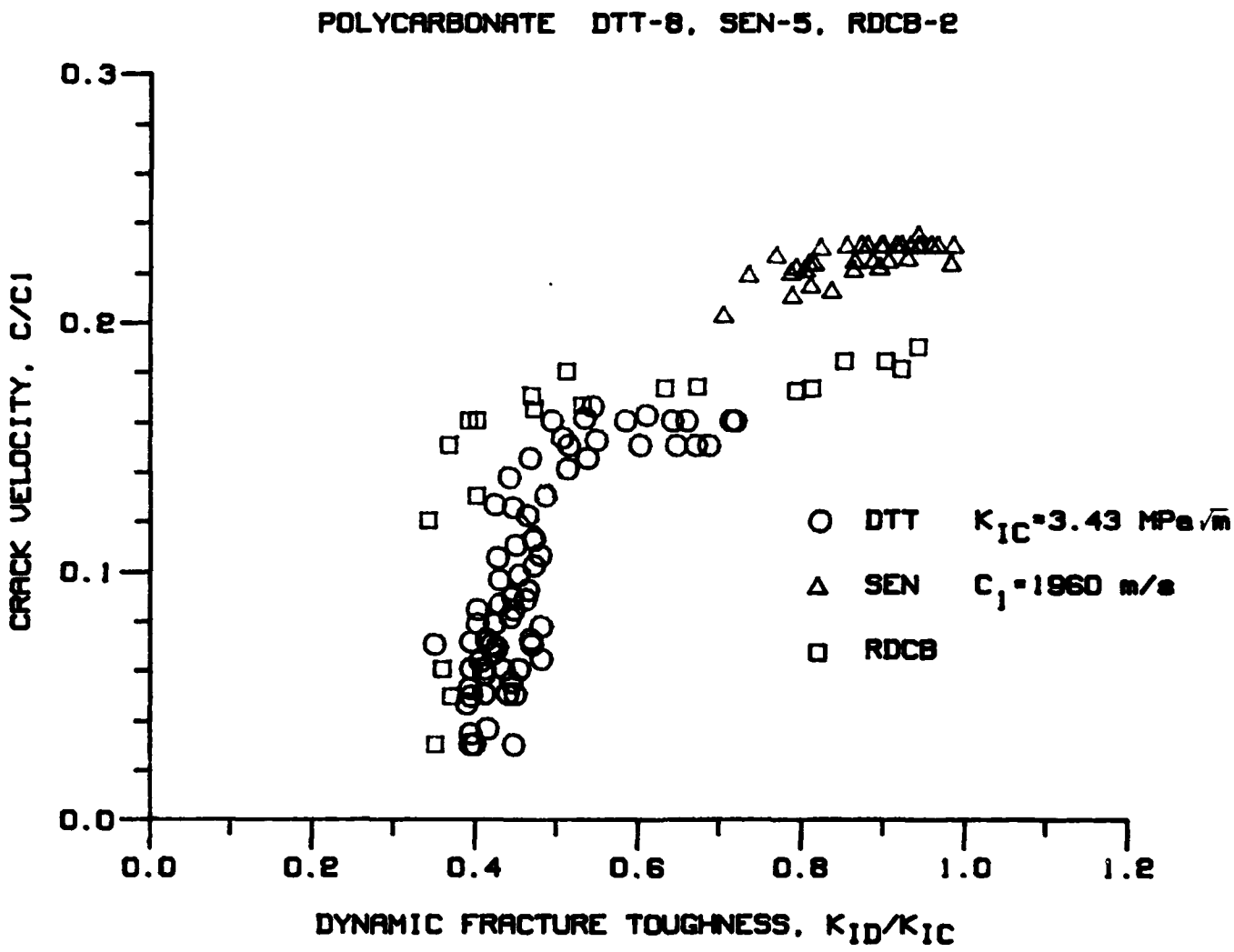


FIGURE 2. DYNAMIC FRACTURE TOUGHNESS VERSUS CRACK VELOCITY RELATION. POLYCARBONATE

