Ceramics International **24** (1998) 579–582

PII: S0272-8842(97)00058-8
0272-8842/98 $19.00+.00

Evaluation of Crack-Growth Resistance Curve for a Particulate Ceramic–Metal Composite

S. M. Barinov & V. Ja. Shevchenko

High Tech Ceramics Research Centre, Russian Academy of Sciences, Ozernaya 48, Moscow, 119361, Russia

(Received 26 February 1997; accepted 14 March 1997)

Abstract: A technique is described to evaluate the crack growth resistance behaviour in brittle ceramic-base materials. In this method, the crack increment measurements during the stable crack propagation process are not required. The crack growth resistance curves are studied for a particulate ceramic–metal composite in the system lanthanium chromite–chromium. Experiments were performed with standard fracture mechanics single-edge notched beam specimens in a temperature range from room temperature up to 1100°C. Effect of temperature on crack growth resistance behaviour is discussed. © 1998 Elsevier Science Limited and Techna S.r.l.

1 INTRODUCTION

Toughening of ceramic-base materials is often associated with the rising crack-growth resistance behaviour and is achieved by utilizing specific microstructures which generate various dissipative processes near the crack tip. A promising way to toughen ceramics is the introduction of metallic particulate constituent into the microstructure of the material. Rising crack propagation resistance, i.e. the increase in current value of the stress intensity factor, K_R, with the crack increment, Δa, occurs if the stable crack growth prior to catastrophic failure is achieved. The rising K_R–Δa curve phenomenon has been studied for various brittle materials. For ceramics, recent data are summarised in Ref. 1.

Generally, to evaluate the crack growth resistance, the experiments with long cracks in standard testing geometries of fracture mechanics specimens have been performed. Excepting for coarse-grained alumina and some fiber- or whisker-reinforced ceramic–matrix composites, the stable crack increments in specimens of standard single-edge notched beam (SENB) configuration are usually less than 1 mm. To measure the crack increments, the loading–unloading procedures must periodically be performed to estimate Δa values using known crack increment–specimens compliance relationship.[2–4] Because of the low stable crack extension, these procedures are difficult to realize in practice for various ceramic-base materials. Moreover, the observed loading–unloading hysteresis affects the correct compliance choice. These are the main disadvantages of the experiments with K_R–Δa curves. Therefore, a technique is needed which could allow to evaluate the stable crack increments in a different manner. The present work is aimed to demonstrate an approach based on the compliance fracture mechanics method, and to investigate slow crack propagation in a ceramic–metal composite in the system lanthanium chromite–chromium.

2 METHOD

According to Ref. 5, the relation between non-dimensional load P^* and non-dimensional displacement under the load u^* for the standard SENB-configuration fracture mechanics specimen can be calculated as follows

$$P^* = 0.00114u^*(1-2a^*)^2/[(1-1.85a^*)^2+0.0013u^{*2}]^{1/2} \quad (1)$$

where $P^* = P/\sigma_y W^2$; $u^* = Eu/\sigma_y W$; $a^* = (a - a_0)/W$; P is the load; σ_y is the yield stress; E is the modulus of elasticity; u is displacement, and a_0 is the length of initial notch. Equation (1) assumes plane strain condition. A common K-calibration procedure has been used for the small-yielding part, as well as a finite element calculation for the non-linear part to obtain this equation[5]. If the dimensionless displacement is small, $0.0013u^{*2} << (1 - 1.85a^*)^2$, so eqn (1) can be simplified as follows:

$$P/EW \simeq 0.00114u(1 - 2a^*)^2/(1 - 1.85a^*) \qquad (2)$$

This expression allows us to calculate the stable crack growth increments using the load–displacement diagram. The procedure is as follows. The first step is calculation of the P/EW ratio vs a^* using eqn (2) with the varying value of u as a parameter. Then, using the experimental $P - u$ diagram, and the above dependencies for $a^* = 0$ (point of deviation from the linear-elastic behaviour), the value of $1/EW$ can be estimated. After that, the values of dimensionless crack increment a^* can easily be evaluated for a certain load-point displacement u by means of the calculated relationships.

