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Spalling fracture experiments with ceramic bars at elevated temperatures

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SPALLING EXPERIMENTS with alumina bars at temperatures up to 1500°C have been conducted in a new testing apparatus. A slender uninstrumented specimen is loaded by a compressive pulse reflected from its free end. A bridging piece is placed into the transition zone between the instrumented wave-transmitter and the specimen within the furnace. High-temperature corrections are taking into account the drop in the wave velocity and the continuous drop of the impedance in the bridging piece, which results in the incremental reflections of the pulse. The results of the experiments indicate that the decay of the strength with the increase of the temperature up to 1500°C is much stronger than that anticipated in preliminary tests. The observations can be interpreted within a continuum damage model.

1. Introduction

SPALLING EXPERIMENTS with alumina bars performed at elevated temperatures up to 1500°C have been conducted in a new testing apparatus. A description of the measuring and evaluation technique for high temperatures is given in the paper.

A slender cylindrical uninstrumented specimen located in an open-end furnace is loaded by the reflection of a compressive pulse of sufficient amplitude from its free end. A bridging piece is placed in the transition zone between the instrumented wave-transmitter (measuring rod) and the specimen, the latter being located in the homogeneous part of the thermal field within the furnace.

The data acquisition consists in measuring 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 is based on the corresponding one for the room temperature. High-temperature corrections are taking into account two kinds of effects: the drop in the wave velocity, which changes the pulse length, and the continuous drop of the impedance in the bridging piece resulting in incremental reflections of the pulse.

2. Experimental arrangement

The set-up combines the principles of pulse initiation and its measurement, typical for split Hopkinson pressure bar, with the spalling phenomenon at tensile dynamic loading, due to the reflections of a compressive stress wave from specimen's free end. The compressive pulse is introduced into the transmitter bar by projectile impact, Fig. 1. It is registered at gauge stations of the measuring bar

and stored. The same happens to the reflected pulse in the bar resulting from the difference of the impedances between the transmitter and the specimen. The transmitted compressive pulse propagates in the specimen, causing basically no material damage. Upon its arrival at the specimen's free end, it gets reflected as a tensile pulse and superposed upon the still arriving compressive tail.

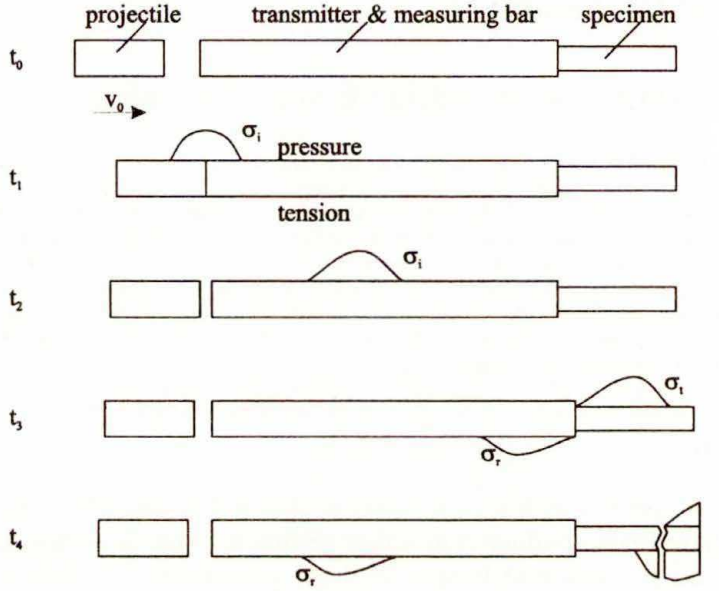

FIG. 1. Experimental arrangement.

