EFFECT OF TEMPERATURE ON THE TENSILE BEHAVIOUR OF A CAS/SiC CMC

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A set of low strain rate tensile tests have been carried out on test pieces of a continuous fibre ceramic matrix composite (CAS/SiC) at temperatures ranging from room temperature to 900°C. A correlation is established between the more significant tensile properties and the deformation and fracture mechanisms observed in these high temperature tests. A substantial decrease of the fracture stress is observed at 700°C and 900°C. However, up to 500°C, the mechanical behaviour is similar to that observed at room temperature. On the other hand, the fracture strain and strain energy density have a maximum at 500°C. This behaviour is explained as the combined action of two processes: oxidation of the Nicalon fibres and the carbon interface and residual stress relaxation, both induced by the temperature increment.

INTRODUCTION

Continuous fibre ceramic composites (CFCCs) are mainly designed for high temperature structural applications as turbo-engines. However, the use of these materials is limited by their intrinsic variability, prize and potential embrittlement. For this reason, a systematic study of the mechanical reliability of the CFCCs is still required.

The objective of the present work is to analyse the effect of high temperatures on the mechanical behaviour of a Nicalon/CAS CFCC. Apart from the loss of toughness reported at high temperatures, the material variability has been also investigated (Puente et al (1)).

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EXPERIMENTAL ARRANGEMENT

The material used in this study is a commercial CFCC comprising a calcium-aluminium silicate (CAS) matrix, reinforced with Nicalon fibres with a $[(0/90)_3]_s$ "cross-ply" structure. Each test-piece consists of 12 plies, with two 90° plies stacked together in the centre.

The alignment conditions, critical for the tensile test of brittle materials, are reported in previous works (Puente et al. (2)). Thirty six tensile tests have been carried out at temperatures ranging from room temperature to 900°C at 0.0005 s^{-1} in a servo-hydraulic testing machine. Twenty one tests have been carried out at room temperature to determine the material variability. The test-pieces gauge length is 100 mm long, 80 mm wide and 2.3 mm thick. The strain measurements have been carried out by means of a extensometer with a gauge length of 25 mm.

The stress strain data have been treated by means of β-cubic splines for the determination of the elastic modulus, E; the matrix cracking stress, σ_{mc}; and the strain energy density (S.E.D.) obtained from the area under the stress-strain curves.

RESULTS

Mechanical properties

Table 1 shows the mean values and standard deviations of the elastic modulus (E), the matrix cracking stress (σ_{mc}), the strain to fracture (ε_f), the ultimate tensile strength (σ_{UTS}) and the strain energy density (SED) as a function of the test temperature.

TABLE 1. CAS/SiC $[(0/90)_3]_s$. Mechanical properties as a function of temperature.

Temp. (°C)	E (GPa)	σ_{mc} (MPa)	ε_f (%)	σ_{UTS} (MPa)	SED (MJ/m^3)
20	119 ± 6	62 ± 9	0.92 ± 0.14	246 ± 28	1.51 ± 0.31
500	105 ± 10	42 ± 10	1.27 ± 0.73	232 ± 44	2.18 ± 1.45
700	109 ± 14	44 ± 6	0.72 ± 0.28	188 ± 35	0.97 ± 0.46
900	110 ± 12	52 ± 11	0.57 ± 0.08	126 ± 13	0.56 ± 0.08

When the test temperature is increased, the ultimate tensile strength tends to decrease slightly up to 500°C. This tendency is more significant at 700°C and above. (Fig. 1). From these data, it is clear that the strength decrease begins slightly at 500°C, where one of the tests is clearly out of the 95% C.I. for the room temperature tests. This trend increases at 700°C and is complete at 900°C, where all the UTS values are out of the 95% C.I. for room temperature. Plucknett et al. (3) confirm this behaviour on CAS/SiC tested in bending

Additionally, Fig. 2 presents the strain energy density of CAS/SiC as a function of temperature. A maximum is obtained at 500°C, but with a large dispersion of results. A reduction of scattering and a loss of toughness is clearly observed above 700°C. Cain et al (4), and Pluncket et al. (5) have observed a similar behaviour for CAS/SiC in four point bending tests. As observed from this figure, the dispersion of the mechanical properties of CAS/SiC is reduced when the test temperature is increased. Nevertheless, the reduction of scattering occurs with a significant loss of strain to fracture.