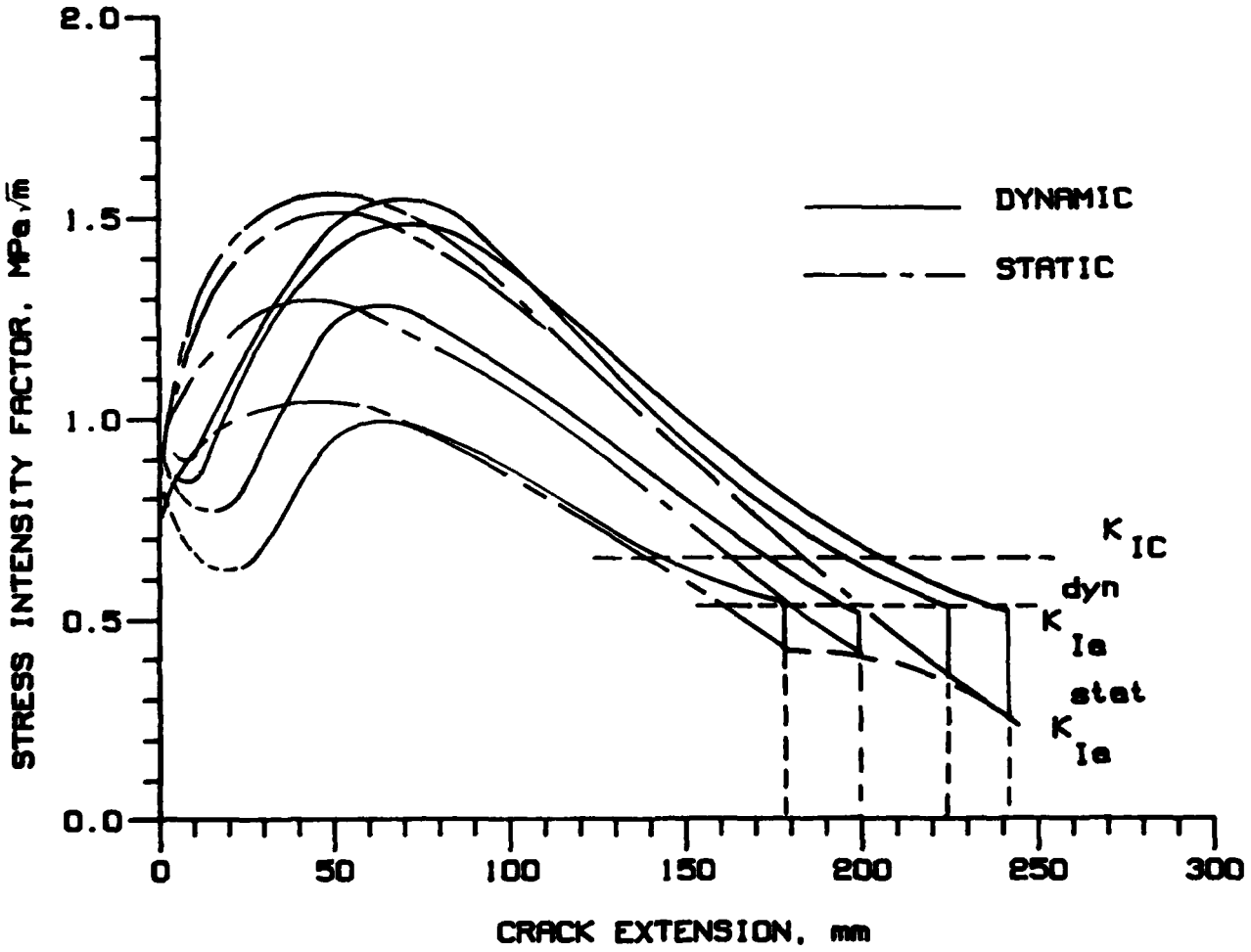


FIGURE 3. STRESS INTENSITY FACTOR VERSUS CRACK LENGTH