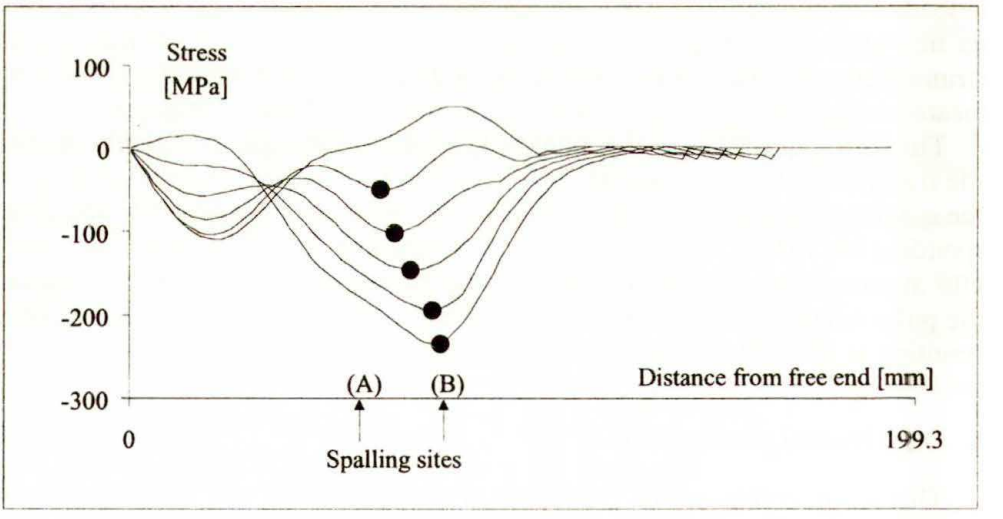

FIG. 2. Resulting transient pulses in the specimen, in a time-step sequence of 0.5μs.

The resulting stress distribution leads to tensile stresses fast growing in time at some distance from the free end. Wherever the peak value of the resulting stress

distribution reaches the level of the tensile strength of the material, spalling develops immediately due to the negligible fracture activation delay in ceramics. By comparing the sites of spall with the evolution of the stress distribution maxima, the spalling strength and the primary site are determined uniquely, Fig. 2.

3. High temperature arrangement

Having in mind applications of ceramics at thermal exposures, experiments have been conducted at elevated temperatures. The specimen is placed in an open-end furnace placed along the axis of the set-up, Fig. 3. The furnace with 204 mm diameter and 356 mm length of the heating area makes possible to conduct the experiments up to 1500°C. The specimen must be shorter than the length of the furnace in order to be placed in its internal homogeneous temperature field. On the other hand, the measuring bar must not reach into the area of elevated temperature due to its limited resistance to thermal load and limited temperature range of application of the strain gauges.

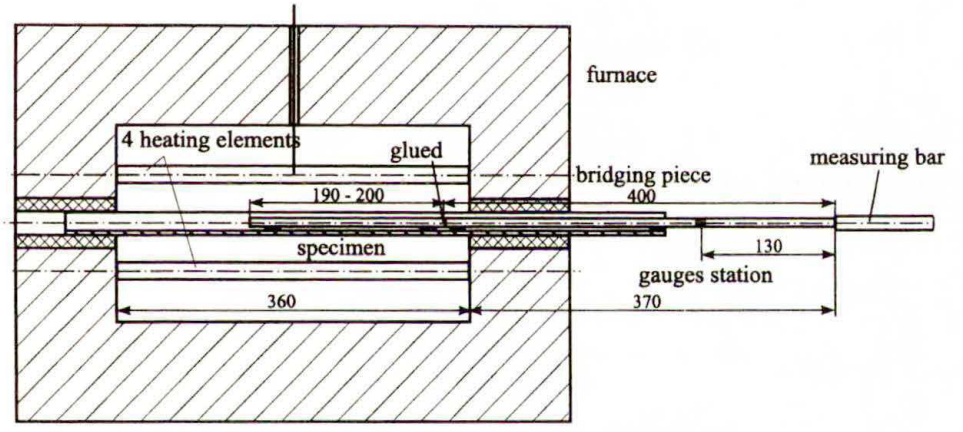

FIG. 3. Experimental set-up at elevated temperatures.

