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DYNAMIC FRACTURE RESPONSES OF Al_2O_3, Si_3N_4 AND SiC_w/Al_2O_3

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DYNAMIC FRACTURE RESPONSES OF Al_2O_3, Si_3N_4 AND SiC_w/Al_2O_3

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ABSTRACT

A hybrid experimental-numerical procedure was used to characterize the dynamic fracture responses of alumina (Al_2O_3), silicon nitride (Si_3N_4) and silicon carbide whisker/alumina matrix (SiC_w/Al_2O_3) composite. A laser interferometric displacement gage was used to determine through the crack opening displacement (COD), the instantaneous crack tip location during rapid fracture at room and 1000°C. Consistent with previous finding, the dynamic crack arrest stress intensity factor did not exist in the ceramics and ceramic matrix composite studied.

INTRODUCTION

The projected use of ceramics and ceramic matrix composites in heat engines will subject these components to severe loading conditions, such as particulate impact at elevated temperature. While recent literature is abundant with data on impact studies of monolithic ceramics, similar research at elevated temperature is missing. From the user's viewpoint, impact studies provide practical failure data which relates directly to the functional capability of the ceramics and ceramic matrix composite components. These impact failures are characterized by shattering which is a complex phenomenon involving microcrack generation, growth and coalescence into macro-cracks which in turn grow, branch and coalesce.

A more generic analysis of impact failure is to study the dynamic crack initiation propagation and arrest stress intensity factors, K_{Id}, K_I^{dyn} and K_{Ia}, respectively as well as crack branching in these brittle materials. While dynamic fracture mechanics has been the subject of active research for the past two decades, it has been exclusively confined to traditional metallic structure with polymers used as a model material in basic research. Similar dynamic fracture mechanics study of ceramics and ceramic matrix composites are virtually non-existent except for [1] in addition to those of the authors and their colleagues [2-10]

In the following, we report on the recent results generated through our continuing study on this subject.

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METHOD OF APPROACH

The hybrid experimental-numerical technique, which was developed by Yang et al [7] for dynamic fracture characterization of high temperature ceramics and ceramic composites, was used in this analysis with improved sensitivity. In the following a brief description of the procedure is provided.

Material and specimen

Materials for the fracture specimen consists of commercially available alumina (Al_2O_3)*, silicon nitride (Si_3N_4)** and a alumina matrix composite with 25% silicon carbide whisker (SiC_w/Al_2O_3)***. The fracture specimens, which are single edge notched three point bend specimens, were machined to the dimensions shown in Figure 1. Three point bend specimens were used because of their simplicity in geometry and relative ease in alignment at elevated temperature. A shallow chevron notch was machined as a starter crack for initiating a true crack by the single-edge-precracked-beam (SEPB) method of [11]. These true crack were normally about 3-4 mm in depth.

Experimental procedure

The loading system consisted of a drop weight tower, which is mounted integrally with the furnace which in turn can operate at a temperature up to 1500°C. The door and two port holes, which are shielded with fused silicate glass panes to prevent undesirable convection current of air in the furnace chamber, provided access for the input and output laser beams of the laser interferometric displacement gage (LIDG) [4,8]. The mass of the steel impactor was 2.2 kg. The specimens were rapidly loaded by the dropweight with an impact velocity of 0.7 m/sec. The impact load was monitored by a load transducer at the top end of a push rod and outside of the furnace as shown schematically in Figure 2.

A pair of LIDG targets were placed at the crack mouth of the specimen. The crack mouth opening displacement (CMOD) obtained from the LIDG records was used to determine directly the crack tip location in a rapidly fracturing three point bend specimen. The LIDG targets were platinum tabs which were mounted directly on the specimen after precracking and then indented by a Vickers microhardness tester to minimize possible experimental error in locating the LIDG targets.

A series of static tests were also conducted at room temperature in order to obtain dynamic fracture data at low crack velocity. This data was necessary to highlight the significant differences between the dynamic fracture responses of metals and brittle ceramics and ceramic composites at K_I^{dyn} substantially lower than the static fracture toughness, K_{IC}.

Numerical procedure

The crack tip location versus time history together with the loading history were used to execute a dynamic finite element code in its generation mode in order to compute the dynamic initiation and the propagation stress intensity factors, K_{Id} and K_I^{dyn}, respectively, associated with the propagating crack. Details of this hybrid experimental-numerical procedure as well as its validation are given in [7,8].

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RESULTS

The above mentioned procedure was used to generate the dynamic stress intensity factor, K_I^{dyn}, versus crack velocity relations for Al_2O_3, Si_3N_4 and SiC_w/Al_2O_3 composite at room temperature and 1000°C. Figure 3 shows a pair of typical LIDG data together with the loading history obtained for the SiC_w/Al_2O_3 specimen tested at 1000°C. Figure 4 shows the resultant crack extension history obtained by this LIDG data at the crack mouth. Figure 5 shows the CMOD and the crack extension histories for the Si_3N_4 specimens tested at room temperature.

As mentioned previously, the crack extension and load histories were then used to compute the dynamic initiation and propagation stress intensity factors, K_{Id} and K_I^{dyn}, respectively, the results of which are reported in the following.

Dynamic fracture initiation toughness, K_{Id}

Since the initial cracks generated by the SEPB method is a true crack, the dynamic initiation stress intensity factor, K_{Id}, obtained in this study should be less than those reported previously [8-10]. Table 1 shows a tabulated comparison of these K_{Id} where K_{Id} in this study is slightly higher than those of [10], but is within the expected scatter band of ± 10%. The high K_{Id} and K_{IC} for Si_3N_4 are attributed to acicular Si_3N_4, which acts as whiskers in the crystalline Si_3N_4 matrix.