HOMALITE-100 SEN SPECIMENS.

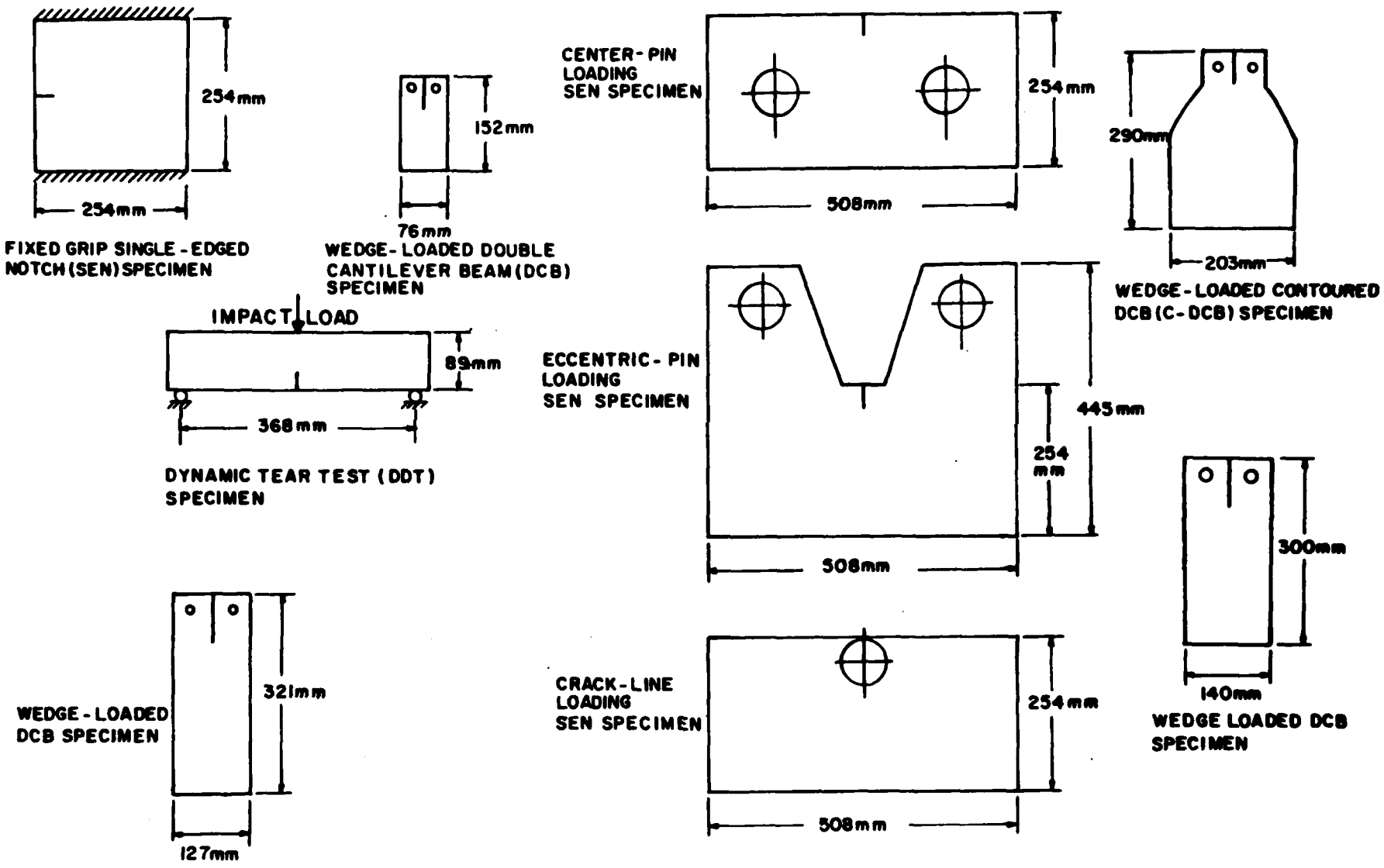
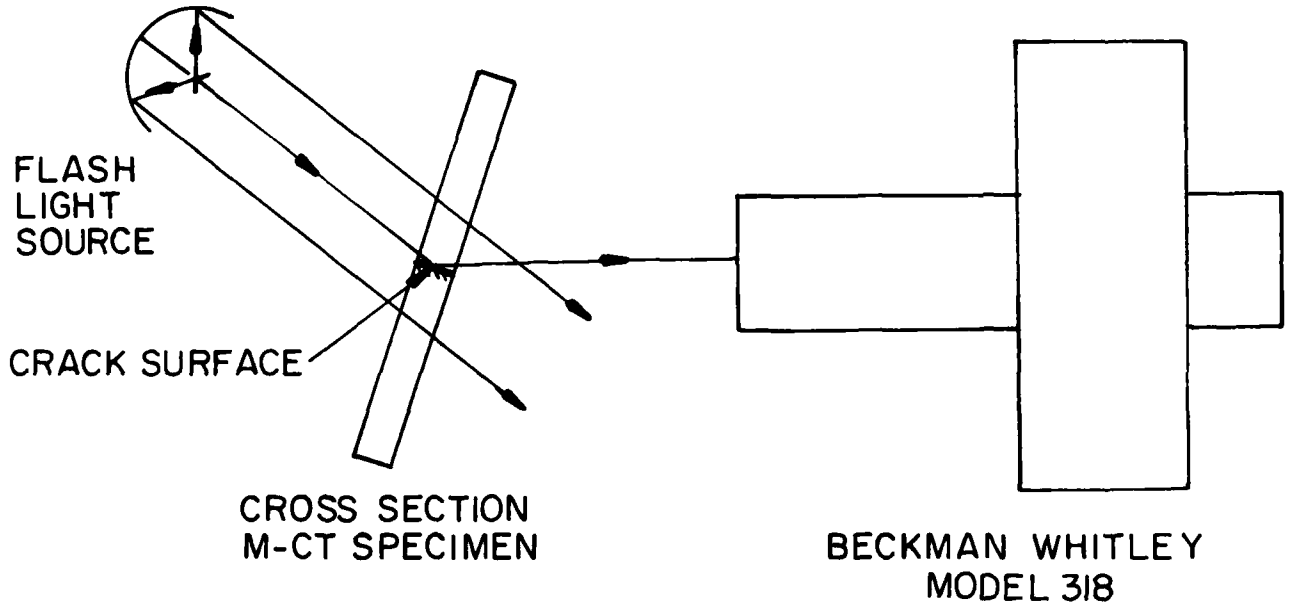