An extension piece made of the same material as the specimen is placed between it and the transmitter bar, in order to bridge over the thermally inhomogeneous field at the opening of the furnace. The bridging piece is glued to the specimen what ensures proper transmission of the pulse into the specimen, and at the same time makes easier the handling of the specimen within the furnace. The unit bridging piece – specimen can be lined up according to the axis of the set-up as a whole from without the furnace, which enables proper positioning of the unit.

The presence of the bridging piece has some influence on the transmission of the pulse into the specimen since there are some slight pulse reflections at the glued joint. Our experience shows, however, that the proper choice of the

extension piece length enables direct pulse measurements on the bridging element and thus takes into account the joint reflection losses. The fracture phenomena in the specimen itself are not influenced by the presence of the bridging piece since the reflected pulse reaches the glued joint only some time after the primary fracture has occurred.

4. Temperature effects

The axial temperature distribution in the bridging piece – specimen unit has been measured with thermoelements on the surface of the specimen. The results are shown in Fig. 4. Inside the furnace the temperature is nearly constant and decreases at a high gradient within the insulation. From the experimental data for some furnace temperatures, the temperature distribution in the bridging piece and in the specimen is interpolated for the temperatures of the tests.

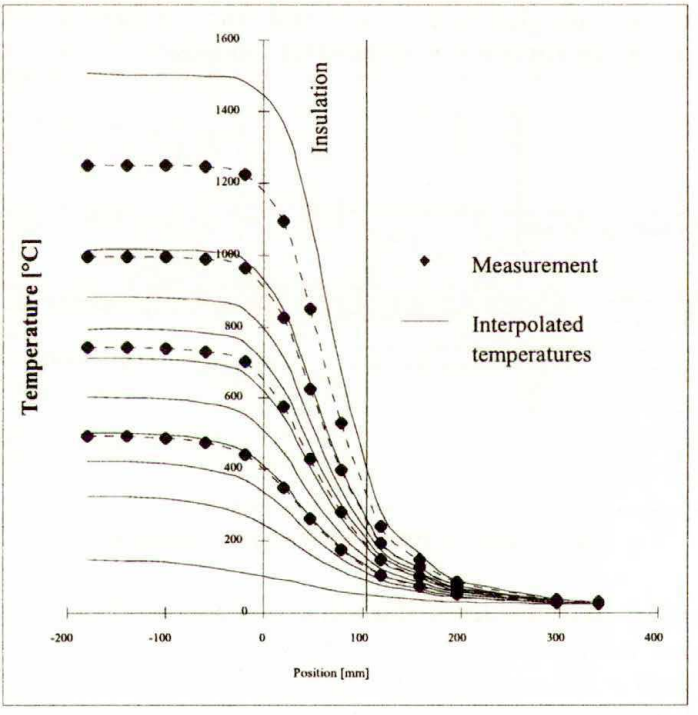

FIG. 4. Temperature distribution in the unit bridging piece – specimen.

Due to the change in the elastic modulus and the thermal expansion of the ceramics, the wave velocity decreases. For the measurement of the wave velocity at elevated temperature, an instrumented specimen is placed in two positions relative to the furnace, Fig. 5. Two gauge stations measure the travel times for each position. The difference of the travel times gives the wave velocity in the

measuring length, which shows a nearly linear decrease at temperatures up to 1000°C and an enhanced decrease above that temperature, Fig. 6.

