JOURNAL OF MATERIALS SCIENCE 26 (1991) 1839–1846

Mechanical properties of a zircon matrix composite reinforced with silicon carbide whiskers and filaments

R. N. SINGH
GE Corporate Research and Development, Schenectady, New York 12301, USA

The influence of a silicon carbide whisker reinforcement on room temperature mechanical properties of a monolithic zircon ceramic and zircon composites uniaxially reinforced with silicon carbide monofilaments was studied in a flexure mode. The strength of a monolithic zircon was increased by the addition of whisker reinforcement, but the composite failure was still brittle in nature. In contrast, zircon composites reinforced with SiC whiskers and filaments showed toughened composite-like behaviour and produced higher first matrix cracking strength and toughness than the composites reinforced with only SiC filaments. In addition, the whisker reinforcement had insignificant influence on the ultimate strength of filament-reinforced composites. These results were related to changes in measured fibre–matrix interfacial properties, which indicated that composites with high first matrix cracking strength and toughness can be designed and fabricated *via* independently tailoring the matrix and the fibre–matrix interfacial properties.

1. Introduction

Ceramic matrix composites with thermochemical and thermomechanical stability at high temperatures are needed in a variety of structural applications. Selection of composite constituent materials useful for some of these applications requires reinforcing fibre and matrix materials with internal stability against chemical reaction and adequate mechanical properties at elevated temperatures. A zircon ($ZrSiO_4$) matrix composite uniaxially reinforced with silicon carbide monofilaments (AVCO SCS 6) was developed to have attractive composite characteristics [1]. For example, as-fabricated composites have shown toughened-composite behaviour with strengths and toughness at 25 °C significantly higher than the monolithic zircon [1]. In addition, internal thermal stability of the composite constituents up to 1350 °C was demonstrated by annealing samples between 25 and 1430 °C for up to 100 h and then by measuring mechanical properties at 25 °C [2]. In a recent study, elevated temperature mechanical properties of zircon–SiC composites were measured between 25 and 1477 °C [3]. The results indicated that composites reinforced with as-supplied and BN-coated SiC filaments were stronger and tougher than the monolithic zircon at test temperatures between 25 and 1477 °C. However, an increasing amount of the plastic deformation was seen in monolithic and composite specimens at temperatures beyond about 1300 °C.

One way to reduce the plastic deformation at elevated temperatures in zircon–SiC composites is *via* whisker reinforcement of the zircon matrix phase. The whisker reinforcement is expected to increase the strength of the monolithic zircon and to provide resistance to creep *via* reduction in grain boundary sliding. Another advantage of the whisker reinforcement may be in enhancing the first matrix cracking strength, which can sometimes be used as a design stress. Therefore, the objective of this investigation was to study the influence of whisker reinforcement on room temperature mechanical properties of a monolithic zircon ceramic and zircon composites uniaxially reinforced with SiC monofilaments. In order to accomplish this goal, composite samples containing SiC whiskers and filaments were fabricated, and their mechanical properties were characterized for a number of composite parameters, such as the first matrix cracking stress and strain, the ultimate composite strength, the modulus, and the toughness. The fibre–matrix interfacial properties were also measured and related to the observed mechanical behaviour. These results on whisker- and filament-reinforced composites were compared with similar results obtained on a monolithic zircon and zircon–SiC composites.

2. Experimental procedure

A zircon powder (zircon Flour, coarse-grained No. 51698) obtained from Remet Corporation, Chadwick, New York, was used in the matrix preparation. X-ray diffraction (XRD) analysis of the as-supplied powder showed tetragonal zircon as the major phase. This powder was milled for 36 h to increase the surface area to about 4 $m^2 g^{-1}$, which increased the powder reactivity for sintering/hot-pressing. A silicon carbide whisker, Tateho SCW-1, obtained from Tateho Chemical Industries Company in Japan was used as a discontinuous reinforcement of the zircon matrix. The crystal structure of this whisker was a cubic beta-silicon carbide. Typical whisker diameter ranged between 0.3 and 0.8 μm and length ranged between 20 and 50 μm. The bulk density of this whisker was between 0.1 and 0.2 $g\,cm^{-3}$. The silicon carbide whisker was used in the as-supplied condition without any other classification treatments. Silicon carbide monofilaments (AVCO SCS-6) were used as a continuous reinforcement in the zircon matrix. These filaments are made by a chemical vapour deposition technique in which about 50 μm thick silicon carbide is deposited on a 37 μm diameter carbon core, followed by depositions of about 3 μm thick carbon and carbon–silicon layers that result in an overall filament diameter of 142 μm [4]. An elastic modulus of 400 GPa, strength of 3.4 GPa, and a failure strain between 0.8 and 1.0% are typical mechanical properties of these filaments at room temperature.

