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DYNAMIC FRACTURE CHARACTERIZATION OF CERAMIC MATRIX COMPOSITES

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Résumé

Une nouvelle procédure hybride, à la fois expérimentale et numérique a été utilisée pour caractériser la rupture dynamique de matériaux composites particules de TiB_2 matrice SiC et SiC_w /matrice Al_2O_3 à la température ambiante et à $1200^\circ C$. La valeur de la ténacité correspondant à l'initiation de la fissure, dans des conditions de chargement dynamique obtenue est supérieure à la ténacité statique K_{Ic} et décroît à $1200^\circ C$. Les réponses à la rupture dynamique des deux composites à matrice céramique ont été caractérisées par le facteur d'intensité de contrainte dynamique (SIF) en fonction des relations de vitesse de fissure. Des petites différences entre les réponses à la rupture dynamique à la température ambiante et à $1200^\circ C$ ont été observées.

Abstract - A new hybrid experimental-numerical procedure was used to characterize the dynamic fracture of TiB_2 -particulate/SiC-matrix and SiC_w/Al_2O_3 -matrix composites at room temperature and $1200^\circ C$. The dynamic fracture initiation toughness, K_{I0} , was found to be greater than the corresponding static fracture toughness, K_{Ic} , and decreased at $1200^\circ C$. The dynamic fracture responses of the two ceramic matrix composites were characterized by the dynamic stress intensity factor (SIF) versus crack velocity relations. Small differences between the dynamic fracture responses at room temperature and at $1200^\circ C$ was observed.

1 - INTRODUCTION

In many of its contemplated applications, a structural component consisting of ceramic matrix composite is often subjected to dynamic loading which could initiate rapid crack propagation in the inherently brittle ceramic matrix. For such a structural component to be fail safe, the propagating crack must be arrested short of a catastrophic failure. This crack arrest capability is often designed into components for aerospace structures and nuclear power plants but so far no such consideration is given to ceramic and ceramic composites under an operating environment.

As mentioned above, only limited results /1-4/ on the room temperature dynamic fracture resistance of glass, reaction-bonded silicon nitride and alumina have been reported to date. These results showed that unlike polymers and metals, the rapidly running crack did not arrest when the driving forces, which in these studies were equated to the dynamic stress intensity factor (SIF), fell below a threshold value, i.e., the dynamic arrest stress intensity factor /5/. More recently, the authors have conducted some preliminary investigation on the dynamic fracture response of alumina at $1000^\circ C$ /6/. Conspicuously absent in this study was the dynamic crack arrest phenomenon at elevated temperature. However, no data describing the high temperature dynamic fracture response of ceramic matrix composite (CMC) materials has been published to date.

Recent experimental investigation on the quasistatic fracture process /7/ of $\text{SiC}_w/\text{Al}_2\text{O}_3$ -matrix composite using chevron-notched, three-point bend specimens showed a sequence of run-arrest phenomena as shown in Figure 1. These results suggest that similar run-arrest phenomena may be duplicated under dynamic conditions thus providing possible dynamic arrest stress intensity factor which were not observed in previous experimental analyses /1-4/.

The purpose of this paper is to report on the dynamic fracture response of two ceramic composite materials at room temperature and 1200°C.

2 - EXPERIMENTAL AND NUMERICAL PROCEDURES

Dynamic fracture testing of structural ceramics under the perceived operating conditions presents numerous experimental difficulties in monitoring simultaneously the time-varying applied load, which is imparted to the heated specimen, and the location of the propagating crack tip. The authors have circumvented the difficulty of measuring the actual load by using a hybrid experimental-numerical procedure where the load train was incorporated into the dynamic finite element model of the fracture specimen. The applied load, which is measured outside of the furnace, is then input to the finite element model. The instantaneous location of the propagating crack tip, which is necessary to drive the finite element model in its generation mode /8/, is inferred from the time variation of a crack opening displacement (COD) which is measured by a non-contacting laser interferometric displacement gage (LIDG) /9/. Three straight-notched, three-point bend specimens were tested at room temperature and 1200°C. Typical specimen dimensions were 76.2 x 9.1 x 6.4 mm for TiB_2 -particulate/ SiC -matrix composite, and 76.2 x 6.4 x 6.4 mm for $\text{SiC}_w/\text{Al}_2\text{O}_3$ -matrix composite. The initial notch depth ratio were 0.5 for both specimens. The notches were machined with a diamond-tipped saw blade which produced a notch width of 0.25 mm.

