High Temperature Spalling of Alumina Bars

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J. PHYS IV FRANCE 7 (1997)
Colloque C3, Supplément au Journal de Physique III d'août 1997

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Abstract: Spalling experiments with alumina bars performed at temperatures up to 1500°C have been conducted in a new apparatus. A cylindrical uninstrumented specimen is located in an open-end furnace and dynamically loaded in tension by the reflection of a compressive pulse from its free end. A bridging piece of the same impedance covers the transition zone between the measuring rod and the specimen, which is positioned in the homogeneous part of the thermal field within the furnace. The data acquisition consists of the measuring of the incoming and reflected pulses in the transmitter, the temperature distribution in the furnace, and the positions of the spalling sites in the specimen. The evaluation procedure takes into account the high-temperature corrections, due to temperature-induced drop in the wave velocity and impedance of the bridging piece. This results in the change of the dispersion and the shape of the pulse. The results of the experiments show that the strength drop with the temperature growing up to 1500°C.

Résumé : Des expériences de rupture dynamique de barres d'alumine effectuées à des températures jusqu'à 1500°C ont été conduites à l'aide d'un nouvel appareil. L'éprouvette cylindrique est placée dans un fourneau et est chargée dynamiquement sous tension par la réflexion d'une impulsion de compression. L'acquisition des caractéristiques consiste d'une part en le calcul des impulsions transmises et réfléchies dans le transmetteur et la distribution de la température dans le fourneau, d'autre part en la mesure des positions des sites de rupture dynamique dans l'éprouvette. La procédure d'évaluation comprend les corrections pour de très hautes températures, à cause du changement thermique qui affecte la vitesse des ondes et l'impédance des connexions. Par conséquent, la dispersion et la forme de l'impulsion sont modifiées. Les résultats expérimentaux montrent que la résistance diminue simultanément avec l'augmentation de la température jusqu'à 1500°C.

1 INTRODUCTION

A brief account is given on the results of an extensive series of spalling tests with alumina ceramic bars at temperature up to 1500°C, conducted with a new experimental set-up. The apparatus has been developed specifically for dynamic testing of high performance ceramics. Numerous tests of the same kind of ceramic bars had been conducted earlier at room temperature [1]. The results showed a substantial dependence of the spalling strength on the specimen's diameter. They indicated also at a different mechanism of energy consumption at dynamic failure, as compared with that of a single crack resistance energy measurements at static loads [2]. The results presented here show a clear dependence of the spall strength on the temperature in the whole investigated range, complementing and improving thus the earlier observations [3], due to an improved evaluation procedure.

2 EXPERIMENTAL ARRANGEMENT

For the purpose of dynamic tensile testing of ceramics, the typical SHPB pulse initiation and gauging arrangements have been combined with the spalling principle, as applied to uninstrumented slender cylindrical specimens, Figure 1. The evaluation procedure consists in the computation of the transient stress pulse in the specimen, Figure 2. It is based on the measurements of the initiated and reflected pulses in the transmitter bar, taking into account the geometrical dispersion of the wave-trains as they travel along substantial distances. Impedance relations at the interfaces of the bars are involved.

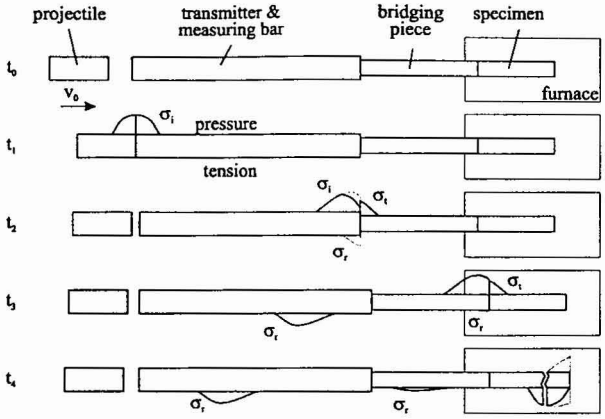

Figure 1: Experimental arrangement

A special procedure has been developed to distinguish between the primary and the secondary spalling sites [4]. The knowledge of the primary spall location enables the determination of the stress at the spall. Due to the negligible fracture delay time in the tested alumina ceramics, the latter quantity can be further defined as the spalling strength of the specimen.

