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RESISTANCE TO THERMAL FATIGUE AND STANDARDS

J.C. GLANDUS, P. BOCH and C. JOUIN

E.N.S.C.I., U.A. C.N.R.S. 320, F-87065 Limoges, France

*P.S.A., Centre Technique Citroën, Chemin Vicinal n°2, Etudes et Recherches, F-78140 Velizy, France

Résumé La résistance aux chocs thermiques d'une pièce mécanique ne dépend pas que des caractéristiques du matériau, mais aussi de données extrinsèques (géométrie, échanges thermiques...). Il semble cependant utile de normaliser les conditions d'évaluation de grandeurs usuellement citées, en particulier ΔTc, et de développer des tests de contrôle des effets de la fatigue thermique.

Abstract Thermal shock resistance of ceramic parts does not depend on materials characteristics only, but also on external parameters (piece geometry, heat exchange...). However, it seems useful to standardize the conditions of measuring of some usual quantities, particularly ΔTc, and to develop some tests to control thermal fatigue damage.

INTRODUCTION

Brittleness of ceramics leads to various drawbacks, particularly a poor resistance to thermal shocks. This makes the use of ceramic parts in thermal engines difficult, and explains the efforts made to improve the understanding of thermal shock features.

VAMAS* is involved in "pre-standardization" studies on thermal shock behaviour of ceramics, in the spirit that standards should be developed not only to allow the ranking of abstruse properties but also to help users' choice. An illustration of this point of view, chosen for the case of strength, would be to standardize fatigue limit /1/, instead of "inert" strength which is generally not a parameter of real applicability. This paper considers the critical temperature drop (ΔTc), and also points out the need for thermal fatigue benches.

I THERMAL SHOCK RESISTANCE AND THERMAL SHOCK TESTS

The thermal shock behaviour of a part of a given shape, made of a given material, and working at a given set of heat exchange conditions, should be studied at three...
sequential levels, namely (i) the temperature field, (ii) the stress/strain field, and (iii) the occurrence and the extent of damage /2/3/4/. It must be pointed out that the knowledge of material parameters (e.g. $R$, $R'$...) is not enough to foresee the behavior of a part, more especially as the main uncertainties concern heat exchanges ++. Hence, there are presently two complementary trends /5/:

- Either the experimental study of a piece as similar as possible as the actual part, subjected to thermal exchanges as similar as possible as the actual exchanges.
- Or the computer assisted derivation of the quantities of interest (e.g. stress) by using only "primary" experimental parameters (e.g. thermal expansion, thermal conductivity, elasticity constants, strength, etc.) and by mapping the data for an arbitrary range of thermal shock severities (from "mild" shocks to "hard" ones, because here there is no more experimental limitation). This approach does not particularize "thermal stresses" from "mechanical stresses" thus unifies thermal fatigue and dynamic mechanical fatigue /7/.

No one of the two approaches focuses on the critical temperature drop ($\Delta T_c$), because even in the simple case of hard shocks ($\Delta T_c = R/\psi(\beta)$) $\Delta T_c$ is reduced to the combination of a material parameter ($R$) and of a material and heat exchange dependent function $\psi(\beta)/4$. However, $\Delta T_c$ is frequently given by ceramics suppliers as a material parameter and continues to be considered by users as a significant characteristic, although the variability in its determination deprives it of physical meaning. This calls for the necessity of standardize the $\Delta T_c$ measurements... but it must be remembered that $\Delta T_c$ is only a reference, which cannot be used to design a piece.

II A STANDARDIZABLE TEST TO MEASURE $\Delta T_c$

The proposal (Fig. 1) corresponds to a technique used by Hasselman /8/. Samples are cylinders ($\sim 60$ mm in length and $\sim 6$ mm in diameter), with a Vickers indentation in their middle. Both ends are covered by thermally insulating caps. A system of pneumatic actuating allows the quick displacement, at a fixed rate, from a furnace at temperature $T_1$ into a bath at temperature $T_2$, the sample being gripped in a low thermal inertia fixture. The indentation initiates thermal cracks and so decreases the Weibull scattering which occurs when cracks are initiated by natural flaws /9/10/. The end caps prevent the initiation of cracks at the edges, and help to approximate the system as an infinite bar.