The loading system consisted of a drop weight tower, which is mounted integrally with the furnace, with a maximum operating temperature of 1500°C. The two port holes and one door, which are shielded with fused silicate glass panes to prevent the undesirable convection of air current in the furnace chamber, provided the passage of the LIDG laser beam. The impact load was monitored by a load transducer at the top end of the push rod and outside of the furnace. The bottom load transducer, which was placed between the bottom end of the push rod and the fracture specimen, was used to validate the hybrid experimental-numerical procedure at room temperature. The two load transducer outputs were recorded on a transient wave form recorder.

The optical principle of the LIDG is that interference fringes are generated by the reflection of an incident laser beam from two small reflecting microhardness indentations /9/. Since the CMC materials used in this study lacked sufficient reflectivity to produce the optical interference fringes, highly reflective platinum tab, typically 3.0 x 2.0 x 0.1 mm, were bonded near the crack tip of a specimen surface with Aremco Ceramabond adhesive. Two indentations were located 0.4 mm apart along the machined crack and 0.5 mm behind the crack tip. The relative displacement of the two indentations, which is the COD, was measured by the interference fringe pattern motion which was monitored by a photomultiplier tube (PMT) and recorded on a transient wave form recorder. The motion of each whole-order fringe is equal to 0.91 μm of the COD.

Three specimens of each of the ceramic matrix composites were also instrumented with KRAK gages to determine the crack extension history during rapid fracture at room temperature. This data was used to construct a master curve, which related the measured COD and the measured instantaneous crack tip location during rapid crack propagation, as shown by the solid curves in Figures 2 and 3. These master (solid) curves can be used to locate the instantaneous crack length from the COD data at elevated temperatures provided a proportional adjustment is made to accommodate for the changes in elastic moduli at elevated temperature. Such estimated master curve for 1200°C are shown by the broken line in Figures 2 and 3.

An implicit dynamic finite element code was executed in its generation mode /8/ to compute the dynamic fracture initiation and propagation fracture toughnesses. The input data to this finite element model consisted of the crack extension history, which was determined by the COD data with the master curve, and the measured impact load. The dynamic fracture initiation toughness, K_{Id} , was computed by using a calibrated COD procedure. The dynamic SIF during rapid crack propagation was determined from the numerically computed dynamic energy release rate using Freund's relation/10/.

3 - DYNAMIC FRACTURE INITIATION

Typical room temperature LIDG data for TiB_2 -particulate/SiC-matrix composite is shown in Figure 4. The onset of dynamic fracture initiation was easily recognized from the sudden change of the fringe motion from which the critical COD was computed. A simple average of the displacement of the two fringe patterns effectively removed any rigid body motion of the specimen. The near field crack opening displacement relation was used to calculate the dynamic stress intensity factor at the onset of crack propagation. K_{Id} at room temperature was $8.3 \text{ MPa } \sqrt{m}$. K_{Id} at 1200°C was $7.6 \text{ MPa } \sqrt{m}$. The crack tip loading rate was on the order of $10^7 \text{ MPa } \sqrt{m}/\text{sec}$ which is comparable with those other impact tests. The same procedure was used to obtain K_{Id} data which were $7.9 \text{ MPa } \sqrt{m}$ at room temperature and $6.3 \text{ MPa } \sqrt{m}$ at 1200°C .

