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Performance Characterization of Ceramic Matrix Composites

Dr. Vishal Kumar[1]*, Sachin Kumar[2], Dr. Ajit Kumar Pandey[3]

[1] Associate Professor (Physics), Govt. Women PG College, Kandhla, Shamli (UP) India

[2] Associate Professor (Physics), Meerut College, Meerut (UP) India

[3] Associate Professor (Applied Sciences), Kashi Institute of Technology, Mirzamurad, Varanasi (UP) India

Abstract* - *The purpose of this study is to evaluate the mechanical properties of ceramic matrix composite (CMC) samples and provide metrics for enhancing the manufacturing process and designing better components. The tensile strength of an uncoated fibre reinforced silicon ceramic was measured using room temperature monotonic uniaxial tensile testing in line with ASTM standard. Measurements of alignment with a gauged tensile specimen were taken in accordance with ASTM E1012 to verify the testing apparatus's monotonic character. Tensile strength data was modeled using the Weibull distribution to get A or B-basis strength characteristics for design values.

Keywords* - *Ceramic matrix composite, tensile testing, silicon carbide matrix, carbon fiber –

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INTRODUCTION

Interest in the use of composite materials has broadened in the past twenty years. The increased use has been, at least partially, driven by reduced manufacturing costs ofreinforcements and superior performance of these materials. Performance characterized by high strength to weight ratios or the capability of structural integrity at very high temperatures make composite materials well suited for many diverse applications. The applications include ranging from sports goods such as tennis rackets, baseball bats and boats, automotive parts including piston rings to engine blocks and advanced aerospace applications such as the National aerospace plane, cargo planes and fighterjets and bombers.[1]

Composites are made by the combination of two or more dissimilar materials in order to achieve properties that the constituent materials cannot provide by themselves individually. In fact, the development of composite is based on the idea of combining materials to utilize jointly the best characteristics of each. The dimensions of one ofthe constituents of a composite material are smaller than those ofthe second, where first being known as reinforcement and the other as matrix.[2]

Different types of materials, e.g. metals, ceramics & glasses and polymers may be combined in different forms in composite materials. The effective method to increase strength properties is to incorporate high strength materials as dispersed phases into the matrix, which can be metal, ceramics or plastics. The dispersed phase may be a particulate matter, organic or glass fibers in continuous or short lengths, metal wires, metal or ceramic whiskers, or ceramic filaments such as Boron or Carbon.[3]

Materials for advanced structural applications, especially at elevated temperatures have been till recently largely restricted to advanced metallic alloys. However, it seems that for certain applications involving very high temperatures, metallic materials have reached a limit in their potential for development. For example, in combustion engines and other energy generating equipments, the development is necessarily limited by the melting point of the alloys. For continued development, ceramics offer significant increase in service temperature. Their low density, chemical inertness and high hardness offer additional potential for extending performance limits as compared to those offered by metallic materials. Ceramics find application for first wall protection, for insulators and windows. In fusion reactors some sort of protection system has to be introduced between the plasma and the metallic first wall in order to protect plasma from impurities and to protect the first wall from plasma disruptions.[4]

Among the possible protection materials, graphite and SiC have the best qualifications. Ceramic insulators are needed for several applications in reactor technology. Since the components arc 2 exposed to high radiation doses and organic insulator possess poor irradiation resistance, the insulating components have to be made up of

ceramics. But, the widespread use of ceramics has been inhibited by their brittleness and poor reliability of strength. In an effort to overcome these problems, application of composite principle has been used in developing ceramic materials with high fracture toughness.[5]

Ceramic Composite Structure

Ceramic matrix composites are gaining grounds in Nuclear applications and Fusion reactor as well. With proper formulation, these may be used for fuel cladding, moderating materials and shielding materials. The various requirements of the shield can be met by the use of alternating layers usually within massive concrete structure. In fusion reactors, first wall materials will be exposed to various high heat fluxes. The high heat fluxes will cause cracking, melting or vaporization of materials. These phenomena will depend on parameters such as strength and duration of the high heat flux, various material properties and the design of the components etc.[6]

Matrix and reinforcement are the two main components of a continuous matrix composite (CMC). What sets this material apart from polymeric or metallic counterparts is the existence of a ceramic continuous phase. Reinforcement phase structures in composites may be any combination of particles, chopped fibers, continous fibers, and laminates.

