RELIABILITY ASSESSMENT OF A SIC BASED COMPONENT FOR HIGH TEMPERATURE APPLICATION

E. TRENTINI, A. FINELLI, M. LABANTI & S. SANGIORGI
ENEA, Materials and New Technologies Unit, MAT-ING, CR Faenza, Italy

ABSTRACT

The aim of this work is the description of the experimental tests and the stress analysis activities carried out to assess the reliability of a ceramic component to be used in a High Temperature Heat Exchanger (HTHE).
The development of Externally Fired Combined Cycle (EFCC) for large power generation and combined heat and power production plants is an option to meet future power generation and cogeneration needs, making use of coal and non standard fuels such as biomasses and wastes.
Research activities have been carried out in the last years in the area of design and bench scale testing of the HTHE which is the most critical element of an EFCC and in the area of high temperature materials.
The specific objective is the design, the construction and the experimental testing of a prototype HTHE in a real aggressive hot gas environment in which more than 100 bayonet ceramic tubes will be mounted.
The component on which the activities are focused is a flanged and end capped tube made of SiC based ceramic material (Silicon Carbide infiltrated by metallic Silicon). In working conditions the tube is pressurized with an inner pressure of 10 bar at the temperature of 1300 °C. Material structural and thermomechanical characterisations, FE analysis of the component and the mounting device were performed. Burst tests at room temperature were performed to validate the results obtained by the predicted behaviour of the component in quite real operating conditions. Additional analysis and tests were performed to explain the mismatch between the predicted and the effective burst pressure.

1 INTRODUCTION

The use of ceramics as structural materials is still limited because of their low fracture toughness and low resistance to mechanical and thermal shocks. In order to characterize the mechanical behaviour of a ceramic material to obtain valuable information for designing, the traditional deterministic approach is, therefore, not adequate, while a probabilistic approach is more suitable to ceramic materials.

Further difficulties arise if the components must undergo safety tests, such as the European directive PED [1], which is based on the deterministic theory that the use of a safety factor guarantees reliability of the component.

This work presents a case study of a flanged and end capped tube to be used in a heat exchanger which has to resist an internal pressure of 10 bar at 1300°C. Mechanical tests were carried out both on the components and on specimens of various geometry manufactured from the tubes, to evaluate the influence of the testing method on the strength and the reliability.

2 MATERIAL DESCRIPTION

The tubes are made of sintered SiC infiltrated by metallic silicon at 1450°C, with a final free silicon content of 11%. The material density is 3.1 g/cm^3 and porosity is very low. The microstructure of the material, as the optical micrograph of figure 1 shows, is typical of SiC materials, with allows numerous grains with an elongated shape are present.

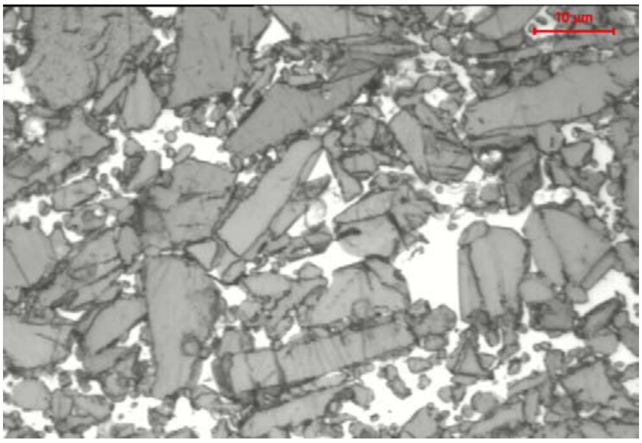

Figure 1: optical micrograph of a polished Si-SiC surface

3 STANDARD MECHANICAL CHARACTERIZATION

A standard mechanical characterization was performed on the material. According to the European standard [2], bar specimens (3 x 4 x 45 mm^3) were manufactured from one of the tubes. The specimens were cut with their longitudinal axis parallel to the longitudinal axis of the tube, due to the limited thickness of the tubes. The bars were polished and chamfered according to the standard. Four-point bending tests were made both at room temperature and at high temperature in order to measure the strength (modulus of rupture, MOR) and Young's modulus [3 - 5] and the results are summarized in table 1 and plotted in the graph in figure 2.

The strength of the material is in good agreement with literature values [Trentini, 6; Wilhelm, 7]: at room temperature the average MOR is 314 MPa, up to 1350°C the strength is higher than at room temperature, reaching a maximum at 1000°C (425-440MPa). Above 1400°C the strength shows a rapid decrease, since the temperature is very close to the melting point of silicon. The fracture behaviour is completely brittle up to 1350°C.

Young's modulus is constant around 340 GPa up to 1000°C, but decreases slowly and drops to 136 GPa at 1400°C.

