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Experimental and Numerical Investigation of Dynamic Fracture Toughness of Ceramic Composites

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ABSTRACT

This study focusses on the experimental and numerical investigation of the continuous carbon fiber-reinforced silicon carbide (SiC), and silicon nitride (Si_3N_4) matrix composites. A testing procedure has been designed to study the Charpy impact testing system. The dynamic elastic-plastic fracture toughness (J_{dSiC}=11.88kJ/m^2 and J_{dSi3N4}=1.77kJ/m^2) as well as the dynamic stress intensity factors (k_{dSiC}=36.88 MPaem^{2}and J_{dSi3N4}=22.03 MPaem^2) have been evaluated. Further on, a good agreement between finite element results and experimental findings was found.

Keywords : Ceramic Composites, CMC, CFC, ASTM, Silicon Carbide, Silicon Nitride, Finite Element, Intensity Factors, Silicon Carbide

I. INTRODUCTION

The literature review shows that ceramic materials has a long tradition, as well as, shows excellent properties e.g. high stiffness and hardness, high thermal and chemical stability, high mechanical strength at high temperature, low thermal expansion, and good resistance to high energy neutron irradiation [1-10].

In 1970's, the first non-oxide CMCs, based on carbon/carbon composites, were developed for aerospace structures (leading edges, rocket nozzles) as well as, advanced weapons equipment, because of their characteristics. Continuous carbon fiber-reinforced aluminum matrix composites [1], or silicon carbide which is one of the promising materials [2-5]. The main problem is that are brittle as monolithic state. A number of works have shown that this problem can be overcome by using continuous carbon fiber-reinforced aluminum matrix composites [1], or silicon nitride (Si_3N_4) as well as silicon carbide (SiC). The main concern regarding the use of ceramics as structural materials is to improve toughness. For instance, silicon nitride (Si_3N_4), offers a high fracture toughness due to a composite microstructure and a high creep resistance controlled by grain boundary chemistry [11]. A number of authors have recognized that silicon nitride with a small grain could exhibit plastic behavior even if it is typically tough and strong [12-39]. The control of grain size and its distribution is one of primary concerns in the processing of Si_3N_4 ceramics [40-55].

Previous studies have shown relations between the microstructure of Si_3N_4 ceramics and various processing parameters; sintering time, [41, 47-49, 51]; sintering temperature [40, 45]; and addition of sintering aids [44] as well as large seed particles [46, 48, 50-55]. Furthermore, there exists a considerable body of literature on Si_3N_4 powder in terms of a/β-ratio [48, 50, 55-62]. In order to reduce sintering temperature, well-established techniques for coating pigment particles with hydrated oxide or hydroxide films have recently been extended to the ceramic fields [63–65]. Slightly superior properties are achieved with sialon ceramics. They are being prepared from different powders, and therefore properties and quality depends from the starting powders. The powder determines the processing, the sintering behaviour and the subsequent formation of the microstructure, which strongly influences many properties of dense materials [66]. Sialon ceramics with fine grained and low strain rate plastic properties, also reported in literature [39]. Actually, sialons focus on the understanding the interrelation between fabrication, composition, and properties of the Si_3N_4 ceramics.

The fracture toughness is one of the most important properties which characterize the ceramic matrix composite. Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw. In other words, is a function of the grain and pore sizes.

Finite element method (Abaqus) can be used to determine the fracture toughness, simulating Charpy test. Charpy test has been used because of its simplicity. Such test can be solved as a three-bending test in finite element software. Generally, numerous studies on the finite element analysis (FEA) for ceramics have been conducted and recognized [67-71]. A closer look to the literature on the conventional FEA methods, however, reveals a number of gaps and shortcomings. For instance, such methods use a set of uniform fracture parameters, while there are some reports where present the effects of the stochastic variability of fracture properties [72-74].

A more systematic and theoretical analysis is required for predicting the strength induced by the pore and grain size distribution. This is an important finding in the understanding of the crack initiation in ceramics because of voids [75-80]. It is well known, that Linear Elastic Fracture Mechanics is considered for a brittle material. The critical crack length when the stress intensity factor is equal to the fracture toughness is to be determined [81, 82]. Seminal contributions have been made by many researchers [83-85].