By combining a ceramic matrix with a reinforcing fiber, a composite material known as ceramic matrix composite may be produced. In order to increase the ductility of the ceramic, the matrix is often a high-temperature structural ceramic like SiN, SiC, or BN. A ceramic matrix composite is created by combining the reinforcement with a composite material. Different types of ceramic matrix composites may be found everywhere. Laboratory studies make use of CVI. The primary operation consists on expanding fiber production to meet rising demand. The braided body is put in a reaction area, and an interface layer and a ceramic matrix layer are produced on the surface of the fiber through a chemical process to produce a ceramic matrix composite material. Most also require to layer additional chemical coatings on their surfaces to avoid oxidation, which greatly increases their oxidation resistance. In Fig., we have a schematic depiction of the mesostructure of the ceramic matrix composite. The macrostructure's protective covering is plainly seen as its outermost layer. This deposited ceramic matrix and its interaction with the mesoscopic fiber surface.[7]

Figure 1: Synthesis of Material Science's Big Data Infrastructure.

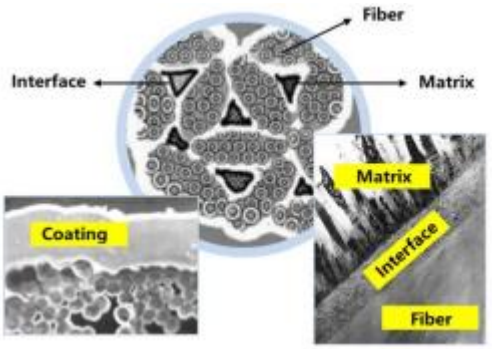

Figure 2: Micrograph showing the microstructure of ceramic matrix composites.

A fiber-woven preform, deposited interface, ceramic matrix, and protective coating make up the constituent parts of the ceramic matrix composite. Ceramic matrices are the primary constituent of these materials. Fibers added to a composite material make it more robust and less prone to breaking under stress, making it ideal for use in extreme conditions. Both oxide and non-oxide ceramic matrices have a grain structure in the microstructure. The tensile strength, brittleness, bending strength, and fracture toughness of a produced material all depend heavily on the grain size of the starting material. Increased focus has also been placed on the role that the grain size impact has in determining the electrical, mechanical, and thermal characteristics of the ceramic matrix.[8]

The fracture behavior of the final composites is modified when porcelain fibers are added to a ceramic matrix. Breaking behavior of typical ceramics (curve 1), a particulate composite (curve 2), and a fiber reinforced composite (curve 3) are shown in the figure (curve 3). Composites may bend significantly before failure occurs, but ceramics have a relatively low strain to failure or collapse spectacularly. Consequently, ceramic composites are becoming more popular for use in structural applications because to their increased toughness.[9]

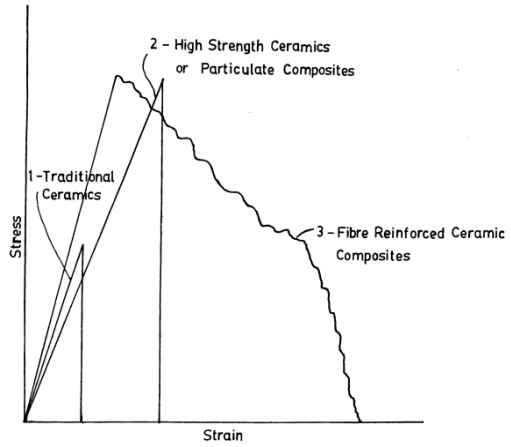

Figure 3: A simulated stress-strain curve for a selection of structural ceramics & composites

Big data, data mining, and data representation are all interrelated and useful in the subject of materials science [1]. They are demonstrated in Fig. 1 to be three interrelated material science technologies. In the context of material science, "big data" refers to the massive amounts of information gleaned through laboratory investigations. Data representation is the glue that holds this data together, allowing data mining to extract the necessary patterns and information. In order to proceed with data mining and associated tasks, such constructing a material database, it is necessary to appropriately classify the material data, which is characterized by variety and heterogeneity. Therefore, the description of material information is of great value to academic study.[10]