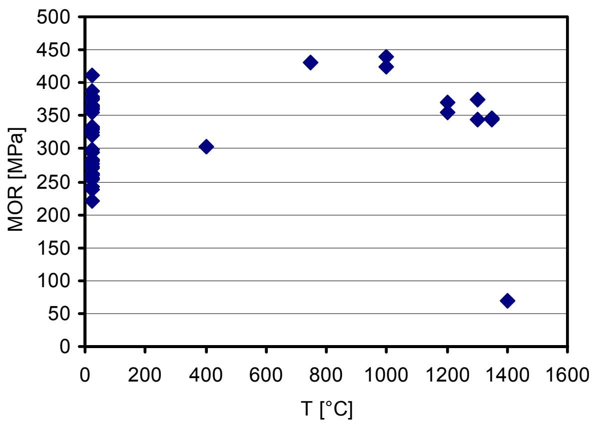

Figure 2: Modulus of Rupture (strength) at room temperature and at high temperature

Table 1: mechanical properties at room temperature and at high temperature

T [°C]	MOR [MPa]	Young's modulus [GPa]
25	314	339
400	302	344
750	431	330
1000	433	334
1200	362	231
1300	360	240
1350	346	211
1400	70	136

A statistical analysis was performed at room temperature, according to the European standard [8]. The Weibull modulus, evaluated by the maximum likelihood method, is 6.7, a good value for a ceramic material with a composite structure. Figure 3 shows the Weibull plot for the material. Since at high temperature the mechanical performance of the material is better than at room temperature, the present statistical analysis is to be considered conservative, if the results are applied at high temperature.

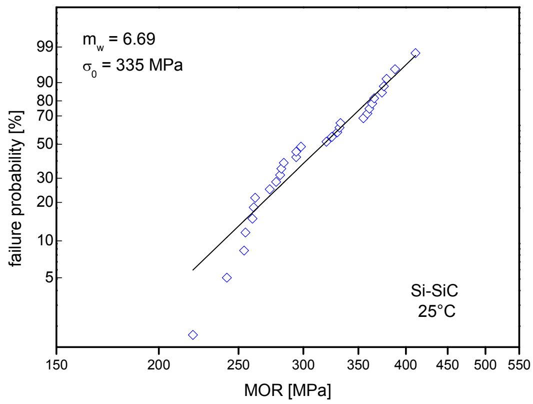

Figure 3: Weibull plot for flexural bars at room temperature

The fracture toughness of the material was measured with the SENVB method, according to the European pre-standard [9]. Four bending bars (3 x 4 x 45 mm^3) were notched and the notch was sharpened with a razor blade and diamond paste. The bars were successively tested in flexure and the fracture toughness was calculated as a function of the bending load and the notch depth. The average fracture toughness is 2.6 $MPam^{1/2}$, a value in good agreement with literature data [Trentini, 6; Wilhelm, 7], but nonetheless a rather low one, which qualifies the material as brittle.

4 STRESS ANALYSIS

A finite element analysis was carried out on the tube, in order to evaluate the stresses in the three main load directions when an internal pressure is applied.

At a pressure of 30 bar the maximum stress is that in the circumferential direction, it reaches 17 MPa. The longitudinal stress is comparable to the circumferential one, reaching about 15 MPa, while the radial stress is much lower and does not exceed 6 MPa. Since the calculated stresses are very low if compared to the flexural strength, it is expected to measure a high burst pressure.

5 BURST TESTS

Burst test were performed on three tubes, in order to evaluate the behaviour of the real component. The tubes were pressurized by means of water, at a rate of 0.5 bar/second.

The average burst pressure is 58.7 bar. The tubes fail in a catastrophic way, breaking into small pieces, so much so that no fracture analysis was possible on the tested specimens.

6 DATA ANALYSIS

The most evident result is that the flexural tests and burst tests give very different strength values. Statistical considerations can partly account for this apparent contrast: in case of flexural tests on small bars the loaded volume is very low and the probability of finding a big critical defect is low, while if a real component is considered, the loaded volume is much greater, therefore resulting in a lower average MOR.

This considered, further compression tests were carried out on C-rings cut from the tubes, according to the European standard [10]. The C-rings have an intermediate loaded volume, in between that of the bars and that of the tubes and the MOR on C-rings was, too, in between that of the bars and of the tubes, as schematized in table 2. A statistical analysis was performed on the C-rings [8]. The Weibull parameters, evaluated by the maximum likelihood method, is 5.6, a lower value than that calculated for the flexural specimens. Figure 4 shows the Weibull plot for C-rings.

Table 2: influence of the kind of test on mechanical properties

kind of sample	MOR [MPa]	loaded volume [cm^3]	Weibull modulus
flexural bar	314	0.24	6.7
C-ring	132	9.8	5.6
tube	35	780	

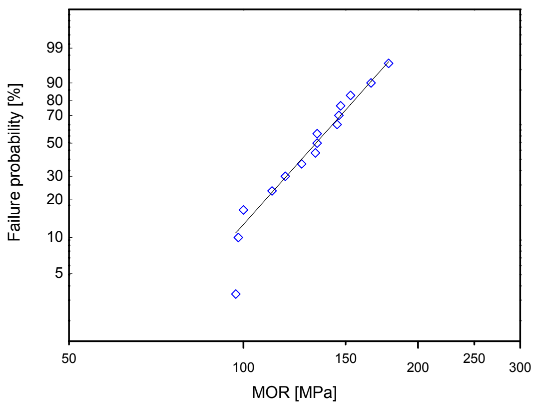

Figure 4: Weibull plot for C-rings at room temperature

Considering that flexural tests give the intrinsic strength of the material independent of possible geometrical weaknesses, the theoretical strength calculated for specimens with a different geometry would be different, proportionally to the loaded volume, as indicated in table 2.