The quasi-static fracture testing of similar ceramic composites was conducted to investigate the temperature dependency of static fracture toughness, K_{IC} /11-12/. Test results showed that K_{IC} data of TiB_2 -particulate/SiC-matrix composite were $4.63 \text{ MPa } \sqrt{m}$ at both room temperature and 1200°C /11/. K_{IC} results of SiC_w/Al_2O_3 -matrix composite were $6.22 \text{ MPa } \sqrt{m}$ at room temperature and $5.03 \text{ MPa } \sqrt{m}$ at 1200°C /12/.

Comparison of test results indicated that K_{Id} is higher than K_{IC} at both temperatures. Similar fracture response was also reported by dynamic fracture initiation testing of a polycrystalline alumina material /13/.

4 - DYNAMIC FRACTURE PROPAGATION AND ARREST

The hybrid procedure was used to determine the dynamic SIF of the CMC materials during rapid fracture. Figure 5 shows the measured crack extension histories of TiB_2 -particulate/SiC-matrix composite at both temperatures. The crack extension history and the measured top impact load were used to run the dynamic finite element code in its generation mode. The resultant crack velocity versus dynamic SIF relation was illustrated in Figure 6 where small differences are noted between the data for room temperature and 1200°C . The impacted three point bend specimen used in this study did not generate the lower dynamic SIF where crack arrest may have occurred. Thus further studies using different fracture specimens are necessary in order to resolve the controversy involving existence or lack of existence of a dynamic arrest stress intensity factor in ceramic composite materials.

The same procedure was used to determine the dynamic SIF of SiC_w/Al_2O_3 -matrix composite specimens. Figure 7 shows the resultant crack velocity versus dynamic SIF relation where again small differences are noted between the data for room temperature and 1200°C . While the trend of a decreasing crack velocity with decreasing dynamic SIF is observed, the available data does not indicate the existence or lack of existence of a dynamic crack arrest stress intensity factor.

5 - CONCLUSIONS

A hybrid experimental-numerical procedure was used to determine the dynamic fracture initiation toughness and dynamic SIF of TiB_2 -particulate/SiC-matrix and SiC_w/Al_2O_3 -matrix composites at room temperature and 1200°C . The dynamic fracture

initiation toughness, K_{I0} , values at room temperature and 1200°C were greater than the corresponding static fracture toughness. Small differences in the crack velocity versus dynamic SIF relations for both CMC materials were observed.

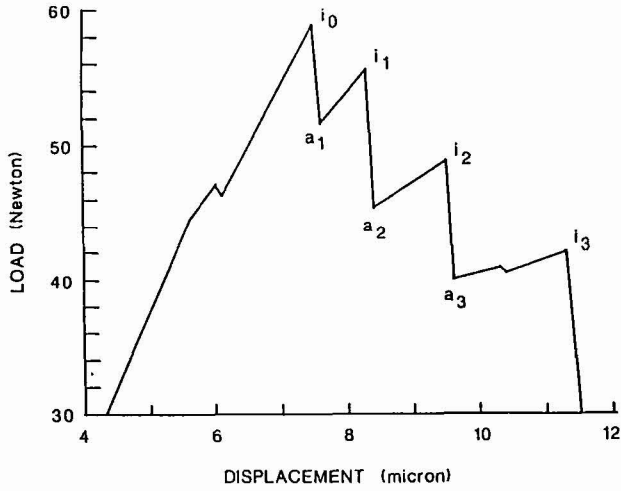


FIGURE 1 Load versus load line displacement. SiC_w/Al_2O_3 -matrix chevron notched three point bend specimen.