Table 1 Comparison of fracture toughnesses

Ref.	Fracture Toughness (MPa $\sqrt{m}$)	Alumina		Silicon Nitride		SiC_w/Al_2O_3 Composite	
		Temp.		Temp.		Temp.	
		Room	1000°C	Room	1000°C	Room	1000°C
This study	K_{Id} K_{IC}	4.9 -	4.4 -	9.9 9.0	- -	5.6 6.0	5.9 -
Yang and Kobayashi (1990)	K_{Id} K_{IC}	5.7 4.3	5.1 -			7.9 6.6	6.9 -
Duffy et al. (1988)	K_{Id} K_{IC}	5.6 3.4	- -				

Dynamic stress intensity factor, K_I^{dyn} and arrest

Figures 6, 7 and 8 show the dynamic stress intensity factor (SIF), K_I^{dyn} versus crack velocity relations for Al_2O_3, Si_3N_4 and SiC_w/Al_2O_3 composite, respectively. Data points for the lower dynamic stress intensity factors and lower crack velocities were obtained through statically loaded specimens. These results show an unambiguous lack of dynamic crack arrest stress intensity factor below which dynamic crack propagation will cease. The crack velocities for impacted specimens in this study were on the average about four times of that of [10] for identical alumina fracture specimens. It was about twenty percent higher for the different SiC_w/Al_2O_3 specimens used in this study.

Figures 7 and 8 show that the crack can propagate at a larger crack velocity under high K_I^{dyn}. Therefore no unique crack velocity versus K_I^{dyn} can be observed in these materials.

CONCLUSIONS

The hybrid experimental-numerical procedure was used to determine the crack velocity versus dynamic stress intensity factor relations in Al_2O_3, Si_3N_4 and SiC_w/Al_2O_3 composite at room temperature and 1000°C. The results, which are in qualitative agreement with [2-10], again showed conclusively the lack of a dynamic crack arrest intensity factor and of a unique crack velocity versus dynamic stress intensity factor relation.

DISCUSSIONS

The fracture surfaces were scanned by SEM and the relative areas of transgranular failures of the silicon nitride grams and the alumina grains in the statically loaded and impact loaded Si_3N_4 and SiC_w/Al_2O_3 composite were compared.

Figures 9 and 10 show typical fracture surfaces of a dynamically and a statically loaded Si_3N_4 and SiC_w/Al_2O_3 specimens at room temperature. Transgranular fracture dominated the fracture in the statically loaded specimen while the dynamically loaded specimen is characterized by the predominant intergranular fracture.

Figure 11 shows the percentage area of transgranular fracture versus dynamic SIF relation for SiC_w/Al_2O_3 specimens. The percentage area of transgranular fracture is in excess of 45% at the lowest SIF of about 1 $MPa\sqrt{m}$. These results are consistent with those of Figure 8 thus suggesting a correlation between the percentage area of transgranular fracture and the crack velocity which is shown in Figure 12. The percentage area of transgranular fracture increases almost linearly with the crack velocity in this figure. The percentage area of transgranular is more than 40% even with the low crack velocity of 40 m/s. The kinematic constraint of a rapidly propagating crack probably enforces transgranular fracture which in turn enables the crack to propagate at a subcritical dynamic SIF. The lack of crack arrest of the propagating crack in this study was thus attributed to the large percentage area of transgranular failures in contrast to that of the arrested precrack tip region discussed previously [10,14].

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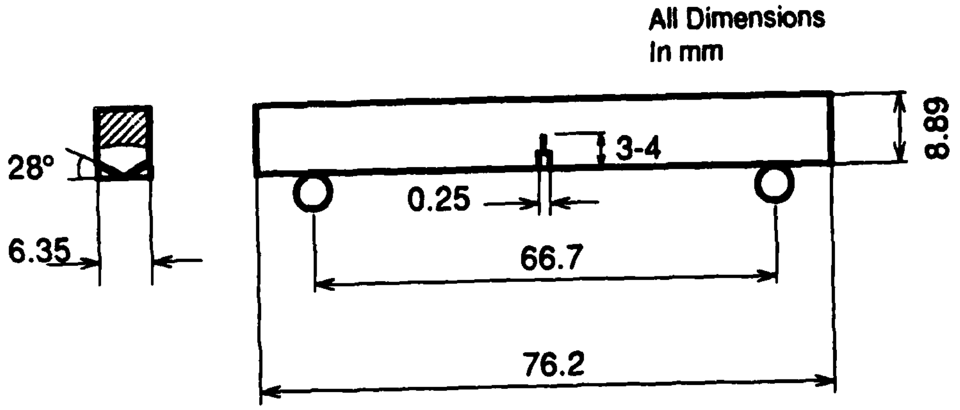


Figure 1. Precracked Three-point Bend Speciem.