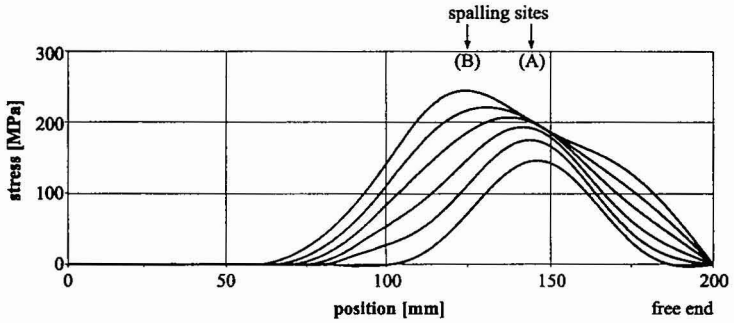

Figure 2: Resulting transient pulses in the specimen, in a time-step sequence 0.5 μs

All these procedures have been successfully tested at the room temperature [4]. The results on the dependence of the strength on the size of the specimen have been obtained in long series of experiments, exhibiting at the same time the advantages of the testing arrangement: low experimental scatter, low costs of conducting serial tests, easy handling of brittle specimens of ceramics.

The main advantage of the arrangement, however, is related to its adaptability to dynamic testing of ceramics at elevated temperatures. Applied to specimens located within an open-end furnace, Figure 3, the arrangement includes a bridging piece of the same material and diameter as the specimen itself. It is placed into the thermal transition zone, and serves the bridging of the inhomogeneous temperature field at the entrance of the furnace. The specimen itself is positioned in the area of homogeneous temperature distribution. The typical distribution in the unit, Figure 3, has as a consequence a variable wave velocity field in the transition region, due to thermal expansion and thermal dependence of elasticity moduli of the ceramics.

In order to determine the dependence of the wave velocity on the temperature, auxiliary tests have been conducted with long rods of the tested material. They were subsequently positioned in two different predetermined locations within the furnace, Figure 4. Gauging the pulse propagation times at reflections from the hot free end of the rods enabled a relatively easy determination of the effective wave velocity at single chosen temperature levels, Figure 5.

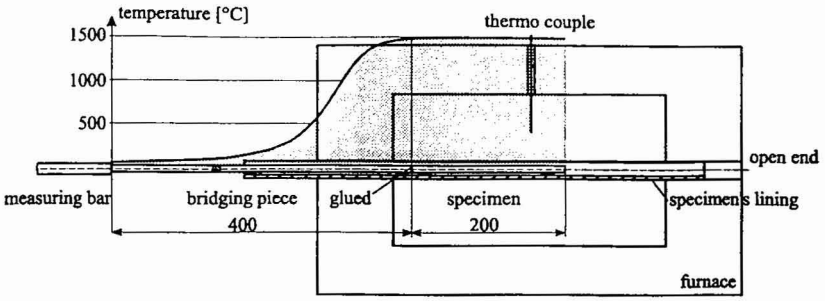

Figure 3: Experimental set-up and the temperature distribution in the unit bridging piece - specimen

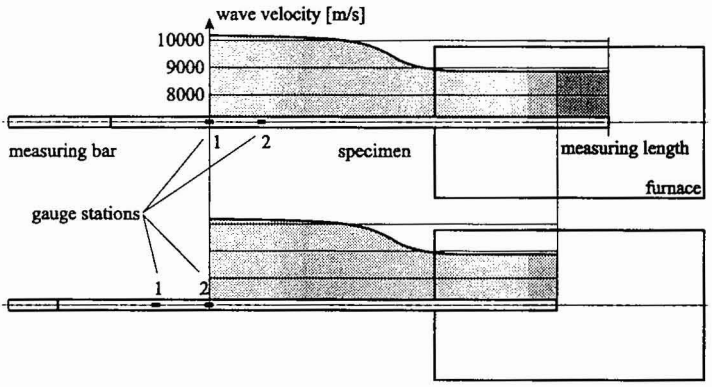

Figure 4: Measurement of the wave velocity at elevated temperatures

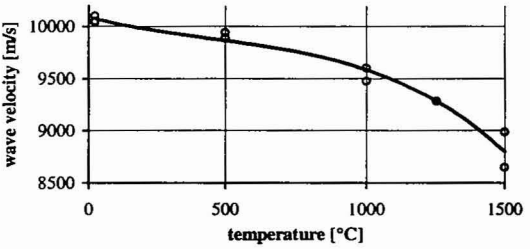

Figure 5: Temperature dependence of the wave velocity

3 EVALUATION PROCEDURE

Complementary to the evaluation procedure for spalling strength at the room temperature [4], three additional effects related to the elevated temperatures' influence on the stress pulse propagation in the specimen need to be taken into account.