The present study describes an experimental and finite element investigation of fracture toughness of carbon fiber reinforced ceramic composites. The dynamic fracture toughness of continuous carbon fiber reinforced SiC, and Si_3N_4 matrices composites were evaluated by using the instrumented Charpy impact testing method which is easily able to estimate the fracture toughness of the CFC. The experimental results were compared with the additional finite element results, which were in a good agreement.

II. METHODS AND MATERIAL

The testing configuration was based on the ASTM standards E-23 for metallic material (notched / unnotched), while the typical specimen dimensions are 55x10x10 (mm). In this study, the test specimen configuration was modified as shown in Fig. 1, in order to compared with the additional experimental results. The specimen had a slit in the central part, where the width is 0.2mm.

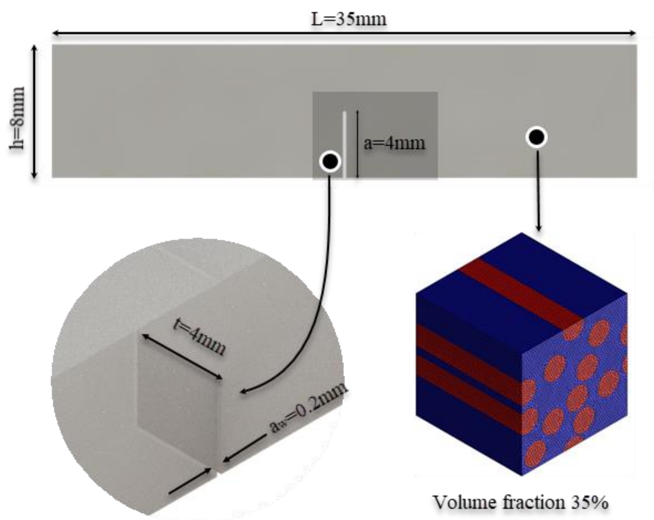

Figure 1: A test specimen configuration.

A. Materials

Two different types of composites were adopted in the present experimental procedure. Firstly, the high modulus carbon fiber was used as reinforcement. The two matrices were SiC, and Si_3N_4, respectively, while fine powders have also been used as fillers (β-SiC, a-Si_3N_4). The effective volume fraction of the unidirectional carbon fiber reinforced ceramic composites is equal to 0.35 (fig. 1). The mechanical properties of the materials are given in Table 1.

<u>Carbon Fiber</u>

Longitudinal Young Modulus (GPa) = 230.0
Transverse Young Modulus (GPa) = 20.0
Shear Modulus (GPa) = 12.0, Poisson ratio =0.18
Density (kg/m3) = 1780.0

<u>SiC and Si3N4 Matrices</u>

Longitudinal Young Modulus (GPa) = 225.0 and 316.50
Transverse Young Modulus (GPa) = 225.0 and 316.50
Shear Modulus (GPa) = 75.0 and 126.10
Poisson ratio =0.14 and 0.26
Density (kg/m3) = 2550.0 and 3154.0

III.FINITE ELEMENT METHOD

Dynamic explicit finite element (FE) simulations of the Charpy impact test were carried out by using Abaqus [86]. The C3D15 element with 9 integration points is used for the crack tip (singularity), while 20-node quadratic brick elements (C3D20R) are used for the other regions. Between these two types of elements, the C3D20R element yields still better results for the same number of degrees of freedom. The whole model was meshed with 476,500. Moreover, the specimen was considered as deformable, while the striker as discrete rigid body. The boundary conditions are shown in figure 2.

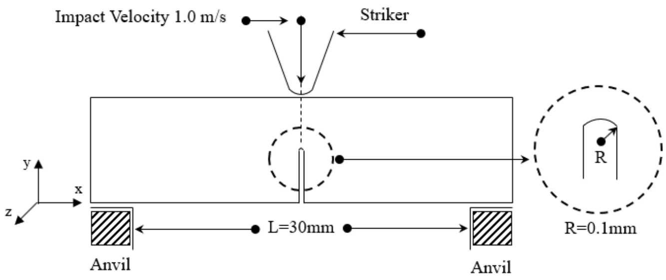

Figure 2 : Boundary conditions.