The current value of the stress intensity factor K_R is calculated using current load, with corrections for the crack increment:

$$K_R = 1.5YPL(a_0 + \Delta_a)^{1/2}/BW^2 \qquad (3)$$

where L is span; B is the specimen thickness, and $Y = Y(a_0 + \Delta_a)$ is a common K-calibration polynomal given in Ref. 6.

Validity of eqn (1) has been proved by testing of several metallic alloys,[5] so there was no reason to investigate this equation. However, to verify the validity of the assumption which has been made to simplify eqn (1), the values in square brackets were compared. It was estimated that the second term is much less than the first one at the limiting experimental values of $a^* = 0.26$ and $u^* = 5.10^{-4}E/\sigma_y W$, even if ratio E/σ_y is in the range of 10^2–10^3. Moreover, the unloading curves went approximately through the origins. Therefore, the contribution of the plastic component to the total non-linear strain is assumed to be small.

3 EXPERIMENTAL DETAILS

Experiments were performed with the specimens of the ceramic-metal composite 60 wt% $LaCrO_3$–40 wt% Cr.[7,8] This material has been considered as a candidate for high-temperature applications, e.g. for electrodes and heaters, in heat–power installations. Because of severe thermal environments, the reliability of the ceramic-metal composite depends strongly on the crack propagation resistance.

The specimens of the material were made using powder mixtures of chromium with particle size 1–20 μm and lanthanium chromite with average particle size 20 μm. The mixtures were explosive compacted followed by sintering. Details of the preparation route were described elsewhere.[8] The density of the sintered material was about 96% of theoretical. X-ray diffraction studies showed substantial broadening of both chromium and lanthanium chromite diffraction lines confirming the structural fragmentation and/or high level of residual stress resulting from the explosive treatment.

The geometry of the standard configuration SENB-type specimens for testing was $B \times W \times l = 4 \times 6 \times 40\,mm^3$. A thin side notch was machined with a diamond saw-cut wheel. Depth of the notch was 0.5 W, the measured tip curvature radius was about 50 μm. The specimens were loaded by 3-point bending at a span of 24 mm in a furnace filled with argon, using a stiff screw-drived testing machine. The cross-head speed was $8.10^{-6}\,m\,s^{-1}$. The testing temperatures were 20, 700 and 1100°C.

4 RESULTS AND DISCUSSION

Figure 1 shows the load–load-point displacement diagrams for the specimens tested at different

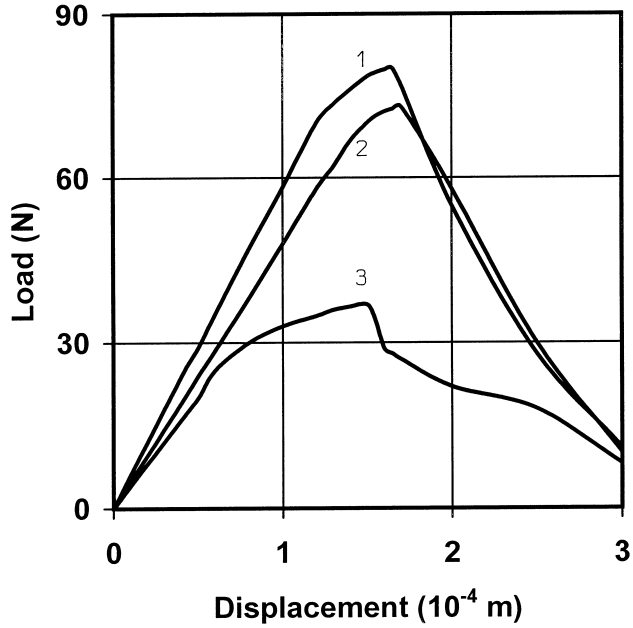

Fig. 1. Load-displacement curves of SENB-type specimens of lanthanium chromite–chrome composite. Testing temperatures: 1—20, 2—700, 3—1100°C.

temperatures. Non-linear deformation occurs even at room temperature. With an increase of the testing temperature to above 700°C the non-linear deformation increases. Because of the inherent brittleness of both chromium and lanthanium chromite constituents of the composite, it can be supposed that the non-linearity is due to the slow crack growth phenomenon as a result of various dissipative processes near the crack tip, e.g. microcracking, crack branching, or bridging in a wake-zone.