The fabrication of silicon carbide whisker and filament reinforced composites was done by uniaxially aligning as-supplied SiC filaments, and then incorporating the zircon matrix containing SiC whiskers around each of the filaments. The incorporation of SiC whiskers into the zircon matrix was accomplished by mechanical mixing of zircon powder and whiskers without the use of a milling media. This produced a fairly uniform distribution of whiskers in zircon powder and retained the integrity of the whiskers as shown by a high-aspect ratio (length-to-diameter) of whiskers in a sample of zircon composite in the green state (Fig. 1). The final consolidation of composites was done by hot-pressing between 1580 and 1610 °C in a flowing nitrogen atmosphere. These procedures resulted in fully dense composites with an insignificant porosity ($< 1\%$). The composite samples with 20% (by volume) whisker loading (in zircon matrix) and 25% (by volume) filament loading (zircon matrix and SiC whiskers) were fabricated. The matrix phase containing zircon and SiC whiskers was fine grained with an average grain size of about 3 μm. The X-ray diffraction analysis of the fully consolidated composites showed zircon as the major matrix phase. A small amount of the free zirconia phase was also detected by the X-ray diffraction analysis of the as-fabricated composites.

Mechanical properties of whisker and filament reinforced composites were determined from load–deflection data obtained in a 3-point flexure mode. The uniaxially reinforced composite samples, having typical dimensions of 3.2 cm length, 0.8 cm width and 0.15 cm thickness, were individually hot-pressed and ground to a finish of 60 μm. The 3-point flexure tests were performed with lower support pins 2.54 cm apart which resulted in a span-to-thickness ratio of about 17. All the tests were performed in a universal testing machine at a crosshead rate of 0.0127 $cm\,min^{-1}$. The stress was calculated from the load, which was measured by a load cell, and the strain was calculated either from the crosshead displacement or measured using a resistive strain gauge attached to the middle of the specimen. The Young's modulus was calculated from the slope of the linear portion of the stress–strain curve. The work-of-fracture (WOF) was obtained by dividing the area under the load–deflection curve by the cross-sectional area of the sample. Cross-sections of failed composites were examined by a scanning electron microscope (SEM) to determine the fracture morphology and the extent of fibre pullout. The mode of failure (tensile versus shear) in 3-point flexure tests was determined by visual observation of samples during the test. Generally, four samples of each type were tested under similar conditions to establish average mechanical properties.

Fibre–matrix interfacial properties have a strong influence on the mechanical behaviour of ceramic matrix composites [5–7]. A modified indentation technique was used to measure the fibre–matrix interfacial shear strength as described by Brun and Singh [8]. In this technique, a thin slice (1 mm thick) was cut perpendicular to the filament axis and polished in such a way as to produce a small amount of filament relief. This thin slice was then placed on a resilient substrate, and the filaments were individually loaded by the indenter until the first evidence of filament movement was observed. The first evidence of filament motion was detected by a sudden load drop in the load–deflection curve, which was generated by

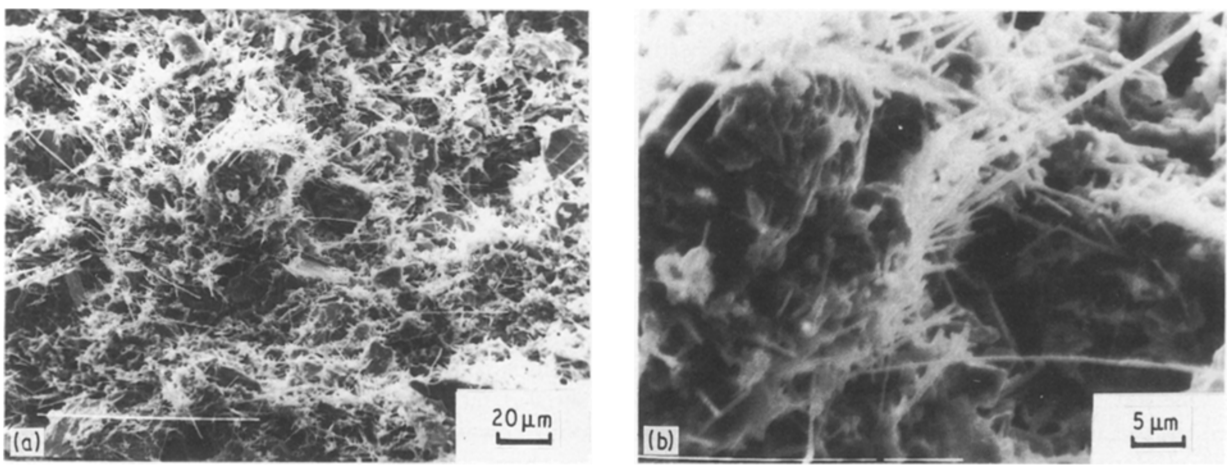

Figure 1 SEM fractographs showing the distribution of SiC whiskers in a zircon matrix powder in the green condition.

measuring the load by a load-cell when pushing on the filament at a constant displacement rate of 0.0508 mm min^{-1} [9]. The interfacial shear stress was calculated from the load required to initiate filament motion and the circumferential area of the filament in contact with the matrix. Then, the sample was turned over and measurements were repeated on already pushed filaments. The load to move the filaments for the second time was invariably lower than that for the first push, which made it possible to separate bonding and frictional components of the interfacial shear stress. Typically, 10 to 15 filaments were pushed in each sample to obtain an average value of the interfacial shear strength. Generally, interfacial shear stress and mechanical properties were measured on the same sample to establish a direct correlation between interfacial properties and mechanical behaviour.