FIGURE 4. SPECIMENS USED IN FRACTURE DYNAMIC ANALYSIS



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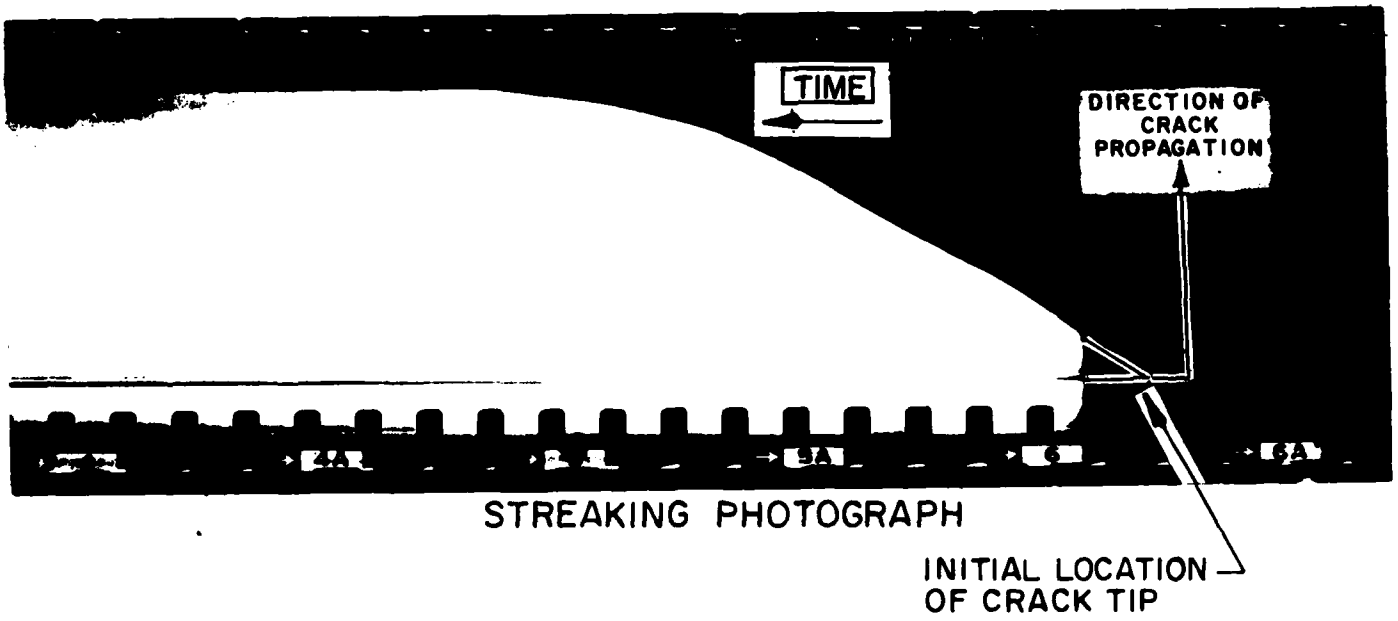
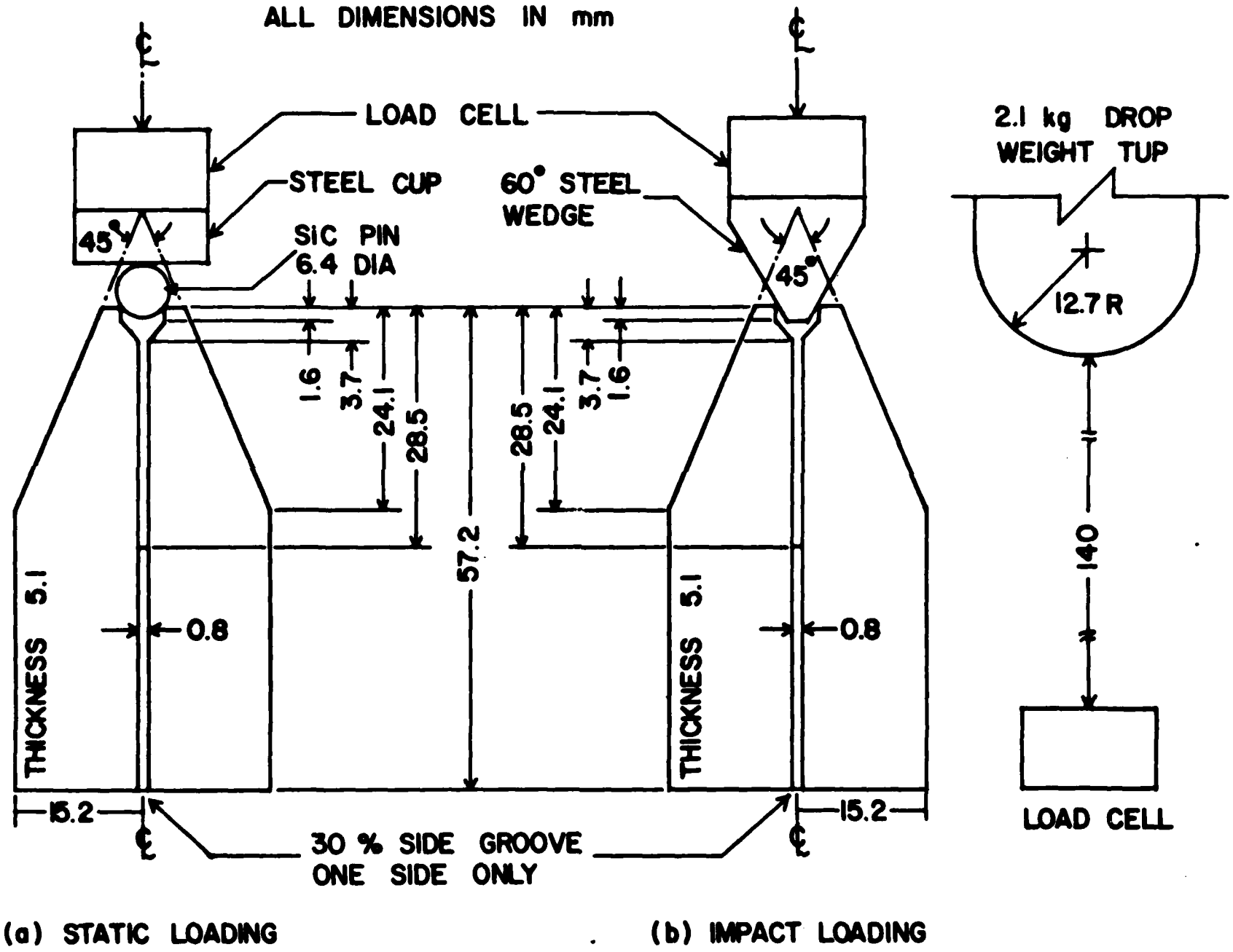


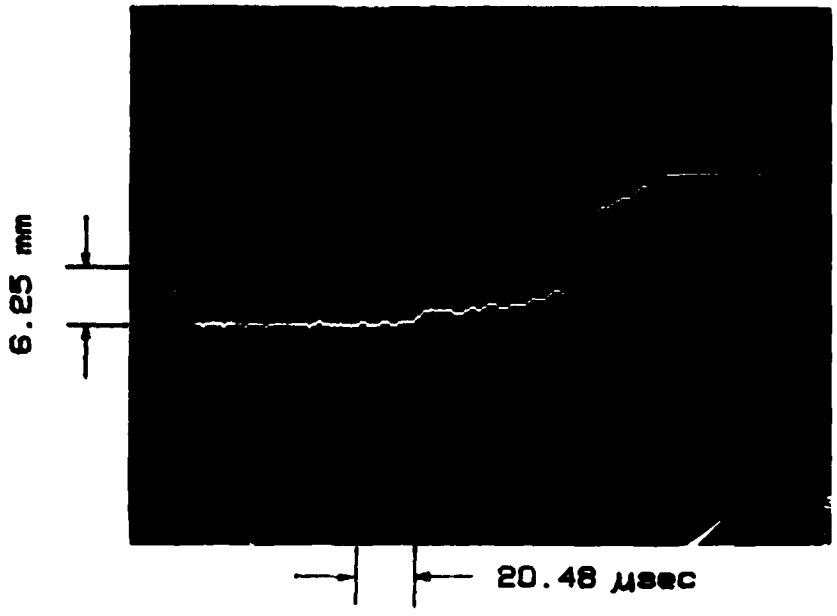
STREAKING PHOTOGRAPH

FIGURE 5. STREAKING PHOTOGRAPH OF A PROPAGATING CRACK TIP IN A POLYCARBONATE M-CT SPECIMEN (THICKNESS 6.4mm)