Estimated values of the critical stress intensity factor at initiation of the crack propagation from the notch tip were 3.20, 3.04 and 0.91 MPa $m^{1/2}$ for the specimens tested at 20, 700 and 1100°C, respectively. Therefore, the degree of the brittleness of the composites is very high, even at elevated temperature.

Shown in Fig. 2 are the K_R vs dimensionless crack increment, a, curves for the specimens tested. The crack growth resistance increases monotonously with crack increment. It can be noted that deformation of the specimen after a peak in load has been achieved did not result in an decrease of crack growth resistance. During the stable crack propagation, the about two-fold K_R increase can be revealed at the relative crack increment less than 0.2.

The rising K_R-curve behaviour in the ceramic-metal particulate composites can be attributed to both the screening action of the wake microcracking zone and the crack bridging by metallic and/or ceramic grains.[9] During the cooling of the composite from sintering temperature, tensile tangential stresses are developed due to the difference in the thermal expansion coefficients and elastic properties of the components. These stresses, being imposed on interfaces, promote the microcracking process during the stable crack propagation. The higher the residual stress level, the greater the tendency of the composite material to grain-boundary microcracking. The explosive treatment promotes these stresses, as shown by the X-ray diffraction measurements data, at least qualitatively.

Shown in Fig. 3 are the temperature dependences of the values of the stress intensity factor at the very start of the crack, K_{R0}, and at maximum load on the load–displacement diagrams, K_{Rm}. Obviously, the toughening increment diminishes with an increase in testing temperature above 700°C. The reason is assumed to be in the lowering of the residual stress level due to the annealing of the composite material at the testing temperature. These data can be considered to confirm indirectly an assumption that the microcracking rather than plastic crack bridging gives the major contribution to the rising K_R-curve behaviour. In the case of the crack bridging, an increase in testing temperature should result in enhancement of $K_{Rm}-K_{Ro}$ value, just because the plastic deformation of chromium rises with temperature. An additional argument for this conclusion is the absence of the plasticity of chromium at room temperature.[10]

Thus, the described method allows to study the crack propagation resistance curve in a simple way and for small crack increments, when the indirect crack length measurements are difficult to perform. The method can be recommended for experimental purposes, but detailed comparison of the results with the data obtained by more common methods should be carried out in future.

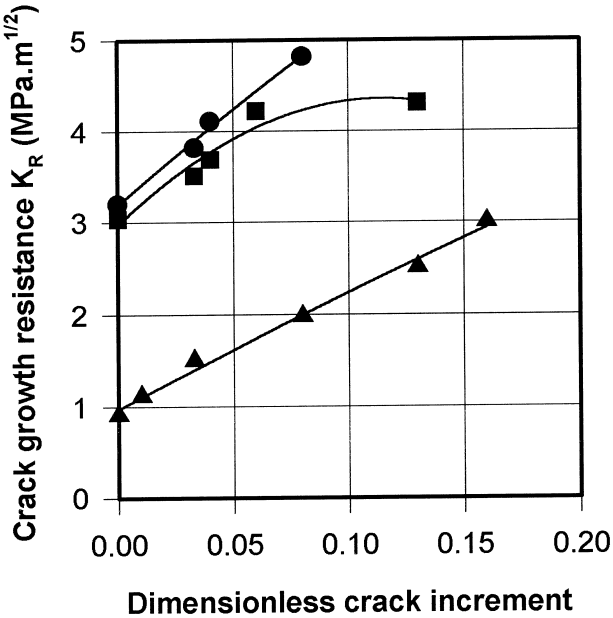

Fig. 2. K_R vs a curves for the specimens tested at 20°C (●), 700°C (■) and 1100°C (▲).