3. Results and discussion

3.1. Physical Properties

A summary of physical characteristics of zircon composites reinforced with either silicon carbide whiskers or silicon carbide whiskers and filaments is given in Table I. It contains data on composite density and volume fractions of whisker and filament reinforcements. An average density of 3.92 g cm^{-3} is obtained for composite specimens containing zircon and 20% silicon carbide whiskers, and an average density of 3.75 g cm^{-3} was measured for composites reinforced with 20% whiskers and 25% silicon carbide filaments. An examination of a polished cross-section of fully consolidated composites revealed no evidence of porosity (Fig. 2), which is consistent with the average composite density of 3.75 g cm^{-3} for samples containing SiC whiskers and filaments because a theoretical composite density of 3.7 g cm^{-3} is calculated for this composite using an experimentally observed matrix phase density of 3.92 g cm^{-3} (zircon and whisker) and a filament loading of 25%. All of these densities are lower than the calculated theoretical density of 4.16 g cm^{-3} for a zircon composite with 20% SiC whiskers and a theoretical density of 3.92 g cm^{-3} for the composite containing 25% SiC filaments in a matrix comprised of zircon with 20% SiC whiskers. These lower densities may have resulted from the presence of another phase or phases in the fully consolidated composite. A reasonable possibility is the presence of silica and free zirconia phases because of the partial decomposition of the zircon phase as a result of the high processing temperature of 1600 °C. A zircon ceramic is expected to decompose to silica and

TABLE 1 Physical characteristics of whisker- and filament-reinforced zircon–SiC composites

Sample No.	Reinforcement	Fibre content (vol %)		Density (g cm^{-3})
		Whisker	Filament	
1	SiC whiskers	20	0	4.03
2	SiC whiskers	20	0	3.88
3	SiC whiskers	20	0	3.85
4	SiC whiskers	20	0	3.93
1-A	SiC whiskers and filaments	20[a]	25[b]	3.80
2-A	SiC whiskers and filaments	20	25	3.75
3-A	SiC whiskers and filaments	20	25	3.74
4-A	SiC whiskers and filaments	20	25	3.71

[a] Whiskers are 20 vol % of the zircon matrix phase.
[b] Filaments are 25 vol % of the matrix phase (zircon and SiC whiskers).

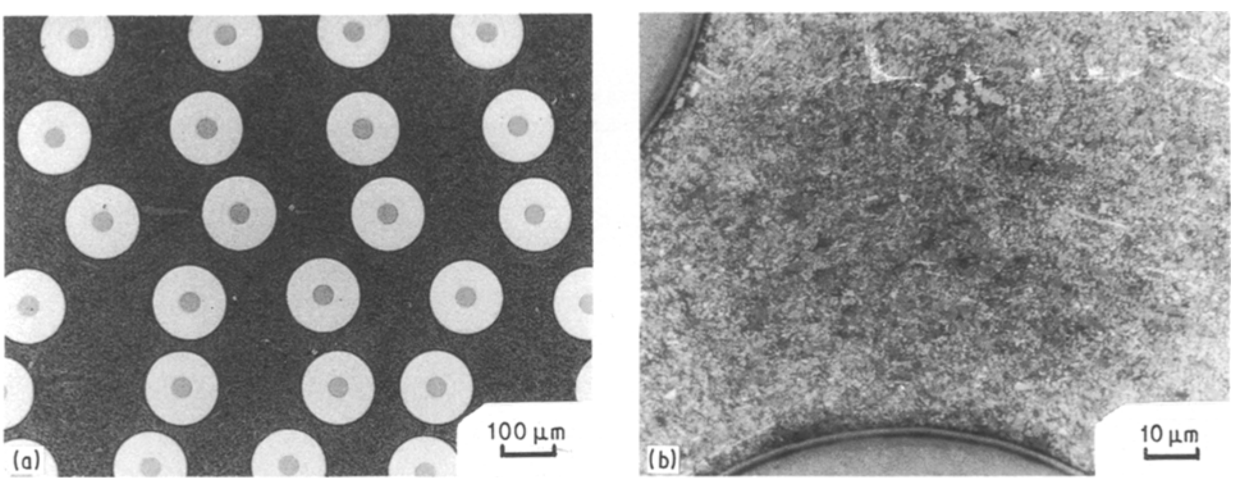

Figure 2 Optical micrographs showing (a) the uniform distribution of SiC filaments in a matrix containing zircon and SiC whiskers, and (b) a fully dense matrix.

zirconia at such a high processing temperature [10]. In order to confirm this possibility, the X-ray diffraction analysis was performed on as-fabricated composites. The results indicated that composites containing SiC whiskers and fabricated at about 1600 °C had more free zirconia phase as compared to composite samples without the SiC whiskers but fabricated at a lower temperature of 1560 °C.