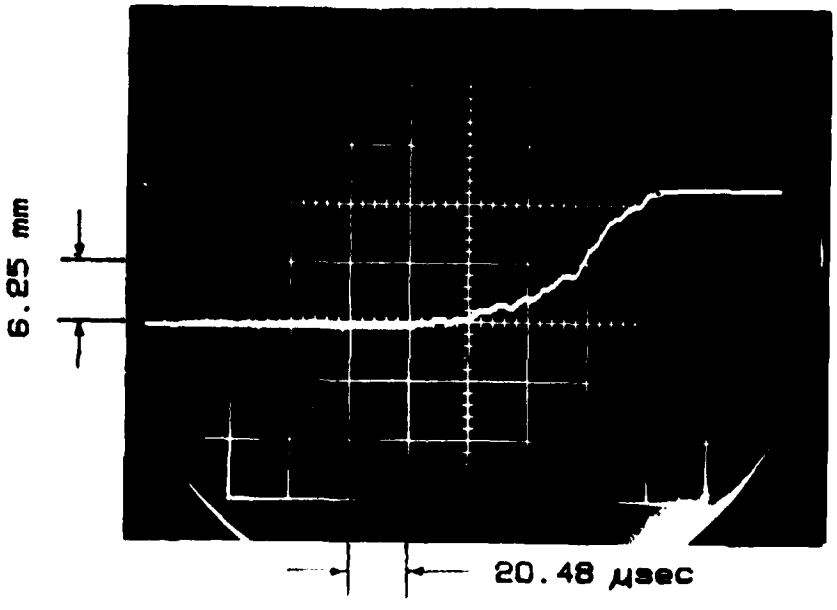


(a) STATIC LOADING (b) IMPACT LOADING

FIGURE 6. WL-MTDCB SPECIMEN (4340 STEEL AND REACTION BONDED SILICON NITRIDE).



(a) KH070785



(b) KH071585

FIGURE 7. CRACK EXTENSION VERSUS TIME, CHEVRON NOTCHED 4340 STEEL WL-MTDCB SPECIMEN.

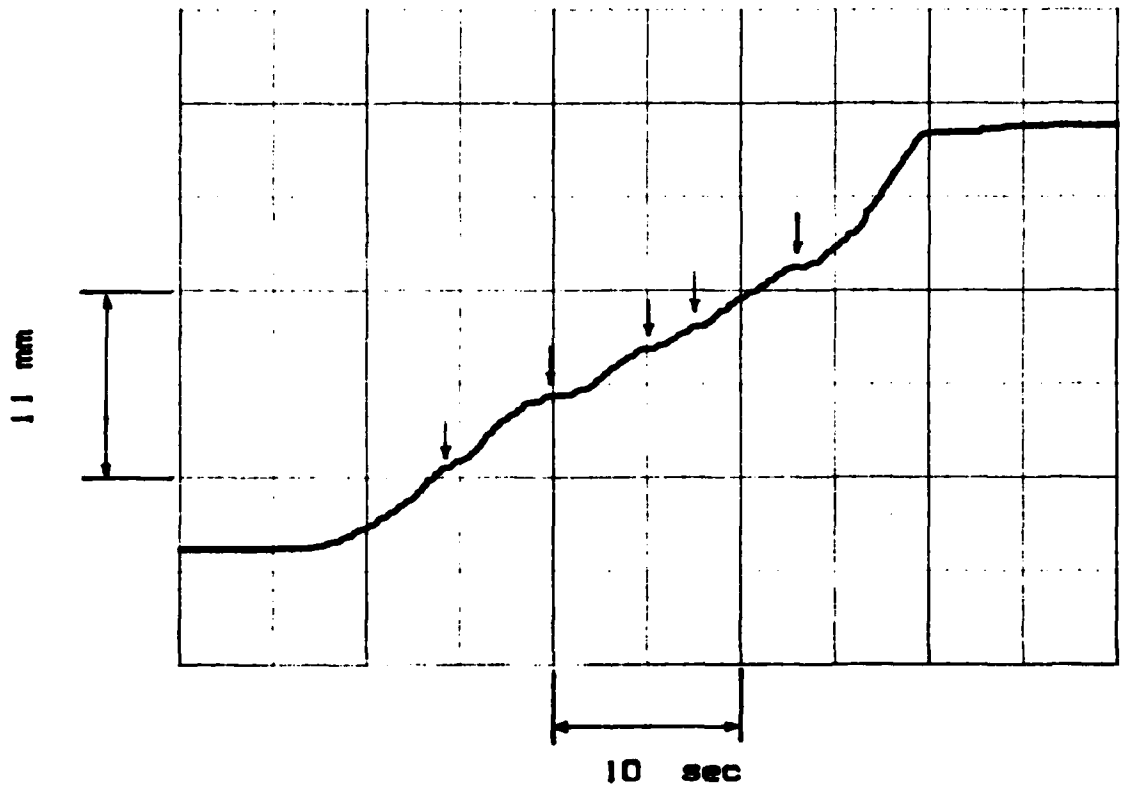


FIGURE 8. CRACK EXTENSION VERSUS TIME, BLUNT NOTCH 4340 STEEL WL-MTDCB SPECIMEN.