Fiber Preforms

Intricate three-dimensional structures may be woven from strands of continuous fiber to create laminates with a variety of properties. Since carbon fiber filaments are very thin, a single strand is really a collection of filaments called a tow, and the tow typically contains anywhere from one thousand to twelve thousand filaments. These tows serve as the principal structural element of the material due to their great load bearing capacity in the direction of fiber orientation. In composites containing particle or chopped fiber phases, for example, the the composite's strength is dependent on the integrity of the interface between the matrix and reinforcement since the reinforcement is discontinuous. Since the reinforcement is does not fully span the material, a complete fracture of the matrix might occur around or between reinforcements. In contrast, if the fiber is unbroken, the matrix may separate from the fiber but the fiber or overall structure are unharmed. Unlike particles and randomly sliced fibers, the fiber is only effective in the direction perpendicular to its orientation, making its orthogonal strength inconsequential. This issue is most evident in layered CFCCs, where the layers are kept together by nothing but the matrix. [11-12]

Since practically all of the stress is given to the matrix alone, failure occurs at a stress far lower than in a fiberparallel loading situation where a load is supplied out-of-plane. Using three-dimensional preforming processes to weave orthogonal fibers across the laminate planes increases the material's out-of-plane strength qualities. These methods add complexity and expense to production, but they bring through-the-thickness fibers to the part, allowing fiber components to sustain out-of-plane stresses.[13]

The preform configuration has a significant impact on the mechanical characteristics of CMCs. Uniaxial CFCCs act substantially differently from woven or braided CFCCs, even if they are made from the same matrix. This is due to variations in fiber crimping intensity among preforms. Crimp is a characteristic of many weaves and braids; it is the degree to which a single fiber deviates from its centerline route, or the direction that fiber would take if other fibres in the preform were absent. Because crimped fibers tend to extend under strain as the twisted strands try to untwist, crimp and stiffness are inversely related. Moreover, the flexural stresses induced by the bends in crimped fibers under tension further lower their strength compared to that of straight fibers. Because of the bending stresses imposed by the crimping process, the stress-strain curves of crimp preform CMCs often exhibit non-linearities.[14]

MATERIAL AND METHODS

This research will utilize the aforementioned information to examine the mechanical properties of an uncoated PIP generated C/SiC CMC, and develop conclusions that may be used in the design and optimization of related components and production processes. The ultimate strength will be determined by tensile testing according to ASTM procedure, and the load train alignment will be checked using ASTM procedure. Electron microscopy will be used to conduct a qualitative study of the fracture surfaces after failure.

There wasn't a huge pool of CMC samples to choose from while conducting tensile tests. Thus, it is essential that the specimen form and testing technique be designed to maximize the number and probability of successful tests. This experimental method is based on the ASTM standard for the monotonic stress test of a rectangular cross-sectioned CFCC at room temperature. The only requirement that wasn't fulfilled is that strain data was gathered using extensometers and strain gages. Due to the tiny size of the gage part, the lead time and cost limits were onerous, but the latter would have necessitated adhering epoxy to the gage piece, changing the gage characteristics. In order to preserve the gage section, it was decided that data on ultimate tensile strength would take precedence over elastic modulus, hence strain values would have to be derived from displacement.

In order to pass the test, the specimen being fractured must fail inside the gage region, far from

the clamping surfaces and any other foreign interfaces. It was possible to bind aluminum tabs to the ends of the specimen using 5 minute set Loctite glue without damaging the specimen. Sufficient surface area was incorporated into the construction of the ends of specimen such that the epoxy's shear strength would be greater than the strength properties of a reference CMC in Table.