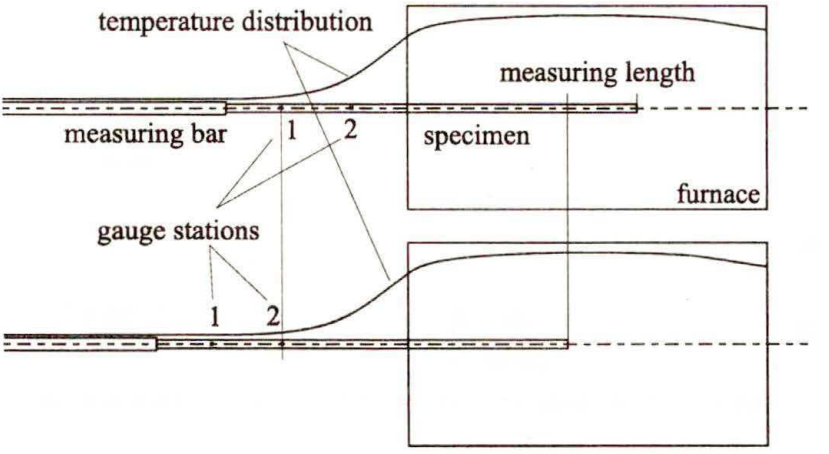

FIG. 5. Measurement of the wave velocity at elevated temperatures.

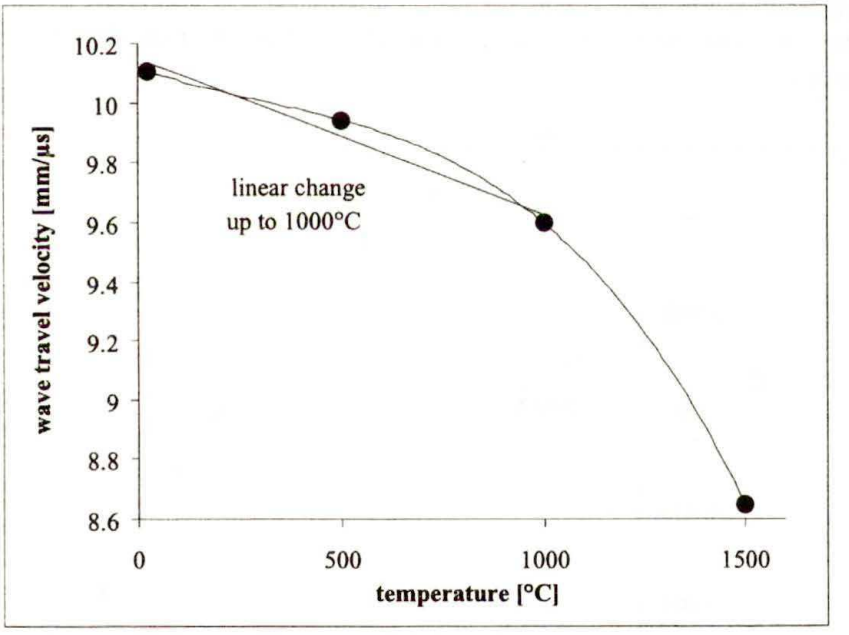

FIG. 6. Temperature dependence of the wave velocity.

The decrease of the wave velocity influences the pulse length in the specimen, the geometrical dispersion and the pulse transmission through the bridging piece.

The stress distribution in the specimen becomes shorter with the decreasing wave velocity at elevated temperature and similar stress distributions arrive with

delay. This effect leads to a new identification of the primary spalling site, and thus of the spalling strength, Fig. 7.

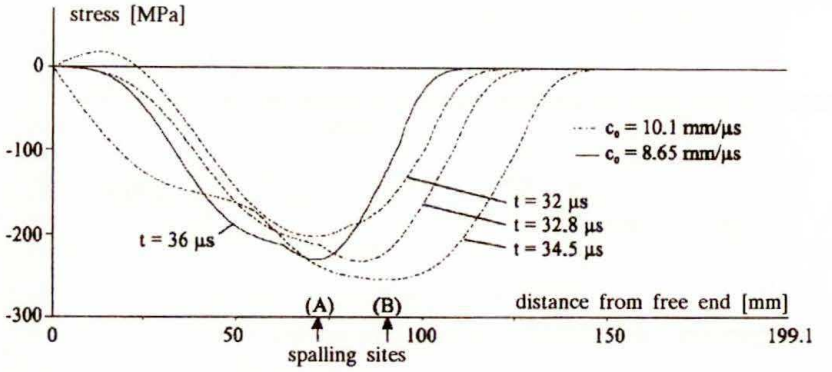

FIG. 7. Influence of decreasing wave velocity on the stress distribution in the specimen.