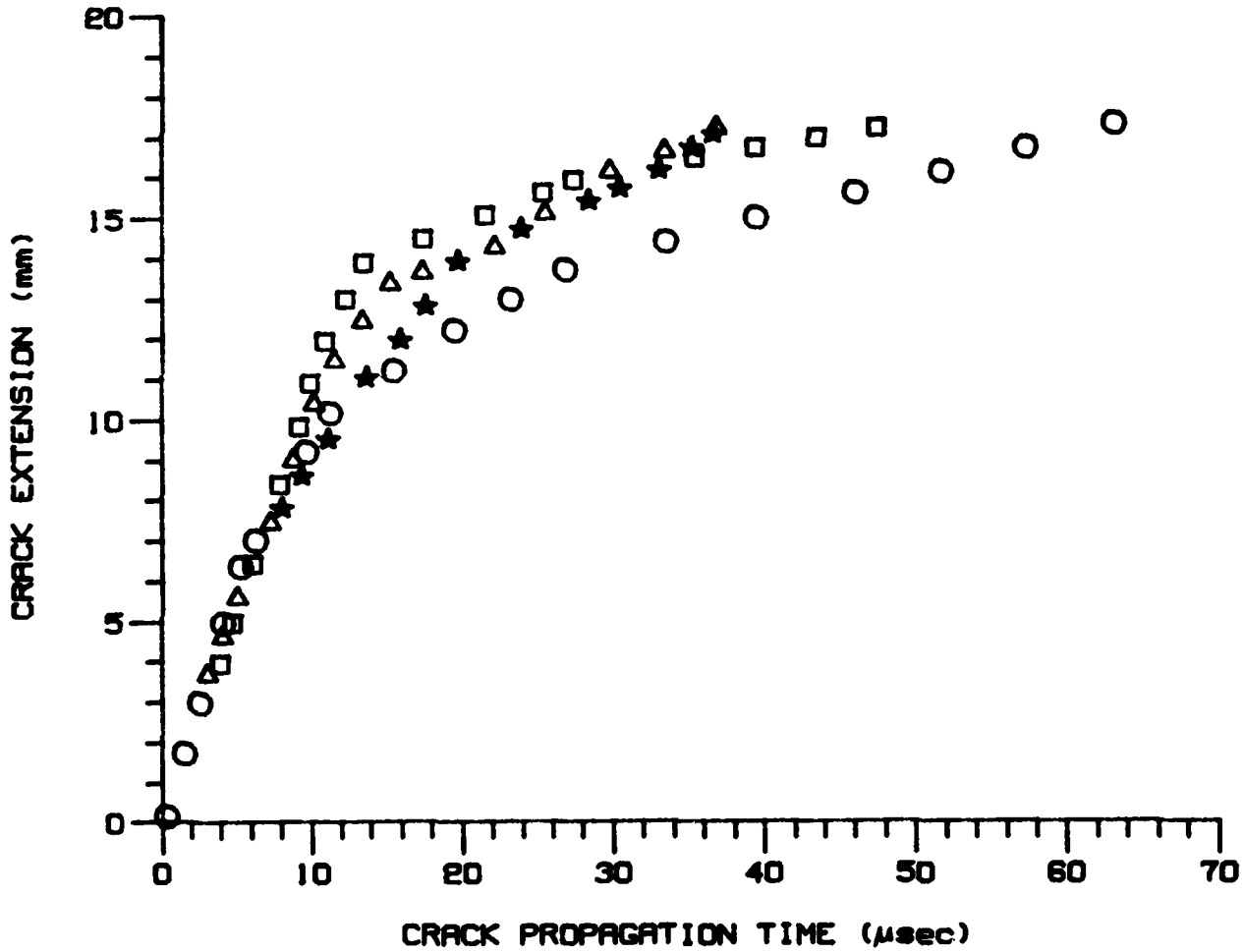


FIGURE 9. CRACK EXTENSION VERSUS TIME. CHEVRON NOTCHED 4340 STEEL WL-MTDCB SPECIMENS.