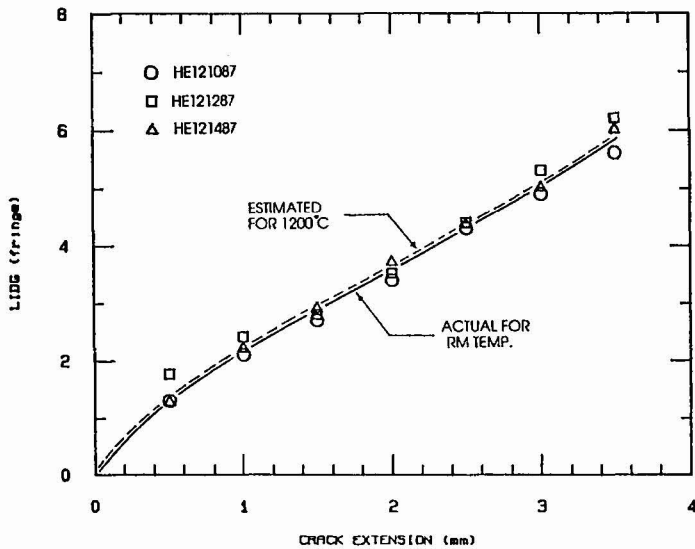


FIGURE 2 Crack extension versus COD master curves at room and 1200°C temperatures. TiB_2 -particulate/SiC-matrix composite.

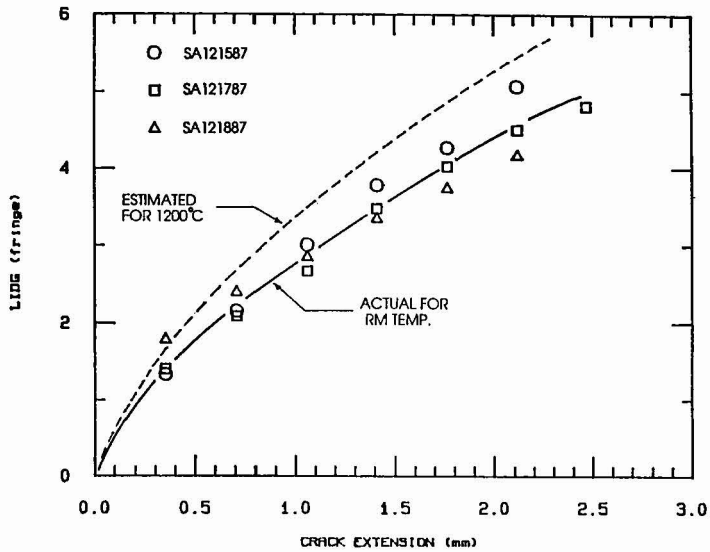


FIGURE 3 Crack extension versus COD master curves at room and 1200°C temperatures. $\text{SiC}_W/\text{Al}_2\text{O}_3$ -matrix composite.

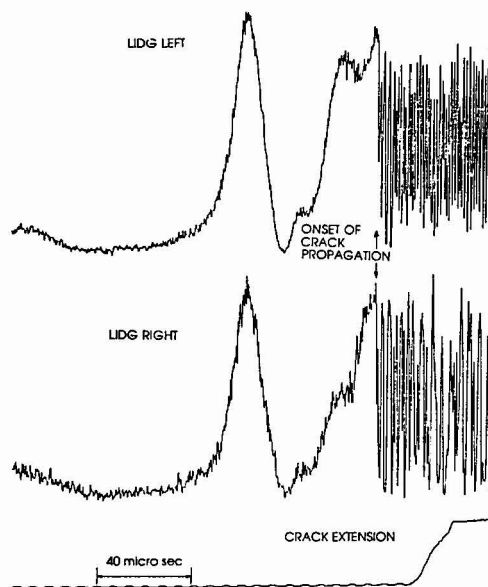


FIGURE 4 LIDG data for both PMTs and crack extension data. TiB_2 -particulate/ SiC -matrix composite.