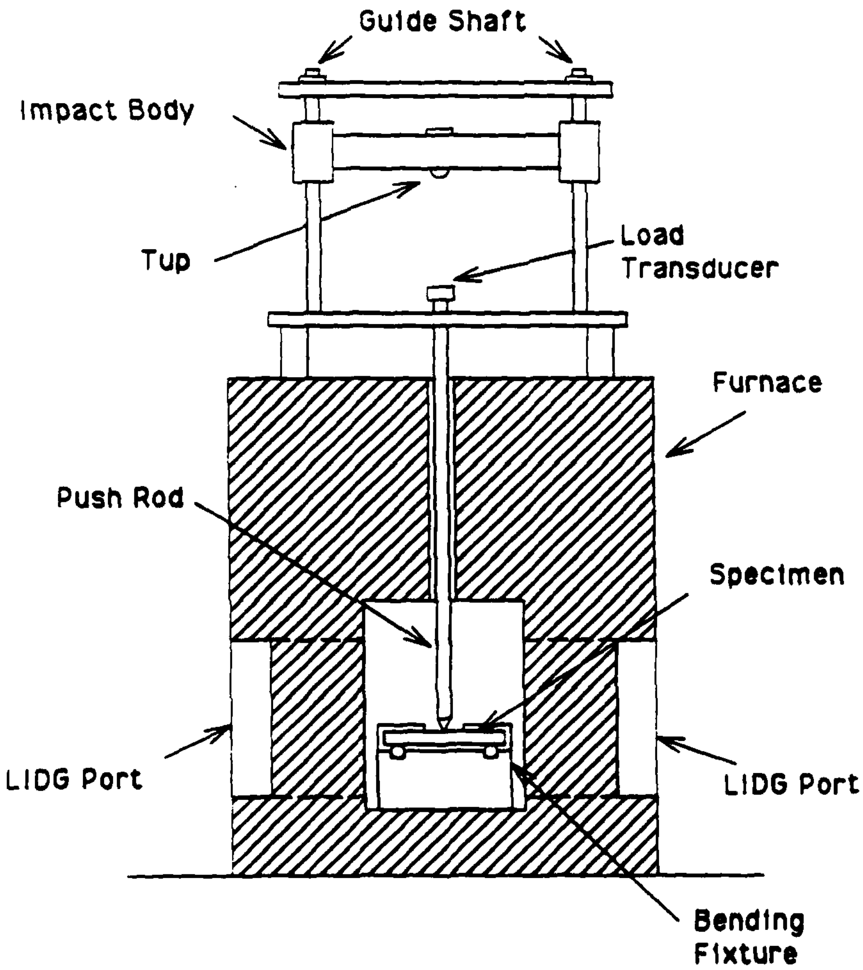


Figure 2. Drop-weight Impact Tester and Furnace with LIDG Ports.

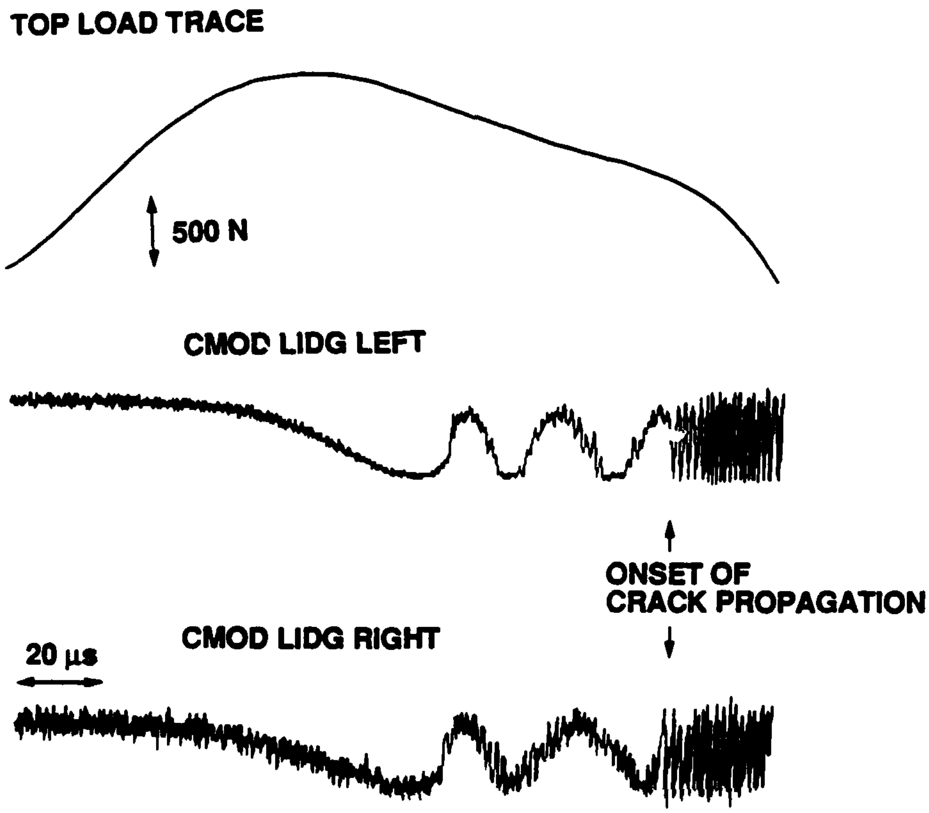


Figure 3. Loading and CMOD Histories at 1000°C. SiC_w/Al_2O_3 Specimen.