1) The drop in the wave speed c_0 with the temperature leads to a shortening of the pulse length thus changing the resulting stress distribution after the free-end-reflection, Figure 6.
2) The change of the wave speed and the shift towards the short-wave spectrum in the Fourier decomposition of the stress pulse leads to an amplification of the geometrical dispersion effects in the bridging piece and the specimen: At a given radius R of the cylindrical bar, any Fourier component of the pulse with a wave length λ will get shifted along the dispersion curve towards lower phase velocities c_λ and higher R/λ ratios, Figure 7.
3) Density ρ, cross-section area A and wave speed c change at increasing temperature what results in decreasing bar impedances of the bridging piece, Figure 8.

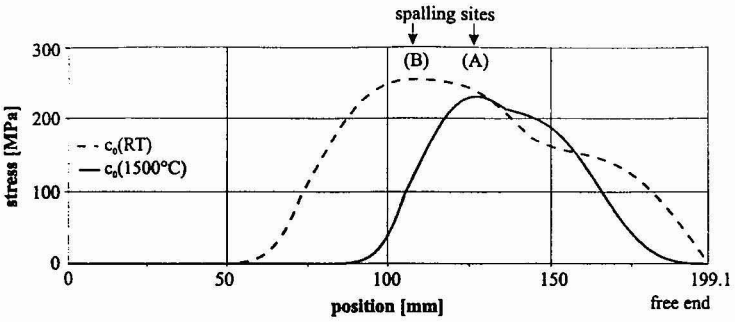

Figure 6: Influence of the decreasing wave velocity on the stress distribution in the specimen

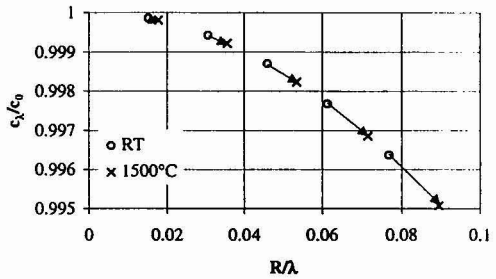

Figure 7: Influence of the wave velocity on the geometrical dispersion of the pulse

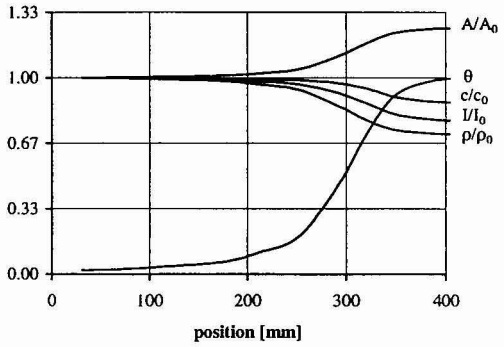

Figure 8: Temperature distribution in the bridging piece and its influence on cross section area, wave velocity, density and bar impedance

The consequence of it is an incremental pulse-matching procedure at each step of the simulation of the stress pulse propagation: the incident stress σ_i and the reflected pulse σ_i^r within the i-th distance increment have to be matched by means of the force balance and mass velocity compatibility conditions with the pulse σ_{i+1} transmitted into the (i+1)-st distance increment, Figure 9. The method of characteristics is applied then in the evaluation of the rather complicated wave pattern, Figure 10, featuring curvilinear wave fronts in the diagram position x versus time t. For the measured temperature distribution in the bridging piece one gets at 1500°C temperature in the furnace a transmission into the specimen of some 89 % of the initial pulse amplitude. The amplitude of the primary reflection makes 7 % of the initial pulse amplitude although due to the pulse length extension it carries some 11 % of the initial pulse energy with. The secondary reflections are practically negligible, carrying some 0.3 % of the stress amplitude, i.e. remaining within the experimental error.