Like the stress distribution, the wave lengths of the Fourier components of the pulse become shorter. With the increasing ratio of the radius to wave-length the velocity of the components drops compared with the uniaxial wave velocity c_0. But the values in Fig. 8 show that this effect of geometrical dispersion can be neglected.

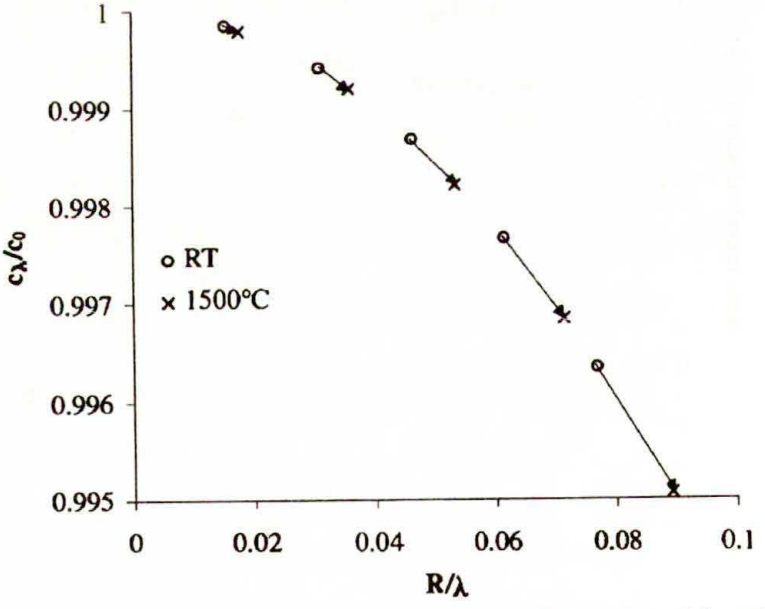

FIG. 8. Influence of the wave velocity on the geometrical dispersion of the pulse.

With the changing wave velocity, the thermal expansion of the cross-section area and the thermal change in the density, the bar impedance $I = A\varrho c$ de-

creases with the temperature distribution in the bridging piece. We will check the effect in a simplified model with linear temperature distribution in the bridging piece, Fig. 9. In two calculations we assume a linear temperature-dependence of the wave velocity up to 1000°C and a third-degree polynomial dependence up to 1500°C.