An optical micrograph showing the cross-section normal to the filaments of a fully consolidated composite is shown in Fig. 2. It shows uniform distribution of filaments in a fully dense matrix containing zircon and SiC whiskers, and filaments are completely surrounded by the matrix phase. Cross-sections of a number of composites were examined in this way, and none of the samples showed filament-to-filament contact that can be deleterious to the composite properties. Sample-to-sample variation in density is small, which is indicative of excellent process reproducibility.

3.2. Mechanical and interfacial properties

The load–deflection behaviours for zircon composites reinforced with either silicon carbide whiskers or silicon carbide whiskers and filaments are given in Fig. 3. The results for composites reinforced with whiskers show an initial elastic region followed by a catastrophic failure that is typical of brittle monolithic ceramics. In contrast, the composites reinforced with silicon carbide whiskers and filaments show an initial elastic regime up to the point of first matrix cracking followed by an extended regime showing toughened composite-like behaviour. Clear evidence of first matrix cracking is shown by a sudden load drop at the end of the initial elastic region. Beyond this sudden load drop, the composites show an increasing load-carrying capacity because most of the continuous filaments are still intact and can support additional loads. A maximum load-carrying capacity is shown by composite samples followed by a gradual drop in load as more and more of the intact filaments fail and pullout from the matrix phase. The load–deflection test for each of these filament-reinforced composite samples shown in Fig. 3 was intentionally stopped because the sample had contacted the bottom of the test fixture as a result of the significant amount of displacement.

The load–deflection curves for a monolithic zircon and zircon composite reinforced with SiC monofilaments are shown in Fig. 4 for comparison with the above results obtained for whisker-reinforced composites. The result for a monolithic zircon is similar to that for samples of whisker-reinforced zircon, i.e., an essentially brittle failure at the end of the initial elastic regime. A zircon composite reinforced with SiC monofilaments shows all the essential features of a toughened composite-like behaviour, but unlike the behaviour of composites reinforced with SiC whiskers and filaments (Fig. 3), this sample shows a sudden load drop after reaching the point of maximum in load-carrying capacity (see Fig. 4). The reason for this difference in load–deflection behaviours between composites reinforced with SiC filaments and composites reinforced with SiC whiskers and filaments is related to differences in the fibre–matrix interfacial properties, as discussed later.

A summary of mechanical properties of zircon composites reinforced with either SiC whiskers or with SiC whiskers and filaments is given in Table II. Composites reinforced with whiskers show ultimate strengths between 320 and 353 MPa, elastic modulus values between 131 and 174 GPa, and WOF values between 1.1 and 1.29 kJ m^{-2}. In contrast, composites reinforced with SiC whiskers and filaments show much higher mechanical properties. For example, critical matrix cracking strengths ranged between 405 and 475 MPa, ultimate composite strengths varied between 629 and 665 MPa, elastic modulus varied between 168 and 192 MPa, and WOF values ranged between 31 and 44 kJ m^{-2}. The ultimate strengths of filament- and whisker-containing composites are higher by a factor of two over the composites containing only SiC whisker-reinforcement. Similarly, the WOF values for whisker- and filament-containing

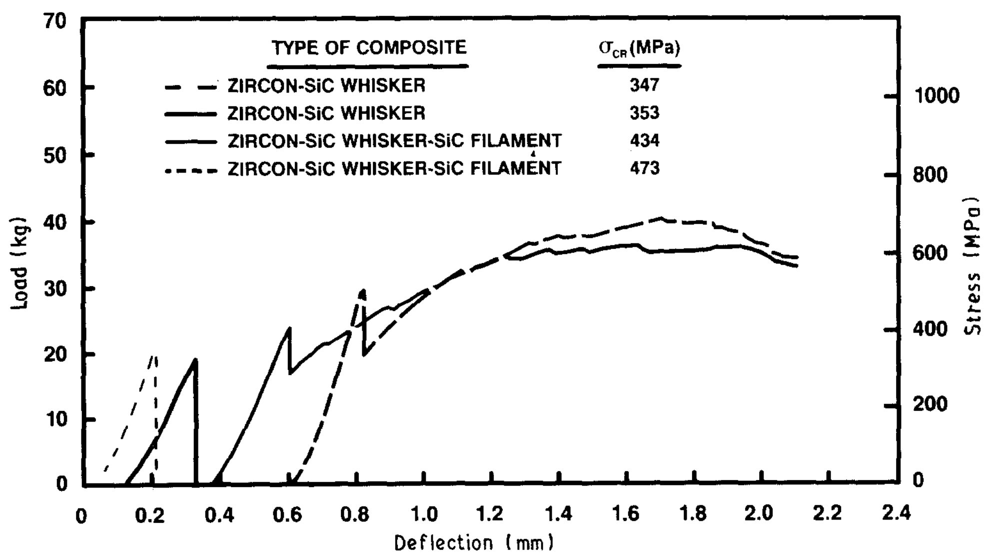

Figure 3 Load-deflection behaviours for zircon composites reinforced with SiC whiskers or with SiC whiskers and filaments.