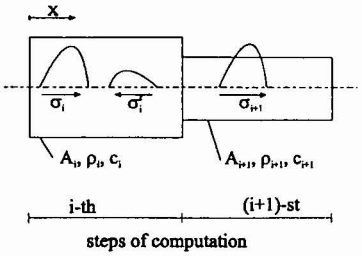

Figure 9: Partial reflection at an element boundary

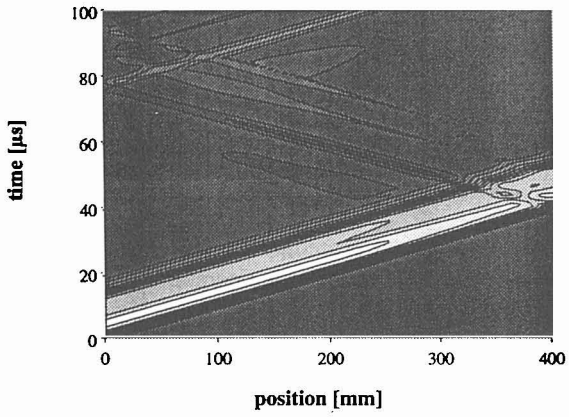

Figure 10: Superposition of the transmitted, the reflected and the secondary reflected part of the pulse at 1500°C

4 EXPERIMENTAL RESULTS

Commercial alumina bars of diameter 8 mm and length 200 mm have been tested in the whole range between the room temperature and 1500°C. The tests at the room temperature were conducted within the cold furnace, in order to check the compatibility of the results with those at the room temperature in the former experimental arrangement [4]. Two test series have been conducted, the first with altogether 28 specimens, and the second with 35 specimens tested at temperatures between 700°C and 1500°C.

The results of the first series were reported [5] [6], and treated as preliminary ones, fully proving the applicability of the experimental method to the testing at elevated temperatures and its compatibility with the results at room temperature. The results of the second series presented here, Table 1, concern the accuracy of the spalling strength determination also. Each temperature point has been tested in 4 to 8 shots in order to enable the determination of the experimental scatter of the method. The scatter varies between 3 % and 11 % of the mean value of the strength. Compared to the room temperature tests [4] no increase of the scatter has been observed at elevated temperature experiments.

Table 1: Experimental results

temperature [°C]	700	1000	1200	1400	1500
no. of specimens	5	4	8	4	4
mean strength [MPa]	268	236	223	250	225
scatter [MPa]	16	12	24	7	25
scatter [%]	6	5	11	3	11

One observes a continuous decay of the mean spalling strength with the increase of the temperature up to 1500°C. The decay is substantially stronger than anticipated in the preliminary series [4], where no pulse-matching procedure had been applied in the evaluation. The results also extend the earlier

observations [5] [6], and enable to introduce a linear spalling strength dependence on the temperature. Figure 11.

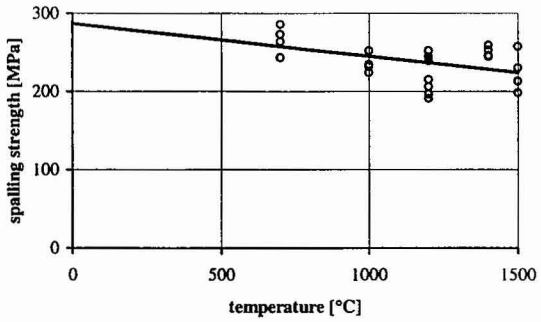

Figure 11: Experimental results for specimens with full cross-section, 8 mm diameter

5 CONCLUSION

The new experimental set-up and evaluation procedure enable very efficient determination of strength parameters in spalling of ceramics at a wide range of temperatures, combining low costs with relatively high accuracy of the results.

6 ACKNOWLEDGEMENTS

The work presented here has been performed in relation with the DFG project Na218/1-2 on dynamic testing of high performance ceramics. The financial support of the German Research Foundation (DFG) is hereby gratefully acknowledged. Mr. C. Schrott's co-operation has been of great help in conducting the experiments.

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