IV. RESULTS AND DISCUSSION

A. Experimental Results

The main focus of the experiments was to calculate the total absorbed energy (E_t), which is the sum of the apparent crack initiation energy (E_i) and the apparent crack propagation energy (E_p). In this study, the most difficult part was to define the crack initiation point. Only a few works in literature demonstrate that the sudden changing of compliance could be adopted as real crack start point. However, four specimens were used for each case. This is generally sufficient to produce good results. The experimental results are listed in table 1. As it can be seen from table 1, the total absorbed energy (E_t) of the C/SiC specimen is much higher than C/Si_3N_4.

TABLE I

Absorbed energy of the samples obtained by the Charpy test and [87].

Specimen	C/SiC	C/Si_3N_4
E_t (Exp.)	0.3518	0.0510
E_i (Exp.)	0.0951	0.0142
E_p (Exp.)	0.2567	0.0368
E_t (Lit. [87])	0.3316	0.0488
E_i (Lit. [87])	0.0724	0.0136
E_p (Lit. [87])	0.2592	0.0.352
[%]	5.74	4.31

On the other hand, by assuming that the composite specimens shows elastic-plastic behavior , the dynamic fracture toughness can be calculated by the following equations,

$$Jd_i = \frac{2E_i}{t(h-a)}$$

where Jd_i is the nominal dynamic fracture toughness, **t** is the thickness of the specimen, **h** is the height of the specimen and **α**, the length of the slit. The additional results are presented in table 2, compared with the additional results [87]. The bold font in table 3 means that the value of this study is lower than that of the literature [87].

TABLE III

Dynamic fracture toughness of the specimens.

Specimen	C/SiC	C/Si_3N_4
Jd_i (kJ/m^2)	11.88	1.77
Jd_i (kJ/m^2) ([87])	10.48	1.96
$Jd_{o'}/Jd_i$ (%)	88.2	**9.7**

Figure 3 shows fracture surface of specimens after the Charpy impact testing. In the case of the SiC matrix, long pull-out fibers were predominantly observed, while a slight fiber pull-out was detected in the Si_3N_4 matrix.

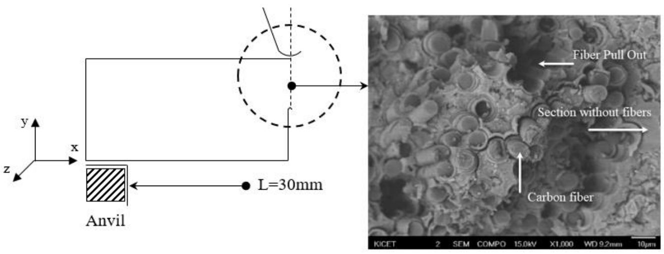

Figure 3 : SEM photograph of C/Sic composite specimen.

B. Finite element results

It is well known that stresses and strains caused by dynamic loading can differ greatly from those associated with corresponding static loading. Fracture during impact loading will give high stress levels near cracks. The fracture behavior of the composite specimens can be understood and predicted, when the dynamic stress intensity factors (SIF) are known. For that reason, a 3D analysis has been conducted in order to evaluate dynamic SIF by using Abaqus software. Now, the most difficult part in FE model was the mesh generation. In order to improve convergence of the solution, a quite small elements were considered in the crack tip. Furthermore, a Matlab code [88] was written in order to calculate stress intensity factors. As it can be seen from table 3, the deviation between experimental and finite element results is quite small.

A difference between these results can only be attributable to the open porosity of the specimens. Silicon carbide (SiC), has higher porosity than silicon nitride, which means a non-linear behavior with microcracking occurs compared to silicon nitride specimen.

TABLE IIIII

Dynamic fracture toughness of the specimens.

Specimen	C/SiC	C/Si_3N_4
Exp. MPaem^2	36.88	22.03
FEA. MPaem^2	37.30	23.22
Difference (%)	1.66	5.10

V. CONCLUSION

In summary, this paper argued that the mechanical properties of most materials depend on the loading rate. The main conclusion that can be drawn is that was that total absorbed energy of the silicon carbide composite was much higher than silicon nitride composite. The main reason for such difference is the open porosity of the specimens. A higher porosity means a non-linear phenomenon with microcracking. After fracture, a fiber pull-out was observed on the C/SiC composite, while a slight fiber pull-out was observed to the silicon nitride specimen. These findings suggest that the fiber pull-out has remarkable contribution to the fracture energy of the specimen. Finite-element results are in well agreement with the additional experimental results.

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