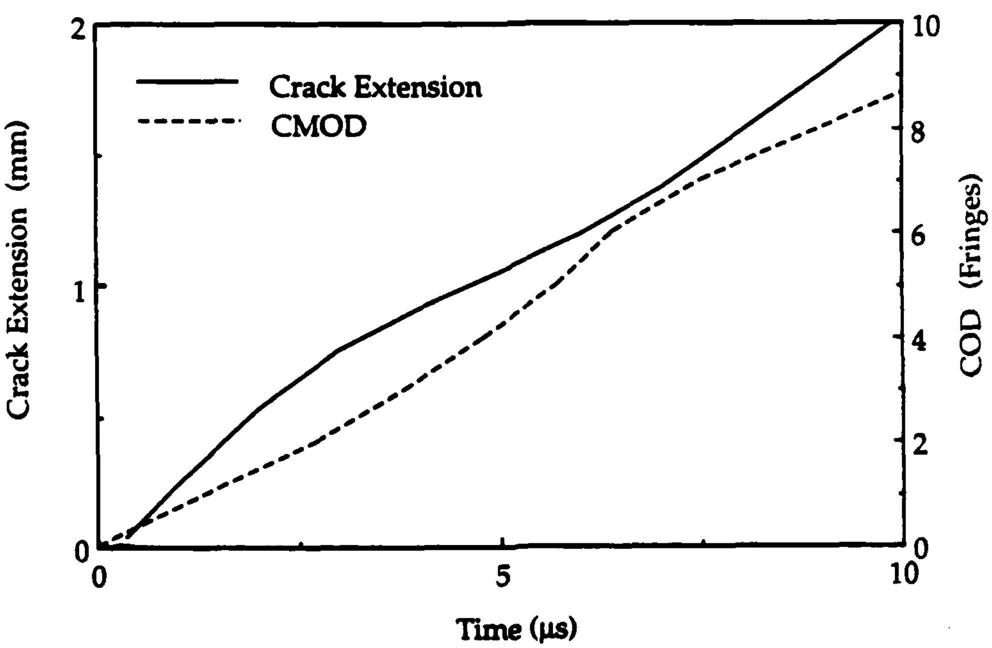


Figure 4. CMOD and Crack Extension Histories at 1000°C. SiC_w/Al_2O_3 Specimen.

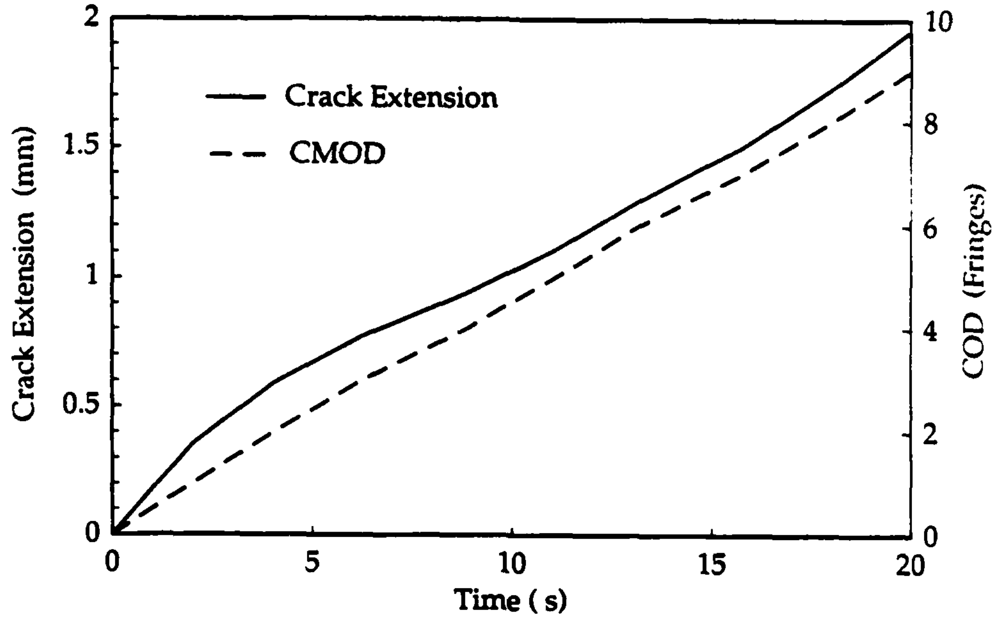


Figure 5. COD and Crack Extension Histories at Room Temperature. Si_3N_4 Specimen.