Table 1: Properties of C/SiC CMC

Property	Value
Volume of Fiber	42%
Mass Density	2.4 g/cc
Strength in Tension	45 ksi
Flexural modulus	14.8 Msi
Yield Pressure	16.2 ksi
Pressure to Failure	0.23%
Flexure Power	38 ksi
Shear Strength of a Short Beam	4.3 ksi
Strength of Interlaminar Tension	807 psi

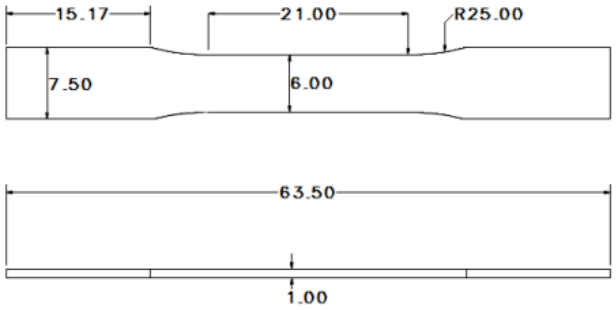

Figure 4: Dimensions of the CMC tensile specimen.

RESULT

Each CMC sample was subjected to a tensile loading program with a single ramp mm movement rate to achieve fracture within the ASTM advised 6 to 10 seconds, hence minimizing their exposure to environmental stresses. From a total of 10 samples, eleven fractures occurred in the gage section and three did not; the latter data was not included in the analysis.

Table 2: Sample dimensions.

	Width Measurements(mm)			Average Width	Thickness Measurements			Average Thickness	Mean Area(mm^2)
R252-1	5.84	5.90	5.75	5.91	1.13	1.21	1.25	1.23	7.15
R252-2	6.18	6.12	5.68	6.09	1.30	1.37	1.25	1.27	7.75
R252-3	6.02	5.88	6.19	6.00	1.36	1.42	1.35	1.44	8.56
R252-4	6.15	6.15	6.20	6.20	1.36	1.24	1.21	1.24	6.67
R253-1	5.87	5.94	6.02	5.94	1.38	1.37	1.36	1.37	6.14
R253-2	5.61	5.46	6.01	5.86	1.28	1.18	1.25	1.24	7.27
R253-4	6.01	5.80	6.00	5.97	1.23	1.24	1.26	1.24	7.42
R253-5	6.16	5.96	6.19	6.07	1.25	1.24	1.22	1.24	7.53
R254-2	5.56	5.62	5.66	5.65	1.26	1.20	1.19	1.22	6.86
R254-3	5.44	5.62	5.56	5.61	1.22	1.25	1.24	1.24	6.75

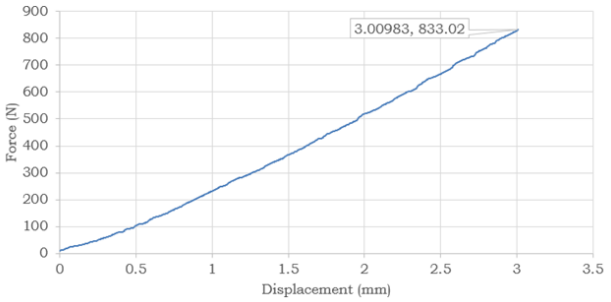

Figure 5: Curve of force versus displacement.

Elongation is determined only by the original gage length measurement, without accounting for the tabbed and tapered portions. The strain in the specimen is calculated using this length and the load train displacement of the testing machine. In order to extrapolate strain measurements, the following formula is used:

$$\epsilon = (l - l_0)/l_0$$

Where

$l - l_0 = machinedisplacement$

and

$$l_0 = 21mm$$

Mean cross-section area & applied force from a load train are used in the stress equation.

$$\sigma = F/A$$

The data is then used to draw a stress-strain curve, which can be used to learn more about the material.

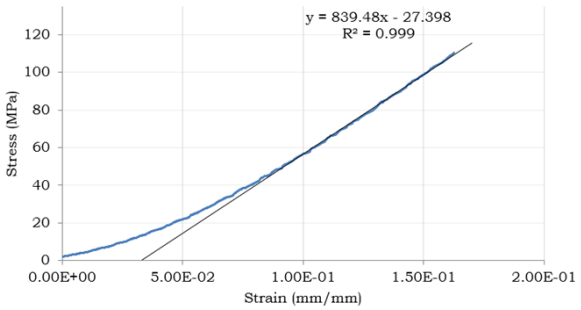

Figure 6: Fractured specimen stress-strain diagram.