There is still a difference between the theory and the experimental values. The difference can be attributed to factors independent of the material, such as geometric irregularities of the tube, which can be partly or totally eliminated with the machining necessary to manufacture the C-rings and flexural bars.

A more elaborated finite element model was developed, in order to take into consideration the following deviations from the ideal tube geometry: non constant wall thickness, both along the tube axis and in each tube section; conic shape of the tube; curvature of the tube axis. With the new model, the stresses in the pressurized tube are higher than in case of ideal tube with a perfectly regular shape, at the burst pressure (about 60 bar) they reach 40-44 MPa both in the circumferential and longitudinal direction. Figure 5 shows the circumferential stress in a pressurized tube.

Therefore, the geometrical irregularities and the statistical considerations can contribute to explain the low strength values measured in the tubes.

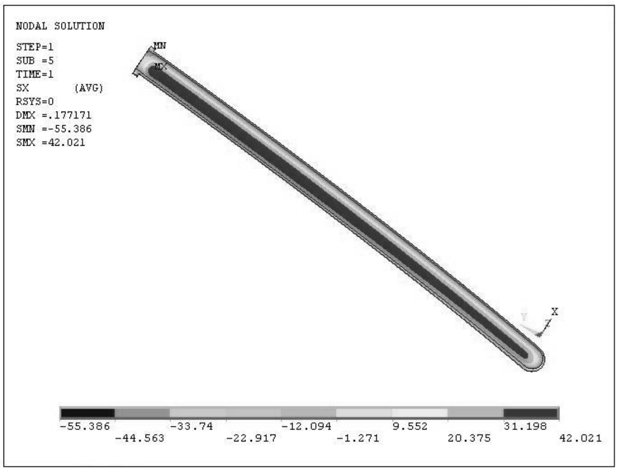

Figure 5: circumferential stress in a tube (with irregularities) pressurized at 60 bar

7 CONCLUSIONS

A mechanical characterization of a ceramic component was made; tests were performed both on the component and on specimens of various geometry manufactured from the tubes. The tests on the tube and finite elements analysis showed a strength of 40 MPa, the strength of C-rings cut from the tubes is higher, with an average value of 132 MPa; the flexural tests on small bars cut in the longitudinal direction gave the best results, with an average MOR of 314 MPa. Statistical consideration can partly explain this difference, as in case of tests on low-volume specimens (flexural bars) the probability of finding a big critical defect is low and the strength consequently higher. A finite element analysis showed that small geometrical irregularities can increase the actual stress in the tube, therefore lowering the burst pressure values.

The results obtained in this work show that the kind of test influences the strength and the reliability, therefore the methodology for reliability assessment needs further investigations and development in order to be fully applicable.

8 REFERENCES

[1] Pressure Equipment Directive 97/23/EC
[2] European standard ENV 843 Advanced technical ceramics – Monolithic ceramics – Mechanical properties at room temperature – Part 1: Determination of flexural strength
[3] European standard ENV 843 Advanced technical ceramics – Monolithic ceramics – Mechanical properties at room temperature – Part 2: Determination of Young's modulus, shear ratio and Poisson's ratio
[4] European standard ENV 820 Advanced technical ceramics – Thermomechanical tests for monolithic ceramics – Part 1: Flexural strength tests at elevated temperature
[5] European standard ENV 820 Advanced technical ceramics – Thermomechanical tests for monolithic ceramics – Part 51: Determination of elastic moduli at elevated temperature
[6] E. Trentini, PhD thesis "Produzione di intagli acuti controllati in materiali fragili", Università di Trento, 2002
[7] Wilhelm M., Werdenich S., Wruss W., "Influence of resin content and compaction pressure on the mechanical properties of SiC-Si composites with sub-micron SiC microstructures", Journal of the European Ceramic Society, 21 (2001) 981-990.
[8] European standard ENV 843 Advanced technical ceramics – Monolithic ceramics – Mechanical properties at room temperature – Part 5: Statistical analysis
[9] European pre-standard prENV 14425-5 Advanced technical ceramics – Fracture toughness – Part 5: Single-Edge-V-Notched-Beam (SENVB) method
[10] European pre-standard prENV 843-X Advanced technical ceramics – Monolithic ceramics – Mechanical properties at room temperature – C-ring tests

9 ACKNOWLEDGEMENTS

The authors would like to thank professor L. Deseri of the Università di Ferrara and Mr. G. D'Elia, A. Malvezzi and G. Pampolini for their contribution to FE analysis and mechanical characterization.