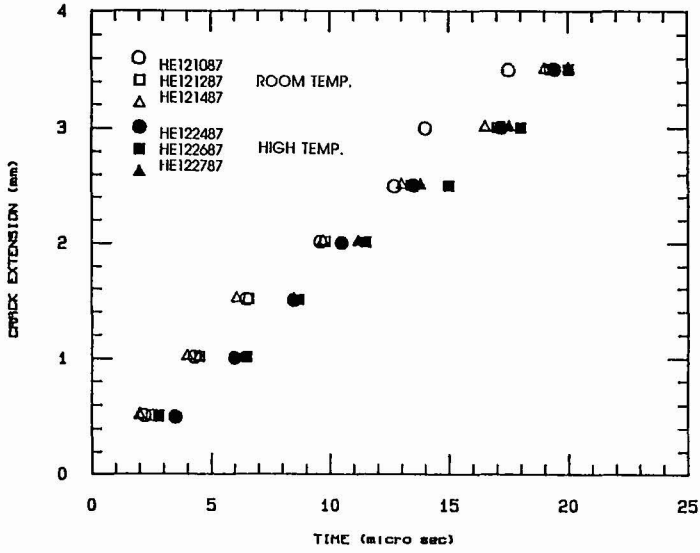


FIGURE 5 Crack extension versus time relation at room and 1200°C temperatures. TiB₂-particulate/SiC-matrix composite.

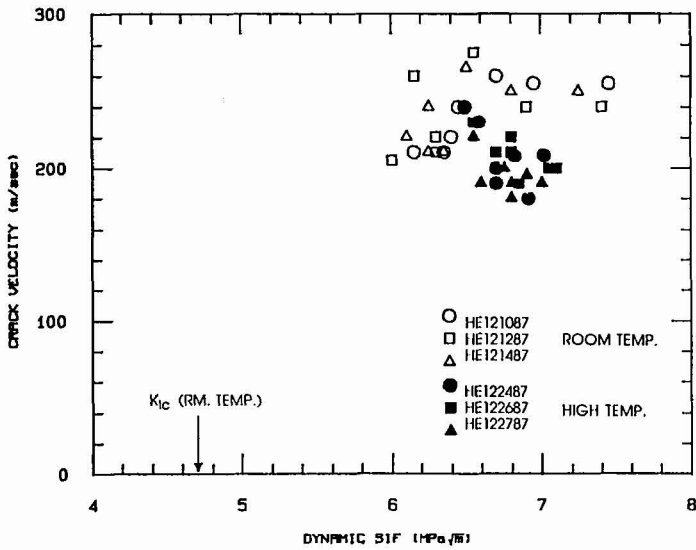


FIGURE 6 Dynamic SIF versus crack velocity relation at room and 1200°C temperatures. TiB₂-particulate/SiC-matrix composite.

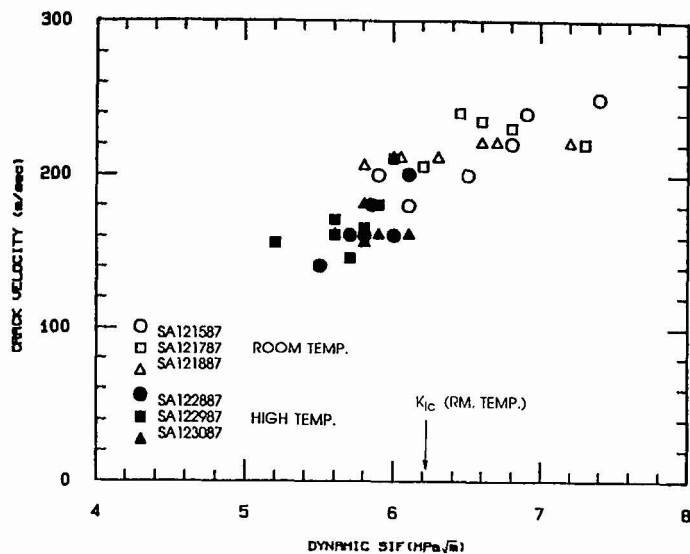


FIGURE 7 Dynamic SIF versus crack velocity relation at room and 1200°C temperatures. $\text{SiC}_w/\text{Al}_2\text{O}_3$ -matrix composite.

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