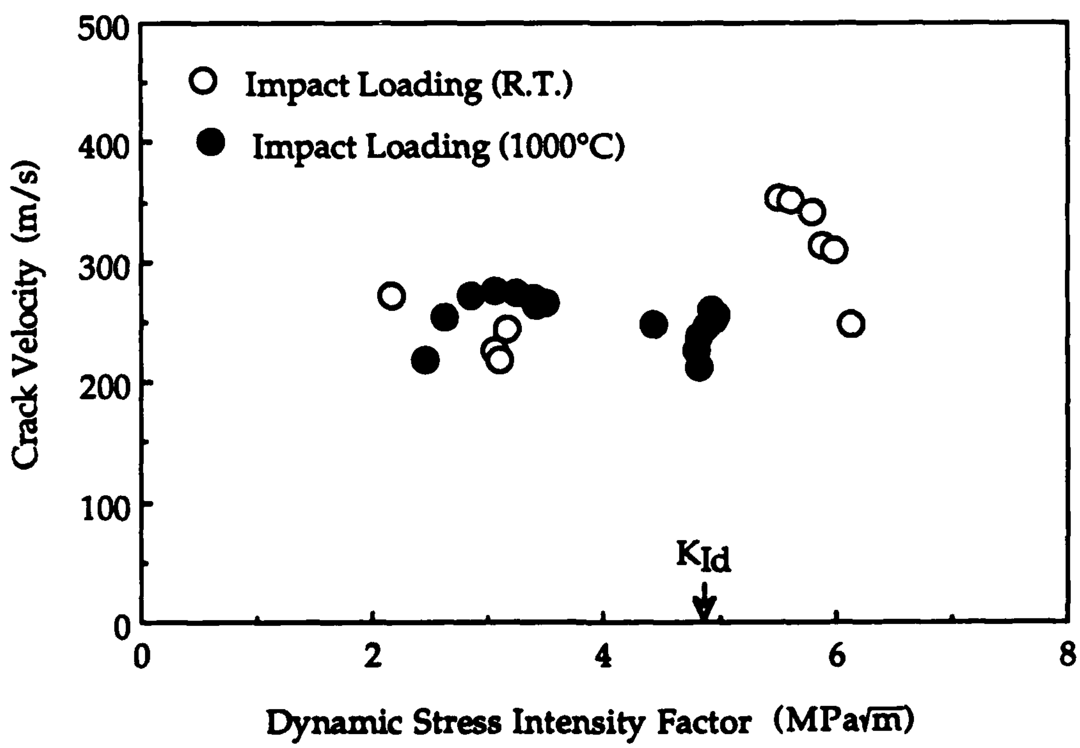


Figure 6. Dynamic SIF versus Crack Velocity Relation of Al_2O_3.

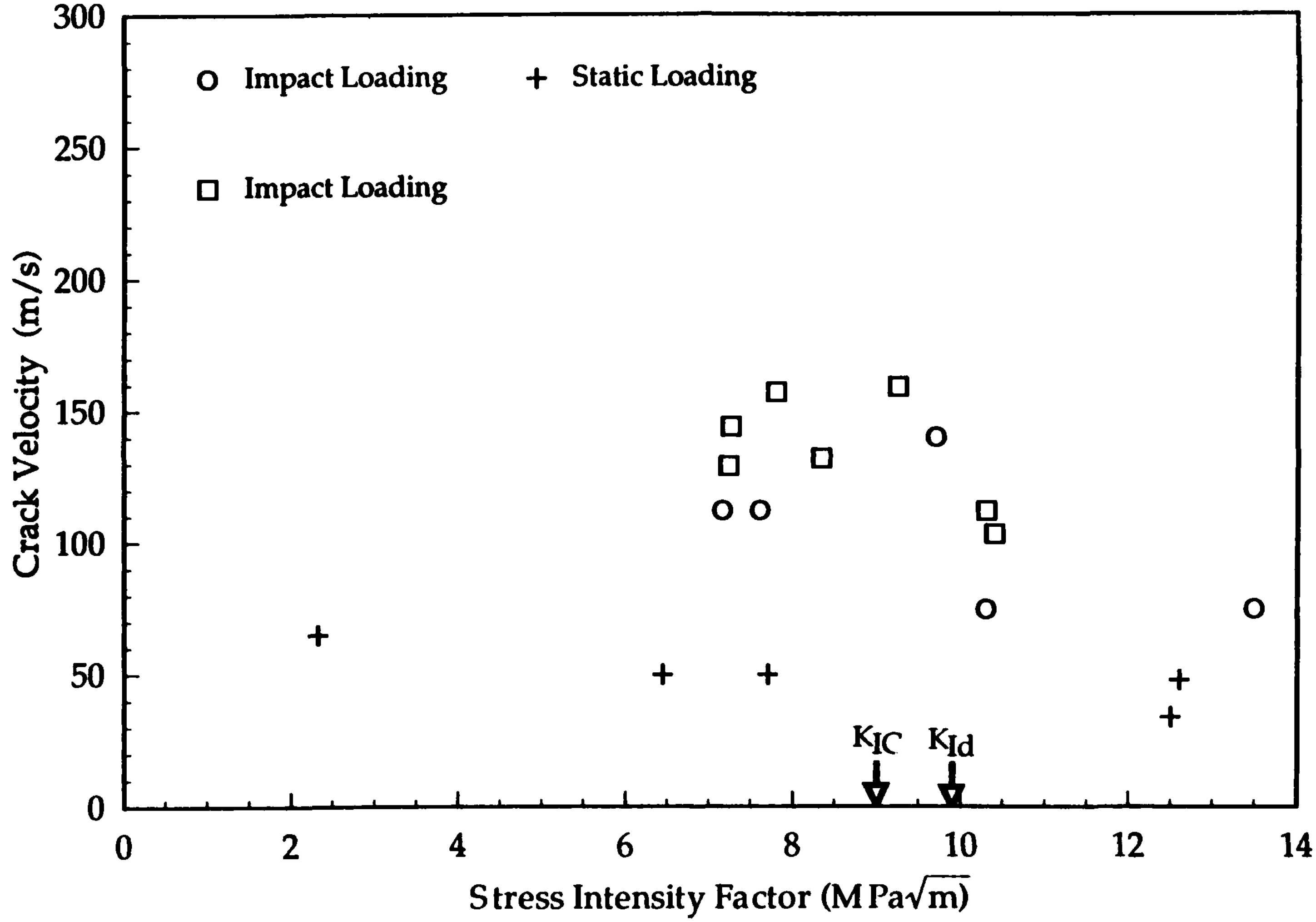


Figure 7. Stress Intensity Factor versus Crack Velocity of Si_3N_4 at Room Temperature.