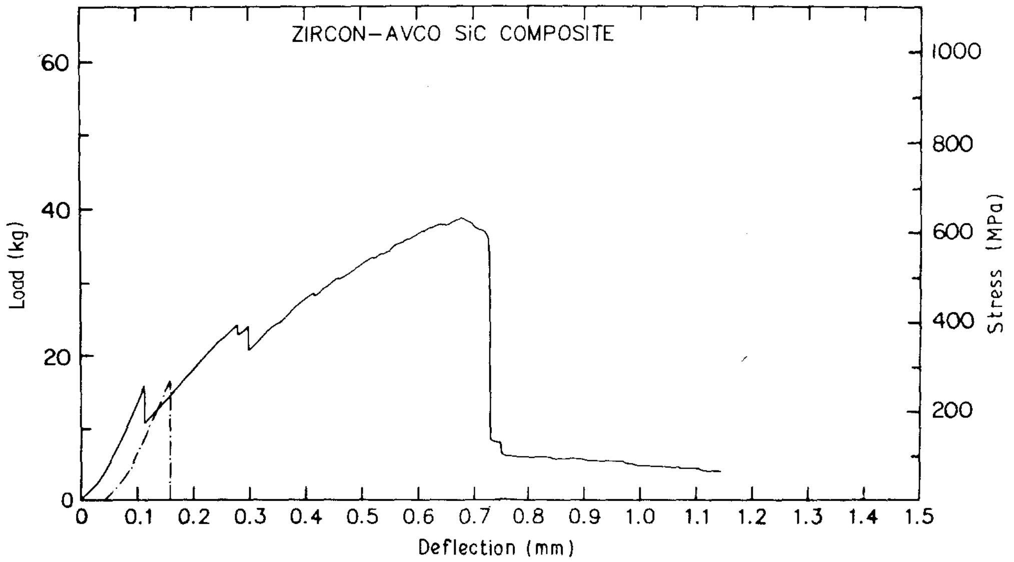

Figure 4 Load-deflection behaviours for a (-·-·) monolithic zircon and (—) zircon composite reinforced with as-supplied SiC monofilaments.

TABLE II A summary of mechanical property data for zircon composites reinforced with SiC whiskers and filaments

Sample No.	Reinforcement	First matrix cracking		Properties at maximum load		Elastic modulus (GPa)	WOF ($kJ\,m^{-2}$)
		Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)		
1	SiC whiskers	347	0.244	347	0.244	142	1.29
2	SiC whiskers	320	0.252	320	0.252	131	1.21
3	SiC whiskers	347	0.207	347	0.207	168	1.14
4	SiC whiskers	353	0.202	353	0.202	174	1.10
1-A	SiC whiskers and filaments	474	0.256	638	1.64	168	33
2-A	SiC whiskers and filaments	434	0.246	657	1.50	176	31
3-A	SiC whiskers and filaments	405	0.206[a]	629	0.90	197	44
4-A	SiC whiskers and filaments	450	0.235[a]	665	1.05	192	32

[a] Measured by a strain gauge attached at the centre of lower support pins.

TABLE III Influence of whisker addition on mechanical and interfacial properties of a monolithic zircon and zircon matrix composites reinforced with SiC filaments

Composite constituents			Average mechanical properties				Average interfacial shear stress	
Matrix	Whisker	Filament	σ_{cr} (MPa)	σ_u (MPa)	E (GPa)	WOF ($kJ\,m^{-2}$)	First push (MPa)	Second push (MPa)
Zircon[a]	–	–	281 ± 88	281 ± 88	195 ± 23	1.2 ± 0.1	–	–
Zircon	SiC	–	342 ± 15	342 ± 15	154 ± 21	1.2 ± 0.1	–	–
Zircon[a]	–	SiC	287 ± 28	700 ± 56	244 ± 6	18 ± 4.2	39 ± 4	16 ± 4
Zircon	SiC	SiC	441 ± 29	647 ± 17	183 ± 14	35 ± 6	4.4 ± 1.8	1.6 ± 0.8

[a] Data from [1].

composites are higher by a factor of 30 in comparison to samples reinforced with whiskers alone. This significant improvement in strength and toughness (WOF) of monolithic zircon occurs because of the reinforcement by continuous filaments.