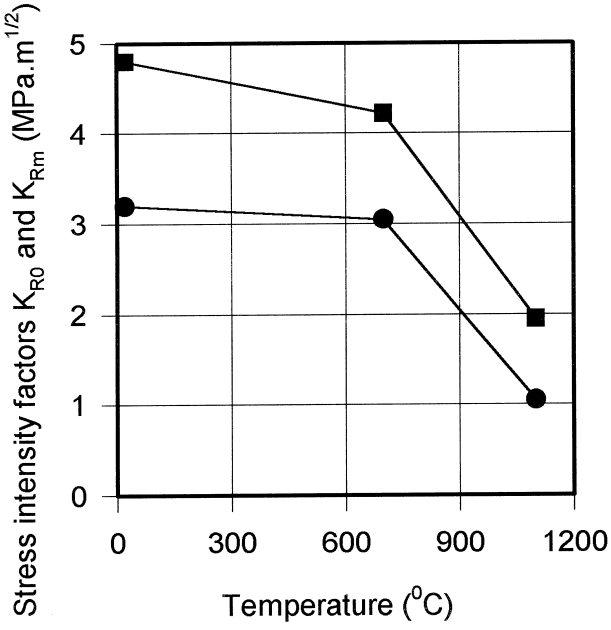

Fig. 3. Effect of testing temperature on the stress intensity factor at the crack initiation from the notch tip, K_{Ro}, (●) and at the peak load on the load-displacement diagram, K_{Rm}, (■).

5 CONCLUSION

A technique is described to study the rising crack growth resistance behaviour in brittle ceramic-matrix composites. The method is very simple and no loading–unloading procedure is required to estimate the crack increments. The stress intensity factor, K_R, vs crack increment curves are investigated for a high-temperature ceramic–metal composite in the system lanthanium chromite–chromium. The toughening and the slow crack growth processes are demonstrated for this material over a wide temperature range. It is suggested that microcracking rather than plastic crack bridging in a crack-tip wake zone gives the main contribution to the rising crack-growth resistance behaviour in these ceramic–metal particulate composite. The toughening increment diminishes with an increase in testing temperature, probably due to the annealing of residual stress which promotes the microcracking process.

ACKNOWLEDGEMENT

The author would like to thank Dr V. S. Ivanov for his help in specimen preparation.

REFERENCES

1. STEINBRECH, R. W., R-curve behavior of ceramics. In *Fracture Mechanics of Ceramics, Vol. 9*, ed. R. C. Bradt, D. P. H. Hasselman, D. Munz, M. Sakai and V. Shevchenko. Plenum, N.Y., 1992, pp. 187–208.
2. MARKOCHEV, V. M. & MOROZOV, E. M., The work-of-fracture and the plastic strain work in fracture toughness testing. *Phys. Chem. Mechanics of Materials (USSR)*, **N5** (1980) 66–70.
3. MARKOCHEV, V. M. & MOROZOV, E. M., Energy relations at deformation of a crack-containing specimen. *Strength Problems (USSR)*, **N6** (1978) 71–74.
4. SAKAI, M., URASHIMA, K. & INAGAKI, M., Energy principle of elastic-plastic fracture and its application to the fracture mechanics of a polycrystalline graphite. *J. Am. Ceram. Soc.*, **66** (1983) 688–694.
5. BROBERG, K. B., On stable crack growth. *J. Mech. Phys. Solids*, **23** (1975) 215–233.
6. SRAWLEY, J. E., Plain-stain fracture toughness. In *Fracture,* Vol. 4 ed. H. Liebowitz. Mashinostroyenie, Moscow, 1974, pp. 47–67.
7. KRASULIN, Yu. L., BARINOV, S. M. & IVANOV, V. S., Interparticle welding, mechanical properties and fracture resistance of $LaCrO_3$–Cr cermet. *J. Mater. Sci.*, **21** (1986) 3901–3906.
8. KRASULIN, Yu.L., BARINOV, S. M. & IVANOV, V. S., Structure and fracture of powder metallurgy refractory materials. *Science*, (1985) 78–160.
9. EVANS, A. G., Perspective on the development of high-toughness ceramics. *J. Am. Ceram. Soc.*, **73** (1990) 187–201.
10. TREFILOV, V. I., MILMAN, Yu. V. & FIRSTOV, S. A., *Physics of Strength of Refractory Metals*. Naukova dumka, Kiev, 1975, pp. 14–60.