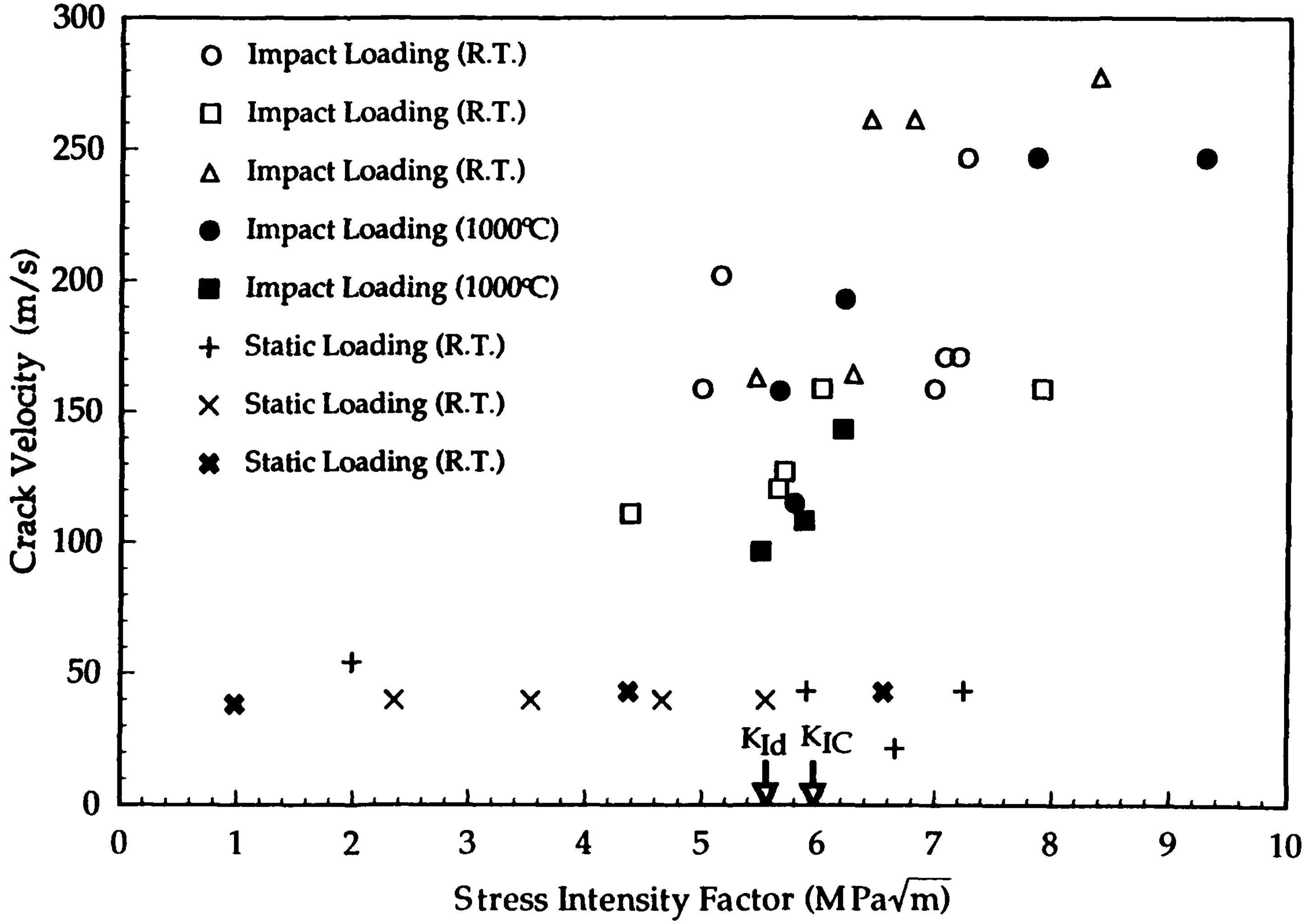
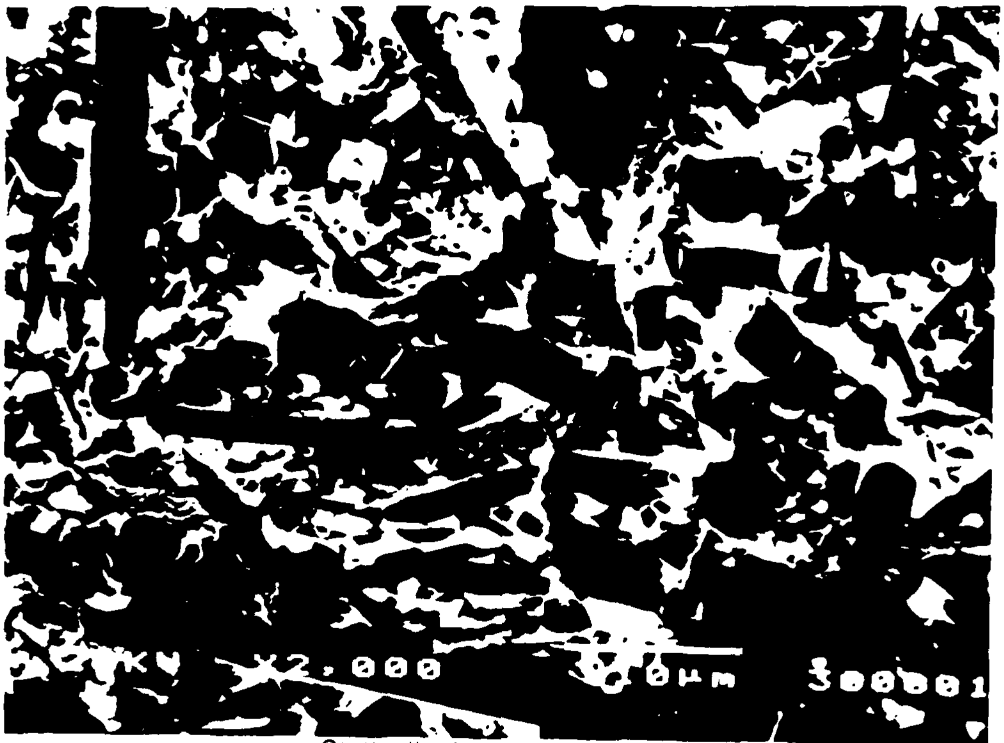
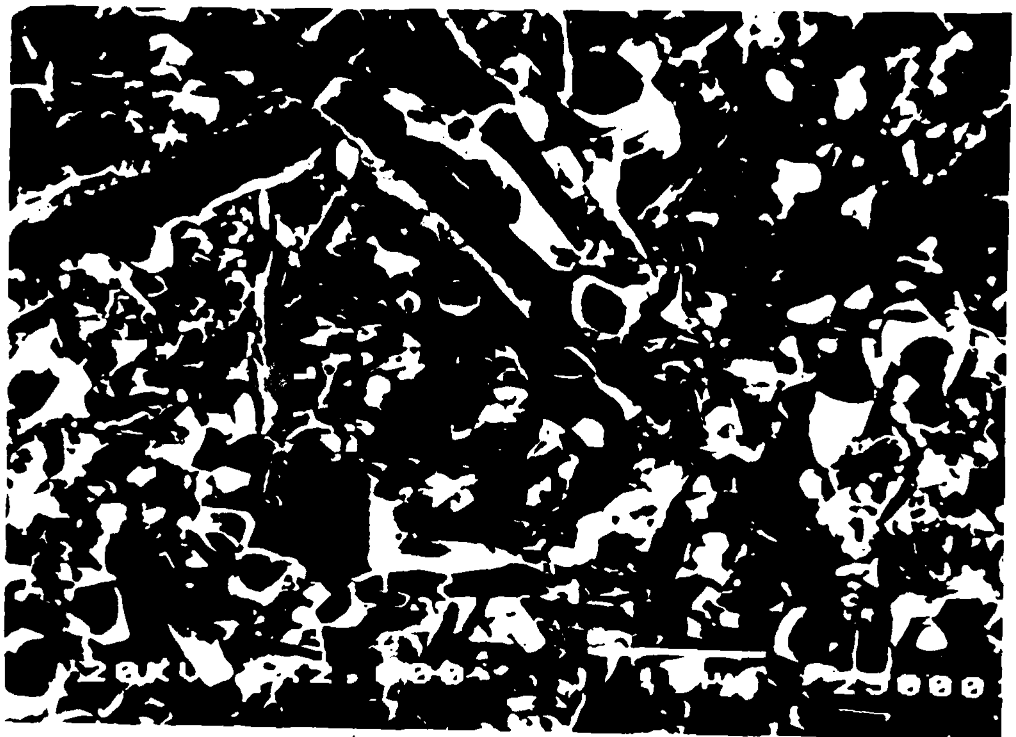