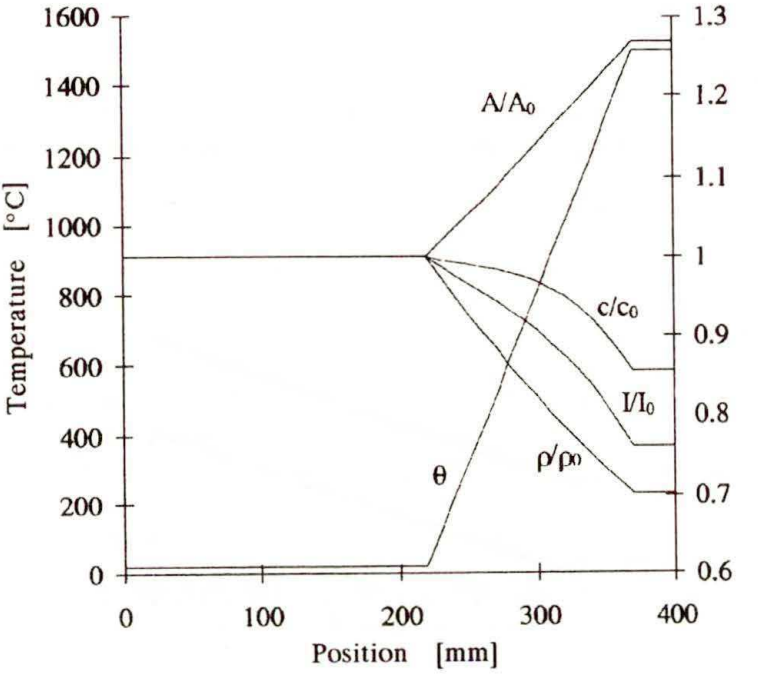

FIG. 9. Linear temperature distribution and influence on the cross-sectional area, wave velocity, density and bar impedance.

In finite bar elements we assume the applicability of the linear wave theory. At the boundary of an element, a part of the pulse in the first element is transmitted to the next element, and the other part is reflected back in the element, Fig. 10.

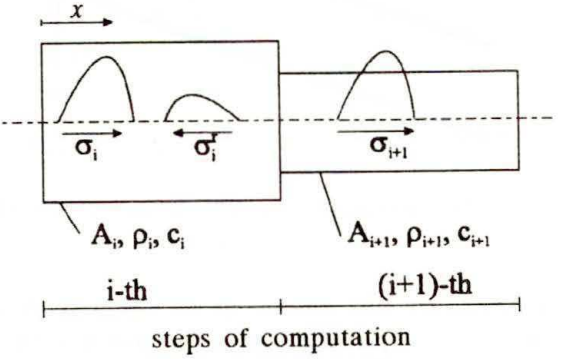

FIG. 10. Partial reflection at the element boundary.

The transmitted part is obtained from formula (4.1), the reflected one from (4.2).

$$\sigma_{i+1} = \frac{A_i \varrho_{i+1} c_{i+1}}{I_i + I_{i+1}} \sigma_i , \tag{4.1}$$

$$\sigma_i^r = \frac{I_{i+1} - I_i}{I_{i+1} + I_i} \sigma_i . \tag{4.2}$$

The secondary reflected part of the pulse is obtained by the reflection of the reflected one and is transmitted to the specimen with delay. In Fig. 11 the transmitted, the reflected and the secondary reflected pulses are superposed.

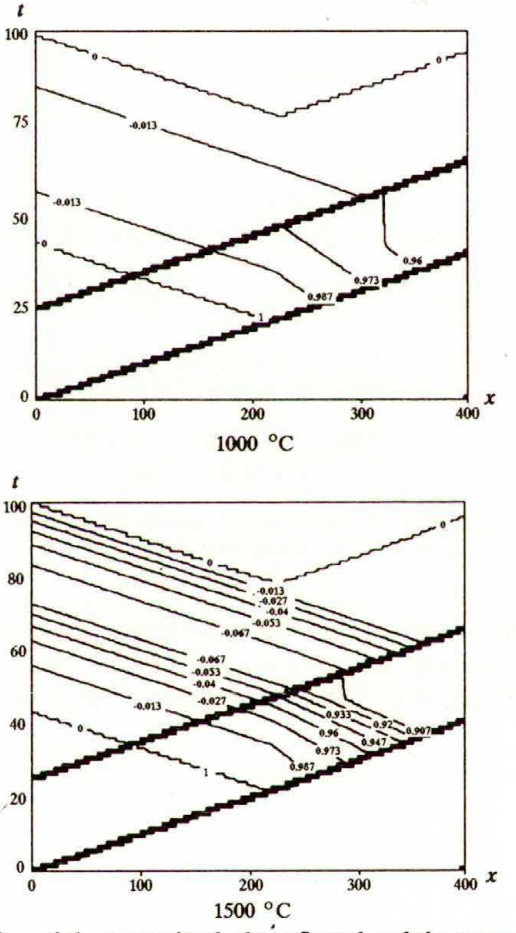

FIG. 11. Superposition of the transmitted, the reflected and the secondary reflected part of the pulse.