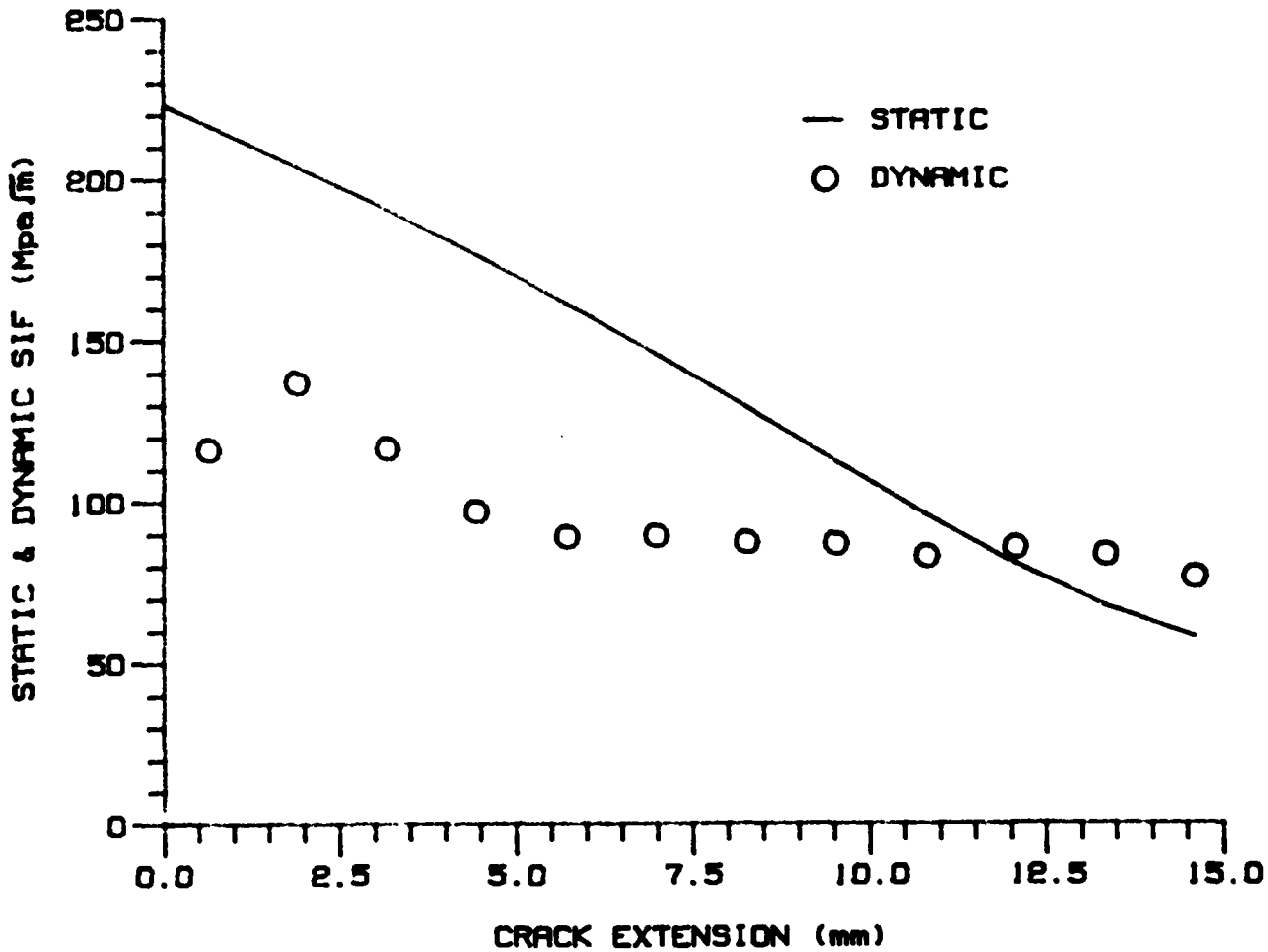


FIGURE 10. STRESS INTENSITY FACTORS VERSUS CRACK EXTENSION
CHEVRON NOTCH 4340 STEEL WL-MTDCB SPECIMEN.