Figure 8. Stress Intensity Factor versus Crack Velocity of SiC_w/Al_2O_3.



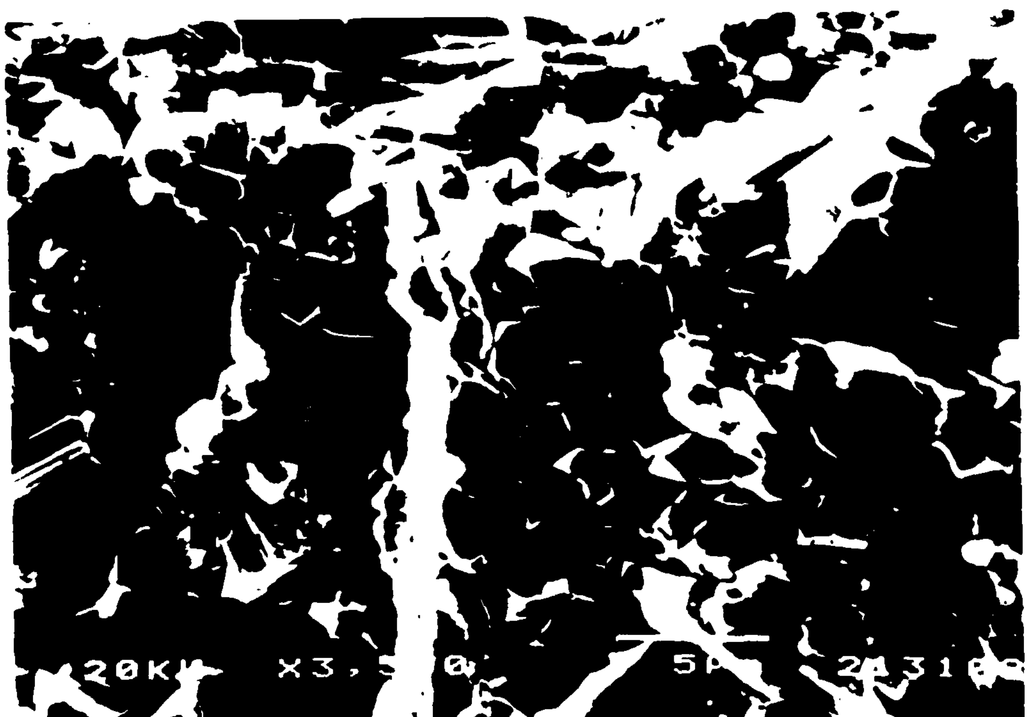
Statically Loaded Specimen



Impact Loaded Specimen

Figure 9. Fracture Surfaces of Si_3N_4 Specimens Tested at Room Temperature.