For the given temperature distribution in the bridging piece, one gets at the temperature of 1000°C in the furnace a transmission into the specimen of 96% of the initial pulse amplitude. The amplitude of the primary reflection is 2.5%,

and the one of the secondary reflection is 0.1%. At 1500°C the initial pulse amplitude is transmitted in 89%. In this case the amplitude of the primary reflection increases to 7% and that of the secondary reflection to 0.3%. These results show that the secondary and higher order reflections are negligible.

The integration of the transmitted parts along their characteristic leads to formula (4.3), which shows that the transmitted pulse amplitude depends on the temperature in the furnace θ_f alone.

$$\sigma_t(\theta_f) = \sigma_i \sqrt{\frac{A_0 \varrho(\theta_f) c(\varrho_f)}{A(\theta_f) \varrho_0 c_0}}. \tag{4.3}$$

5. Experimental results

Commercial alumina bars of diameter 8 mm and length 200 mm have been tested in the whole range of temperature 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. Altogether 28 specimens were tested, at higher temperatures the number of experiments per temperature point was reduced from six to one due to increasing time cost.

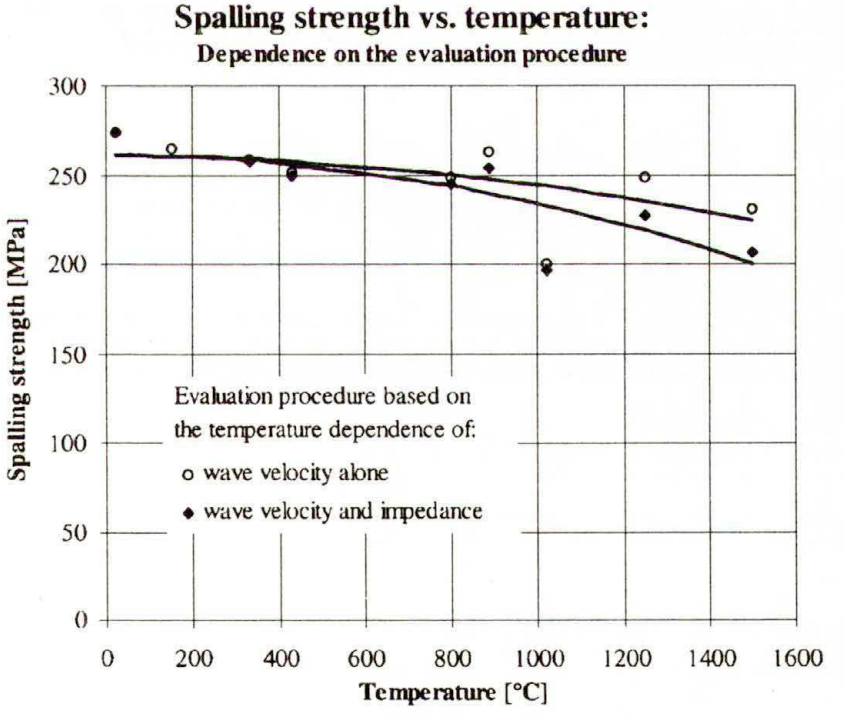

FIG. 12. Experimental results.

The results of the tests can be therefore treated as preliminary ones only, not representing the full statistics of the strength at elevated temperatures. They prove, however, doubtlessly the applicability of the experimental method to testing at elevated temperatures.

The consideration of the incremental reflections of the pulse caused by the continuous drop of the impedance indicates that the decay of the strength with the increase of the temperature up to 1500°C is much stronger than that anticipated in preliminary tests, Fig. 12. The observations can be interpreted within a continuum damage model.

6. Conclusion

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

Acknowledgments

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