Table III shows a comparison of mechanical properties of whisker-reinforced composites of this study with those performed earlier [1] on a monolithic zircon and zircon matrix composite reinforced with SiC filaments to study the influence of whisker-reinforcement on mechanical properties. The incorporation of 20% whiskers into a zircon matrix increased its average strength from 281 to 342 MPa. The elastic modulus was decreased from a value of 195 for a monolithic zircon to a value of 154 GPa for the zircon composite containing 20% whiskers. In contrast, the WOF value remained at 1.2 $kJ\,m^{-2}$. Incorporation of SiC filaments into a zircon matrix resulted in an average first matrix cracking strength of 287 MPa, an average ultimate strength of 700 MPa, an average elastic modulus of 244 MPa, and an average WOF of 18 $kJ\,m^{-2}$. The first matrix cracking strength in these composites is similar to the strength of monolithic zircon, but all of the other properties are enhanced as a result of the reinforcement by SiC filaments. The results for composites reinforced with

SiC whiskers and filaments produced an average first matrix cracking strength of 441 MPa, which is higher than the first matrix cracking strength of 287 MPa for composites reinforced with SiC filaments. The ultimate strength of whisker- and filament-reinforced composites is 647 MPa, which is similar (700 MPa) to samples reinforced with SiC filaments alone. An average modulus of 183 GPa for whisker- and filament-reinforced composite is higher than that for the whisker-reinforced zircon composite, but smaller than the average value of 244 GPa for composite samples reinforced with SiC filaments. The average WOF value of 35 kJ m^{-2} for specimens containing SiC whiskers and filaments is twice that of composites reinforced with SiC filaments alone. These results can be explained on the basis of discussions given below.

There is a clear evidence of the enhancement in strength of monolithic zircon as a result of the whisker reinforcement. This whisker-induced strengthening is also carried over into enhanced first matrix cracking strength in samples reinforced with SiC monofilaments. Therefore, whisker reinforcement of a ceramic matrix can be used to enhance ceramic matrix strength and thereby first matrix cracking strength of continuous filament-reinforced composites. It is not clear if this enhancement in matrix strength is a result of the reduced flaw size, the increased failure strain, and/or changes in the elastic modulus of samples. An average failure strain of 0.15% was measured for the monolithic zircon in an earlier study [1]. Zircon composites reinforced with SiC whiskers of this study resulted in an average failure strain of 0.226% (see Table II), which is much higher than the value for a monolithic zircon. The modulus of zircon whisker composite is lower than the modulus of a monolithic zircon, which suggests that the enhancement in strength of whisker-reinforced zircon is the result of increased strain to failure. The increased strain to failure may have come about as a result of the reduced flaw size in whisker-reinforced zircon. The ultimate strength of whisker- and filament-reinforced composites was similar to the strength of the composite reinforced with filaments alone. This behaviour indicates that the ultimate strength of continuous filament-reinforced composite depends on properties of continuous reinforcing filaments rather than on the ultimate mechanical properties of the matrix phase. Such behaviour is not unreasonable because at the point of ultimate strength, the matrix phase is cracked and cannot support much of the imposed load or deflection.

The whisker-reinforced zircon produced lower modulus values than the samples of a monolithic zircon, which is an unexpected result because silicon carbide whiskers have much higher modulus than the zircon. One possible explanation of this behaviour is the decomposition of zircon phase into free zirconia and silica because of high hot-pressing temperature of 1610 °C used in the preparation of whisker-reinforced composites. The X-ray analysis of fully consolidated composites has confirmed the presence of free zirconia. The whisker- and filament-reinforced composites produced higher modulus than the samples reinforced with whisker alone, which is consistent with the high modulus of AVCO SCS-6 monofilaments. Therefore, the results from this study suggest that changes in matrix characteristics can be used to alter composite modulus. In this context, the changes in matrix properties can be achieved either *via* addition of other materials into the matrix phase in most cases or *via* changes in processing conditions in some specific systems.

The WOF increased by a factor of two because of incorporation of silicon carbide whiskers into the filament-reinforced zircon composites. Some of the factors that could have caused this are [11], a decrease in fibre–matrix interfacial shear strength, an increase in filament strength, and an increase in filament diameter. The last two possibilities can easily be ruled out because the filament diameter was not changed and there was no possibility of an increase in filament strength because similar filaments were used in this study as well as those in an earlier study [1]. Therefore, a decrease in interfacial shear strength must have resulted in enhanced WOF for whisker- and filament-reinforced zircon composites. In order to substantiate this, fibre–matrix interfacial shear stress was measured in whisker- and filament-reinforced composites. Table III summarizes these results.

An average interfacial shear strength of 4.4 MPa was obtained for the first push and an average value of 1.6 MPa was measured for the second push in composites reinforced with SiC whiskers and filaments. In contrast, zircon composites reinforced with SiC filaments produced an average value of 39 MPa for the first push and a value of 16 MPa for the second push. The interfacial shear strengths for whisker- and filament-reinforced composites are approximately lower by a factor of 10 in comparison to composites reinforced with filaments alone. The reason for lowered interfacial shear strengths in whisker- and filament-reinforced composites will be the subject of another study [12]. However, these observations are consistent with an increased WOF for whisker-reinforced composites of this study. These behaviours point to the fact that composites with high first matrix cracking strength and high toughness or WOF can be designed by proper tailoring of the matrix strength and the fibre–matrix interfacial shear strength.