![Fig. 1 A possible standard test for $\Delta T_c$ measurements.](image)

Various quenching severities, from hard shocks ($\rightarrow R$) to mild ones ($\rightarrow R'$), may be obtained by varying quenching media (molten metal, water, oils... ). The control of damage can be performed by the classical method of breaking the shocked samples --

++ Even for a parameter as simple as Biot's number ($\beta$), and for heat exchange conditions as typical as water quenching, the disagreement between the literature data ranges on an order of magnitude /5/.
which needs numerous specimens - or by non-destructive evaluation: dye penetrant, resonance of samples /11/ etc., which does not require many specimens to determine $\Delta T_c$ and could allow the study of cumulative shocks on the same sample.

III A THERMAL FATIGUE BENCH

The simplicity (of the samples and of the equipment), and good qualities of reproducibility, argue in favour of the previous test as a standardizable test. However, it suffers of two drawbacks, namely (i) it is better suited for shocks at decreasing temperature than for shocks at increasing temperature and it is not convenient to run in the high temperature range, and (ii) it is not adapted to thermal fatigue studies, because even if non destructive evaluation is used it cannot be applied in real time, i.e. it cannot allow a continuous registration of the damage. For this reason, we have built an automated bench with a radiative heating; acoustic emission allows us to control the initiation and the propagation of cracks.

Figure 2 gives a general view of this device and Figure 3 illustrates the block diagram of the whole experimental set. It can be observed that the lower part of the bench consists of a rotative iron table on which up to five samples in the form of discs ($\varnothing \leq 30$ mm) are gripped by means of cooled metallic clips. The use of such a holding method allows us to superimpose a mechanical induced stress field on thermal induced stress field. The upper part of the bench involves a horizontal heating plate in nimonic, the dimensions of which are close to those of the specimen. A pneumatic actuating moves this heating part vertically so that it can be set at about 0.1 to 0.3 mm of the sample for the radiation heating step. This actuating also enables the heating plate to return rapidly during the cooling/rotation stages.

Figure 4 shows the temperature vs time dependence for the hot and the cold faces of a sample of zirconia. It may be pointed out that a heating rate of $20^\circ C/s$ is main-
tained during the first stages (t<40 s) of heating and that, when the steady state is reached, a gradient of 100°C is obtained through the thickness (e=2mm). The radial temperature vs time dependence is illustrated in Figure 5 for the same material. Besides the previous axial gradient, a maximum radial gradient of 40°C/mm is obtained which submits the sample to a triaxial state of stress. This results from the heat conduction induced at the periphery of the sample by the cooling effects due to the metallic clips. The control of the induced damage is performed "in situ" by means of acoustic emission measurements. The metallic gripping clips are used as waveguides, so their cooling is essential to avoid the excessive heating of the transducer. Figures 6 and 7 show the number of acoustic emission counts recorded versus the imposed temperature difference (ΔT) for two commercial qualities of zirconia (from Pochinéy-Demarque, batches ref. ZFME & TZP).

For cumulative shocks of increasing severities, the acoustic emission remains at a rather low level up to a critical value ΔTc for which the crack propagation occurs and gives rise to a significant increase in the measured values; thus one obtains ΔTc (ZFME) = 750°C and ΔTc (TZP) = 1100°C.

The samples being submitted to a single thermal shock for each ΔT value, it may be thought that the total cumulative effect is negligible /11/ and that the critical temperature differences measured are consistent with the thermoelastic analysis results /12/. Apart from the M.O.R (σR), all the thermomechanical parameters are...
identical for the two materials and, if the previous assumption is a valuable one, the $\Delta T c_1$ and $\sigma R_1$ values verify the equality:

$$\frac{\Delta T c_1}{\Delta T c_2} = \frac{\sigma R_1}{\sigma R_2}$$

Indeed:

$$\Delta T c_1/\Delta T c_2 = 1100/750 = 1.45$$

which is close to

$$\frac{\sigma R_1}{\sigma R_2} = 750/450 = 1.65$$

These two ratios are in rather good agreement, and this experiment confirms the applicability of acoustic emission for the non destructive evaluation of thermal damage.

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