Later on in the data, after the graph is straightened out, either because the crumpled fabric has been ironed out or because the sample has settled into the grips, we do our regression analysis. After fitting a linear model to the stress-strain data, the average modulus of elasticity is reported for all specimens in 3.4. While this information is useful, it lacks the precision of data gathered with more accurate strain measurement equipment if other variables than load train displacement had been recorded.

Because composites are anisotropic, there is often a large amount of variance in the data from different samples compared to isotropic, homogeneous materials. In order to accurately determine the mechanical characteristics of composites, statistical data treatment is crucial. For this reason, the Weibull statistic is often used with strength data for polymers, metals, and ceramic composites of varied sample sizes Assuming a Weibull distribution, the failure probability is represented by the function.

$$F(\sigma) = 1 - exp\left(-\left(\frac{\sigma}{\sigma_0}\right)^m\right)$$

In this case, Failure probability under tensile stress, denoted as F, is a function of the form parameter, m, and the scale parameter, 0 (equivalent to the average material strength), as shown below. We may apply a double logarithmic to linearize the eq. and retrieve the shape and scale parameters.

$$ln\ ln\frac{1}{1 - F(\sigma))} = m * ln\sigma - m * ln\sigma$$

and the equation for estimating F (σ)

$$F_i = \frac{i - 0.5}{n}$$

where I is where n represents the number of samples and I is the sample iteration. Figure depicts a probabilistic failure model constructed at a 95% confidence level using the m and 0 parameters obtained from the previous section; this model is utilized in eq.(3.5) to calculate the corresponding strength values for a 99% or 90% material survivability estimate, respectively. The A- and B-basis survival rates are the A- and B- basis material qualities, respectively.

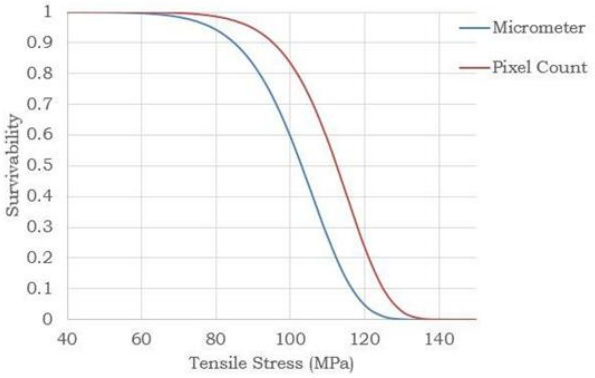

Figure 7: Tensile strength predictions for micrometer (blue) and pixel-counting (red) cross-section measurements, according to the Weibull distribution.

Table 3 lists the micrometer or analytical area values for the A & B basic materials based on this model. These material tensile strengths may be used by component designers, and the median value can be used to satisfy legal reporting requirements for the highest strength value.

Table 3: Data on the tensile strengths of the A- and B-basis.

	Ultimate Tensile Strength (MPa)		
	A-Basis (99%)	B-Basis (90)%	Mean
Micrometer Measured	65.86	83.79	111.9
Analytically Measured	72.64	94.27	121.7

CONCLUSION

Out of ten samples of CMC, three failed at the compression fastening. Even though C1275 suggests a load rate that causes fracture in less than 10 seconds, the actual time to fracture was anywhere between 17 and 21 seconds. It was concluded that this variation was not substantial enough to warrant adjusting the load rate and adding extra variables to the testing procedure, given the load rate was still reasonably consistent and the laboratory atmosphere was not hostile.

Cross-sectional analysis of the specimens showed that their shape was not the simple rectangle predicted by the micrometer measurements. The tensile strength of a composite material depends mostly on the

strength of its fibers. Therefore, the strength qualities of CMC will be significantly diminished by any cause of fiber deterioration. Although there are likely many more differences between these two composites, the fact that the tensile test can reliably estimate their strengths because to these commonalities is encouraging.

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Corresponding Author

Dr. Vishal Kumar*

Associate Professor (Physics), Govt. Women PG College, Kandhla, Shamli (UP) India