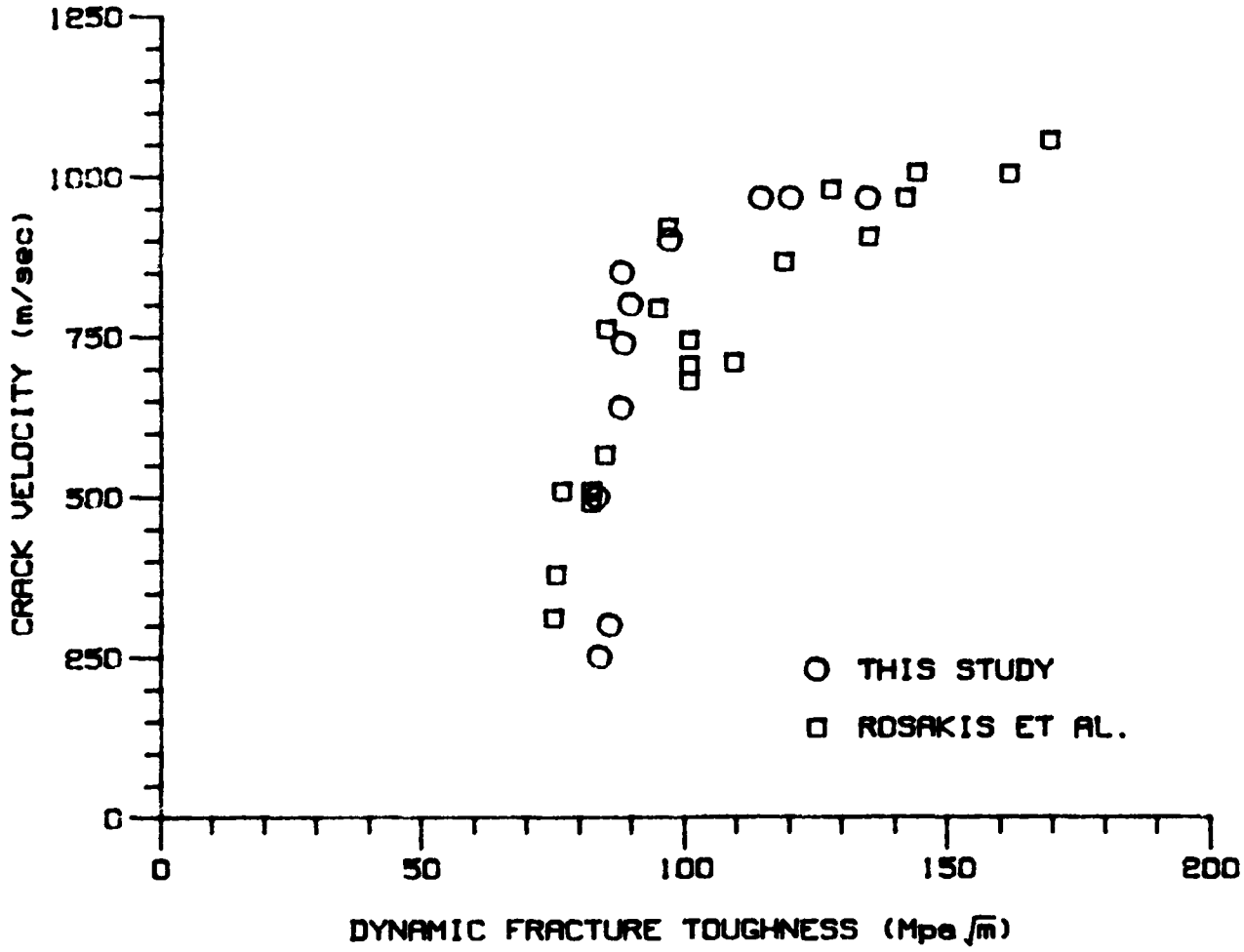


FIGURE 11. DYNAMIC FRACTURE TOUCHNESS VERSUS CRACK VELOCITY RELATIONS OF 4340 STEEL

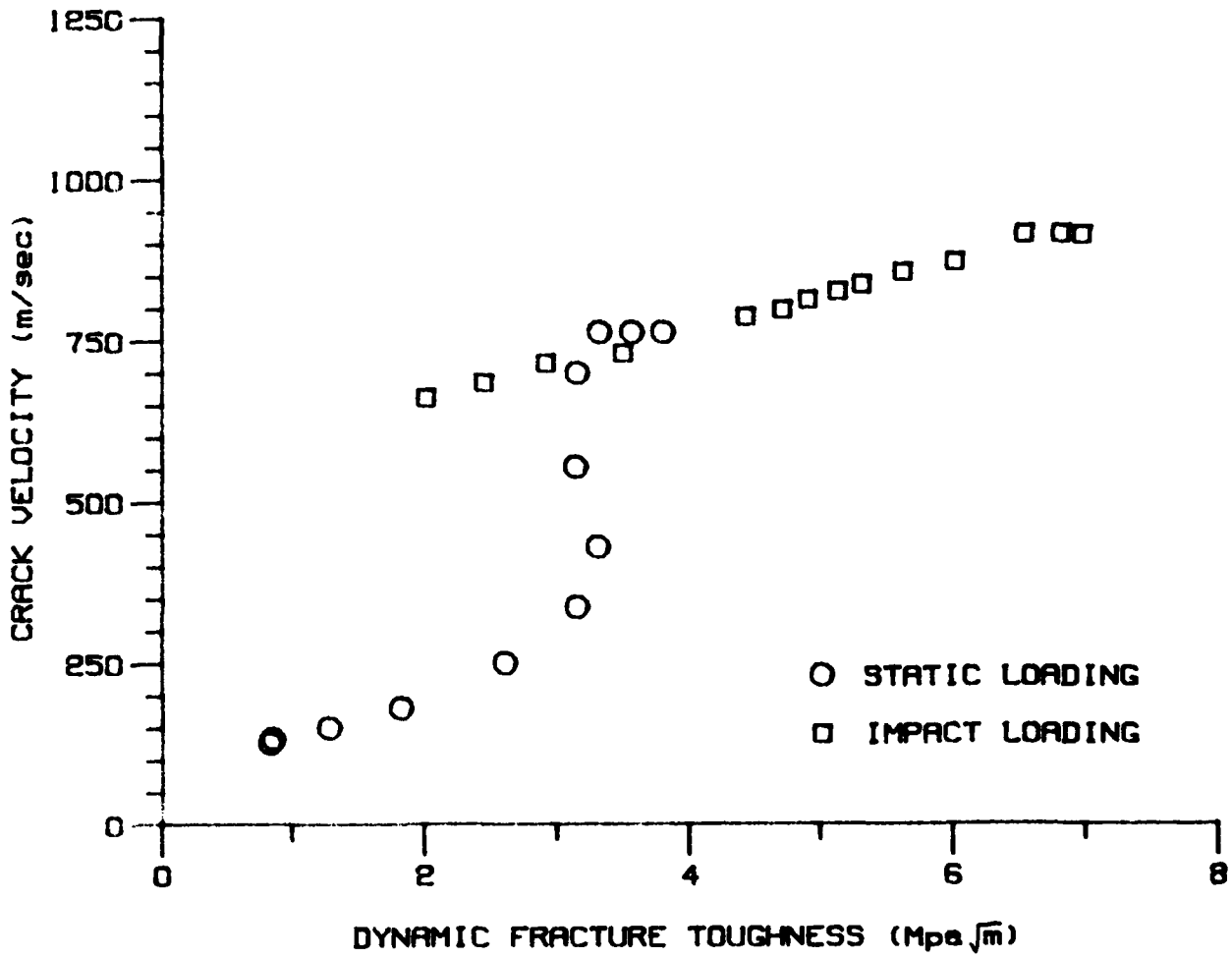


FIGURE 12. DYNAMIC FRACTURE TOUGHNESS VERSUS CRACK VELOCITY RELASTIONS OF BLUNT NOTCH RBSN WL-MTDCB SPECIMENS.

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Dynamic fracture toughness versus crack velocity relations of Homalite-100, polycarbonate, hardened 4340 steel and reaction bonded silicon nitride are reviewed and discrepancies with published data and their probable causes are discussed. Data scatter in published data are attributed in part to the observed fluctuations in crack velocities. The results reaffirmed our previous conclusion that the dynamic fracture toughness versus crack velocity relation is specimen dependent and that the dynamic arrest stress intensity factor is not a unique material property.

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