Statically Loaded Specimen



Impact Loaded Specimen

Figure 10. Fracture Surfaces of SiC_w/Al_2O_3 Specimens Tested at Room Temperature.

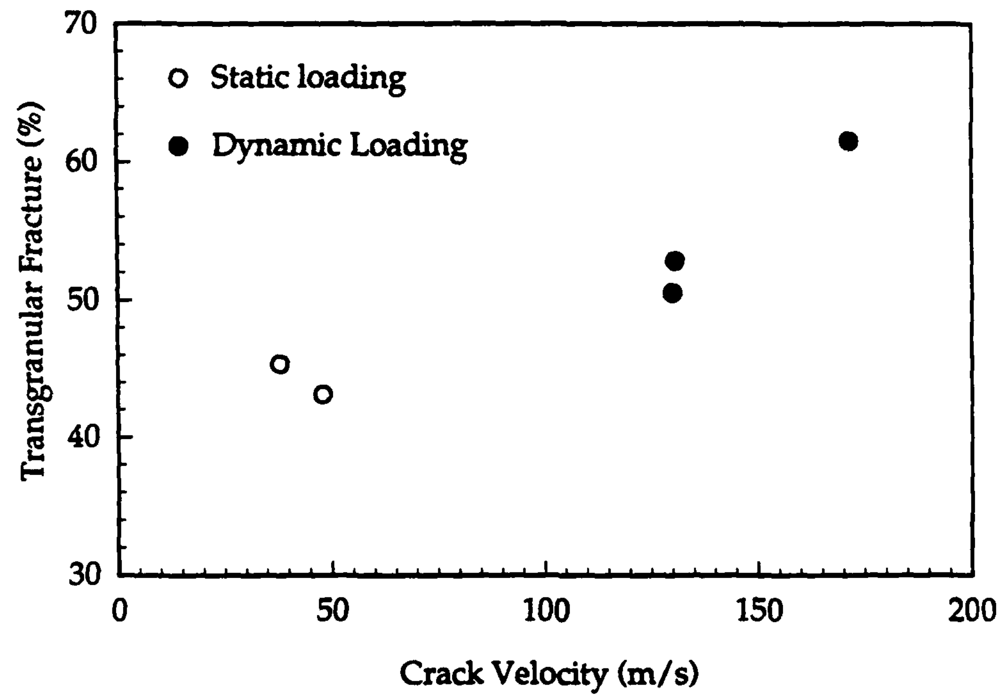


Figure 11. Percentage Area of Transgranular Fracture versus Stress Intensity Factor. SiC_w/Al_2O_3 Specimens.

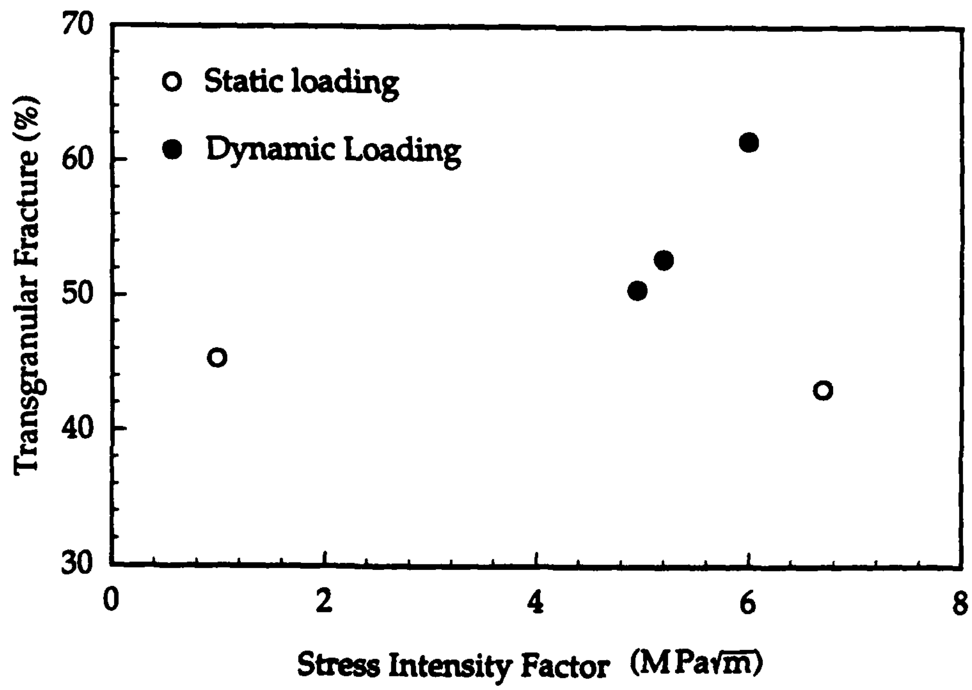


Figure 12. Percentage Area of Transgranular Fracture versus Crack Velocity. SiC_w/Al_2O_3 Specimens.

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