The cross-sections of failed composites were examined in an SEM to determine the fibre pullout and the location of fibre–matrix interfacial sliding. Fig. 5a shows fibre pullout in a composite sample containing SiC whiskers and filaments, and Fig. 5b shows the location of the fibre–matrix interfacial sliding to be between the two carbon coatings on AVCO SCS-6 monofilament. This happens because the outer of the two carbon coatings is strongly attached to the zircon matrix containing SiC whiskers. A similar behaviour for the location of interfacial sliding was also observed in composites reinforced with SiC monofilaments [13].

3.3. Comparison with model predictions

The dependence of a number of composite properties, such as the critical stress for first matrix cracking,

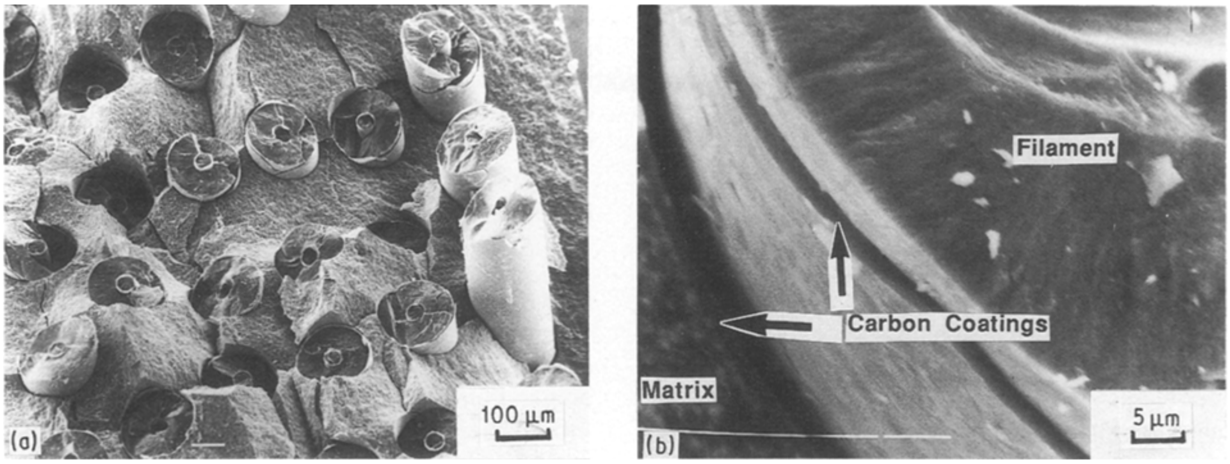

Figure 5 SEM fractographs showing (a) fibre pullout, and (b) fibre-matrix interfacial sliding in a composite reinforced with SiC whiskers and filaments.

WOF, elastic modulus, and ultimate composite strength, on composite parameters, was assessed by comparing the predictions of micromechanics models with the experimentally observed results. Let us first consider the dependence of critical stress σ_{cr} for first matrix cracking on composite parameters as given below and as suggested by Aveston, Cooper and Kelly (ACK) [14]

$$\sigma_{cr} = E[6V_f^2 E_f / V_m E_m E]^{1/3} [\tau\gamma_m / a E_m]^{1/3} \quad (1)$$

where E, E_m, and E_f are moduli of the composite, matrix, and fibre, V_m and V_f are the matrix and fibre volume fractions, τ is the interfacial shear strength, γ_m is the matrix surface energy, and a is the fibre radius. In this model the fibre–matrix interfacial shear stress is assumed to be caused by friction, which is the case for zircon composites of this investigation [15]. A critical stress for first matrix cracking of 89 MPa is calculated for zircon composites reinforced with SiC whiskers and filaments of this study, which is much lower than the experimentally observed value of 441 MPa (see Table III). The values of composite parameters that were used for this calculation were: $E = 183$ GPa, $E_f = 400$ GPa, $E_m = 154$ GPa, $V_f = 0.25$, $V_m = 0.75$, $\tau = 4.4$ MPa, $\gamma_m = 0.04$ kJ m^{-2}, and $a = 70$ µm. This discrepancy between the experimental result and the calculated value of the first matrix cracking stress can be rationalized on the basis of matrix cracking strain. The experimentally observed matrix cracking strain for zircon–SiC whisker composite is 0.226%, which is much higher than the matrix cracking strain of 0.048% (σ_{cr}/E) as calculated from the ACK model. This suggests that in this class of ceramic composites reinforced with SiC monofilaments, the critical matrix cracking stress cannot be enhanced *via* changes in the interfacial properties because interfacial shear strengths higher than the 540 MPa will be needed to make a significant contribution. Such a high value of the interfacial shear stress will most likely result in a brittle composite because of a significant reduction in fibre pullout.

The work of pullout (W_p), which is a measure of composite toughness or WOF, depends on fibre diameter (a), interfacial shear stress (τ), characteristic fibre strength (σ_0), and Weibull parameter (m) as given by Sutcu [11].

$$W_p = (\beta/4)V_f[a^{(m-3)/(m+1)}\sigma_0^{\{2m/(m+1)\}}]/\tau^{(m-1)/(m+1)} \quad (2)$$

This dependence of work of pullout on interfacial shear stress is for composite failure *via* single crack, which suggests that composite toughness should increase with a decrease in interfacial shear stress. This type of dependence is indeed qualitatively shown by zircon composites of this study because a decrease in interfacial shear stress from 39 to 4.4 MPa increased the WOF by a factor of two as given in Table III. The calculated enhancement in WOF based on Equation 2 should be by a factor of about 6, which is much higher than the experimentally observed results.