Fractography

Fractographic observations have been carried out on the test-pieces whose behaviour was closer to the average. Fig. 3.a. shows the pullout extent and the matrix cracking corresponding to 500°C, 700°C and 900°C respectively. The largest pullout length corresponds to 500°C, that is similar to that observed at room temperature. At 900°C, almost no pullout is observed. This reduction is related to the oxidation of the carbon interface that is very active at 900°C. This process is followed by the formation of strong silica “bridges” that stick the fibre to the matrix. The strong adherence between fibre and matrix inhibits the mechanisms of crack deflexion and crack bridging, responsible for the tough behaviour of CAS/SiC at lower temperatures. Therefore, at 900°C, the mechanical behaviour of CFCC is similar to a monolithic ceramic. This behaviour has been also characterised by means of bending tests by Allen et al. (6). Furthermore, these tests confirm that the debonding energy has a minimum about 400°C.

The evolution of matrix cracking with the test temperature is shown in Fig. 3.b. The matrix cracking density decreases from 500°C to the total absence of cracks observed at 900°C. As the load transfer between fibre and matrix is not possible, the first crack that appears in the material is not arrested by the fibres. Therefore, the typical matrix cracking process is not observed at this temperature.

CONCLUSIONS

The ultimate tensile strength of CAS/SiC CMC is progressively reduced when the temperature is increased. This loss of strength is significant above 700°C, and catastrophic at 900°C. However, the strain to fracture presents a maximum at 500°C. The average pullout length is progressively reduced when the temperature is increased. At 900°C, there is an almost total absence of pullout. The matrix cracking density presents a maximum at 500°C. However, this phenomena disappears at 900°C. There is a correlation between the matrix cracking density and the strain to fracture of the composite. Moreover, the ultimate tensile strength shows a similar behaviour as pullout does.

It is well known that the matrix cracking density is related to the sliding stress between fibre and matrix. At 500°C, the sliding stress is higher than at room temperature, and, as the debonding energy at this temperature is reduced, the matrix cracking density is significantly increased. At higher temperatures, the silica "bridging" increases steeply the bonding between fibre and matrix and the crack deflexion mechanisms are totally inhibited.

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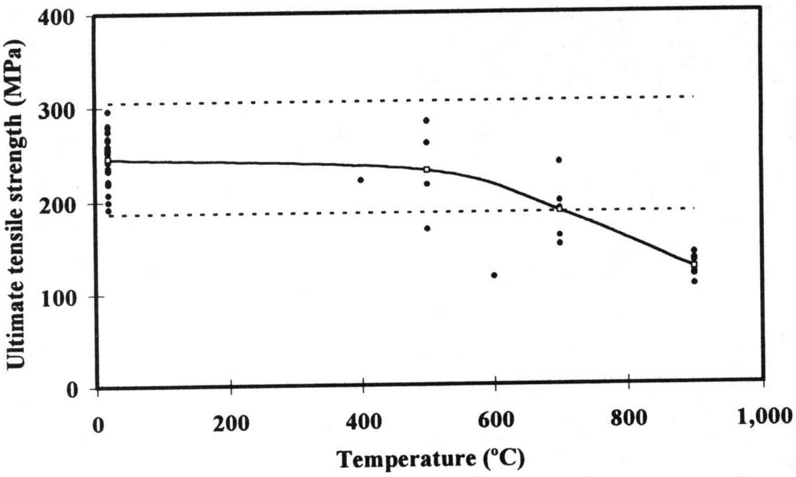

Figure 1. CAS/SiC $[(0/90)_3]_s$. UTS vs. temperature. A β-spline fits the mean values. 95% CI for the population obtained at room temperature are also included.

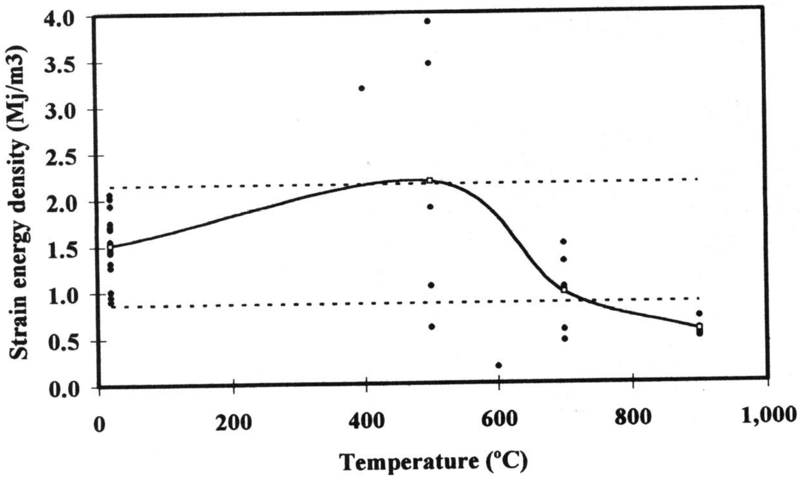

Figure 2. CAS/SiC $[(0/90)_3]_s$. SED vs. temperature. A β-spline fits the mean values 95% CI for the population obtained at room temperature are also included.

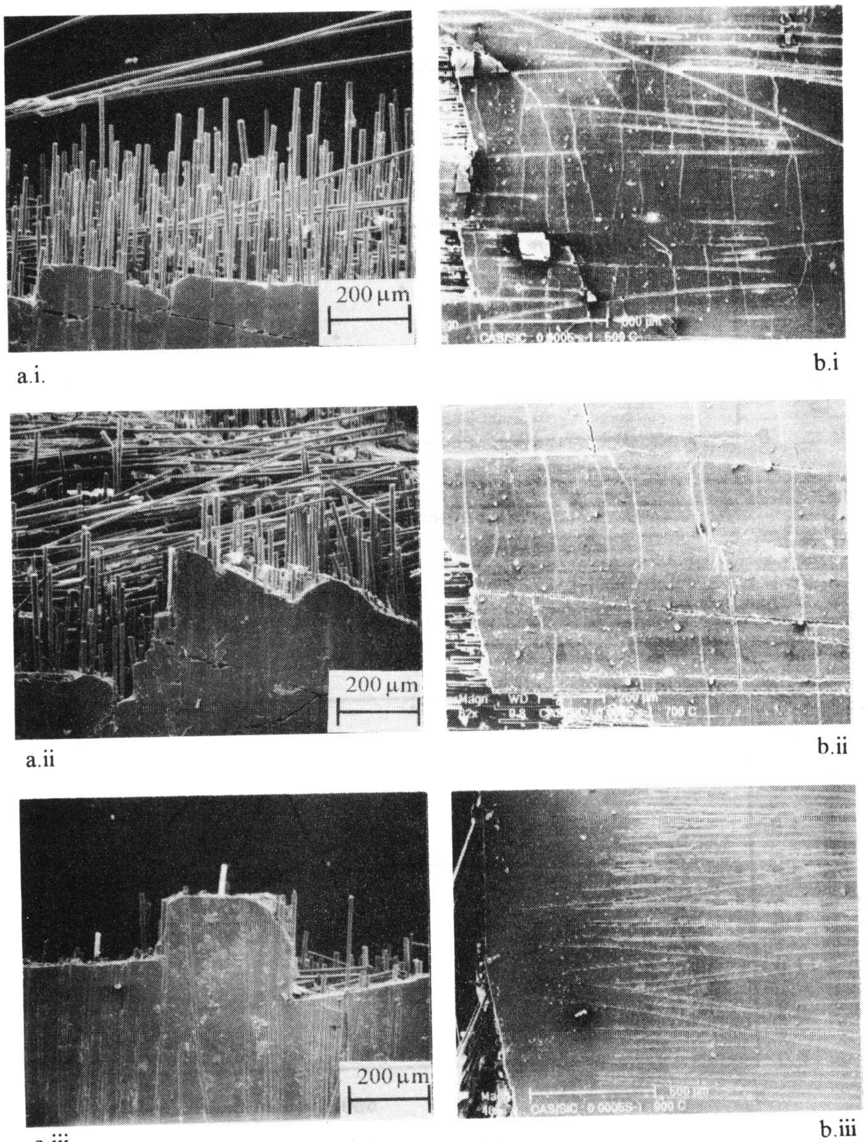

Figure 3. a/ Pullout length at: i/ 500° C, ii/ 700° C and iii/ 900° C.
b/ Matrix cracking spacing at: i/ 500° C, ii/ 700° C and iii/ 900° C.