A rule of mixture was used to calculate the composite modulus of 215 GPa for samples reinforced with SiC whiskers and filaments. This calculated value is higher than the average value of 183 GPa observed for whisker- and filament-reinforced composites. In this calculation, an experimentally observed matrix modulus of 154 GPa, a fibre modulus of 400 GPa, and a filament content of 25% were used. A much better agreement between the calculated modulus and the experimentally observed modulus was observed in an earlier study for zircon composites reinforced with SiC filaments alone [1]. It is not clear if the poor agreement between the calculated and the experimentally observed values for whisker-reinforced composites is a result of the presence of different amounts of the free zirconia and silica phases in the matrix or a result of very low values of the interfacial shear stress.

An ultimate strength of 647 MPa for the whisker-reinforced composite, i.e., the strength at the point of maximum load, is much lower than the calculated strength of 840 MPa. The calculated strength was obtained by multiplying the as-supplied filament strength of 3.36 GPa by the volume fraction 0.25 of the filament because at the point of maximum load the matrix is cracked and as a consequence all the load is carried by the crack-bridging filaments. An explanation of lower composite strength is that the filament strength in the consolidated composite is lower than the as-supplied strength because of the processing-induced damage in filament properties.

4. Conclusions

1. Fully dense zircon composites reinforced with 20% SiC whiskers and 25% SiC monofilaments were fabricated.

2. The strength of a monolithic zircon was increased from 281 to 342 MPa by the addition of SiC whiskers. The whisker reinforcement also increased the critical stress for first matrix cracking in SiC monofilament-reinforced composites. An average critical stress for first matrix cracking of 441 MPa was obtained in composites reinforced with SiC whiskers and filaments. In comparison, composites reinforced with monofilaments alone produced an average matrix cracking strength of 287 MPa.

3. The ultimate strength of composites remained unaffected (between 647 and 700 MPa) as a result of the incorporation of SiC whiskers, which suggested that the ultimate composite strength is controlled by the properties of continuous SiC monofilaments.

4. An average WOF value of 35 $kJ\,m^{-2}$ was obtained for composites reinforced with SiC whiskers and filaments, which is much higher than an average WOF value of 16 $kJ\,m^{-2}$ in composites reinforced with SiC filaments alone. This behaviour was found to be as a result of a lower fibre–matrix interfacial shear strength in whisker and filament reinforced composites.

5. Lower fibre–matrix interfacial shear strengths of 4.4 MPa for the first push and 1.6 MPa for the second push were measured in composites reinforced with SiC whiskers and filaments. In contrast, composites reinforced with only SiC filaments produced much higher interfacial shear strengths of 39 MPa for the first push and 16 MPa for the second push.

6. The results from this study suggested that whisker-reinforcement of the zircon matrix phase can be used to increase first matrix cracking strength in this class of composites reinforced with SiC monofilaments. At the same time, composites with enhanced toughness can also be produced *via* tailored interfacial properties.

Acknowledgements

The author thanks W. A. Morrison for his help in sample fabrication and P. M. Breslin for manuscript preparation.

References

1. R. N. SINGH and A. R. GADDIPATI, *J. Mater. Sci.* in press.
2. R. N. SINGH, *ibid.* in press.
3. *Idem., J. Amer. Ceram. Soc.* **73** (1990) 2399.
4. U.S. Patent No. 4 340 636 (1982).
5. M. SUTCU, *J. Mater. Sci.* **23** (1988) 928.
6. B. BUDIANSKI, J. W. HUTCHINSON and A. G. EVANS, *J. Mech. Phys. Solids* **34** (1986) 167.
7. R. N. SINGH, *Mater. Res. Soc. Symp. Proc.* **120** (1988) 259.
8. M. K. BRUN and R. N. SINGH, *Adv. Ceram. Mater.* **3** (1988) 506.
9. *Idem., J. Amer. Ceram. Soc.* **73** (1990) 2930.
10. C. E. CURTIS and H. G. SOWMAN, *ibid.* **36** (1953) 190.
11. M. SUTCU, *Acta Metall.* **37** (1989) 65.
12. R. N. SINGH, "Influence of Thermophysical Properties on Fibre-Matrix Interfacial Shear Stress in Zircon–Silicon Carbide Composites", in preparation.
13. *Idem., J. Amer. Ceram. Soc.* **72** (1989) 1764.
14. J. AVESTON, G. A. COOPER and A. KELLY, in "Properties of Fibre Composites", Conference Proceedings of the National Physical Laboratory (IPC Science and Technology Press Ltd, Surrey, UK, 1971) pp. 15–26.
15. R. N. SINGH and M. SUTCU, *J. Mater. Sci.* in press.

Received 2 January and accepted 16 May 1990