Estimation of Fracture Conditions of Ceramics by Thermal Shock with Laser Beams based on the Maximum Compressive Stress Criterion*

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Structural ceramics are attracting attention in the development of space planes, aircraft and nuclear fusion reactors because they have excellent wear-resistant and heat-resistant characteristics. However, in some applications it is anticipated that they will be exposed to very-high-temperature environments of the order of thousands of degrees. Therefore, it is very important to investigate their thermal shock characteristics. In this report, the distributions of temperatures and thermal stresses of cylindrically shaped ceramics under irradiation by laser beams are discussed using the finite-element computer code (MARC) with arbitrary quadrilateral axisymmetric ring elements. The relationships between spot diameters of laser beams and maximum values of compressive thermal stresses are derived for various power densities. From these relationships, a critical fracture curve is obtained, and it is compared with the experimental results.

Key Words : Thermal Shock, Fracture Criterion, Laser, Ceramics, Thermal Stress, Finite-Element Method

1. Introduction

In the development of space planes, aircraft (orient express), nuclear fusion reactors, and so on, super-heat-resistant materials should be developed. At present, the structural ceramics are the typical candidate heat-resistant materials. These heat-resistant materials are used under a few thousand degrees of temperature. When the heating load alters, large thermal stresses take place due to the formation of the transient temperatures. Therefore, for the heat-resistant materials, the thermal shock strength should be the most important factor.

Recently, it was proposed that thermal shock strength of ceramics should be estimated by the irradiation by a laser pulse(1). In order to establish this method, a working group was organized with Tohoku University as the central research institution under the national project of "Functionally Gradient Materials"(2). So far, thermal shock tests on plasma-sprayed coatings with ruby laser irradiation have been reported(3). But few reports on thermal stresses of materials caused by thermal shock with laser beams have been analyzed in detail. In particular, it is not known how the spot diameter of a laser beam affects thermal stress occurring in the materials.

This report presents the thermal shock evaluation of machinable ceramics (trade name : MACOR), the diameter of which is sufficiently larger than the spot diameters of laser beams. The specimens are cylindrical and their upper surfaces are irradiated by circular laser beams with uniform power density. The nonstationary temperature distributions and the quasi-stationary thermoelastic stresses were analyzed on uncoupled assumption by the finite-element method (FEM). In particular, the relationships among the spot diameters of laser beams, power densities and thermal stresses are discussed. Also, thermal shock experiments are carried out and the results are compared with those of the numerical calculations.

2. Analytical Model

As shown in Fig. 1, the cylindrical machinable ceramics (trade name : MACOR) are irradiated by laser beams, the power density of which is denoted by P (W/mm^2) and spot diameter by D (mm). The duration of the laser pulse is 1 second. Afterwards, the irradiated surface is cooled convectively. The diameter d of the cylinder is 140 mm, and its height is 50 mm. The mode of laser beams is simply uniform in these calculations. The center of the surface where the

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laser beams are irradiated is placed at the origin of the coordinate axes, where the r-axis is in the radial direction and the z-axis is in the depth direction. The element model with arbitrary quadrilateral axisymmetric ring elements is used for FEM calculations. The initial temperature of the model and the circumference is 20°C. The physical characteristics of the machinable ceramic and the heat transfer conditions are shown in Table 1(4),(5).

3. Heat Conduction Analyses

The maximum temperature was obtained in the center of the laser beam at any time. The time histories of maximum temperatures with power density of 1 W/mm^2 are shown in Fig. 2. It is shown that the maximum temperatures vary suddenly just after stopping the irradiation process of laser beams and in the early period of the cooling process. It can be seen that the maximum temperatures are greatly affected by the spot diameter within a range of small spot diameters. However, beyond a certain spot diameter, the maximum temperatures are not affected.

Table 1 Physical characteristics of the machinable ceramic (trade mame: MACOR) and heat transfer conditions

Density	2.52×10^3 kg/m^3
Coefficient of thermal expansion	1.1×10^{-5} /℃
Heat conductivity	1.675 W/(m·℃)
Specific heat	0.754×10^3 J/(kg·℃)
Tensile strength	98 MPa
Bending strength	98 MPa
Compressive strength	343 MPa
Young's modulus	64 GPa
Poisson's ratio	0.26
Emissivity	0.9
Heat transfer coefficient (air)	W/(m^2·℃)
Top horizontal surface	$\alpha_1 = 1.32(\Delta t/l)^{1/4}$
Vertical surface	$\alpha_2 = 1.42(\Delta t/l)^{1/4}$
Bottom horizontal surface	$\alpha_3 = 0.61(\Delta t/l^2)^{1/5}$

Symbols: $\Delta t = (t_w - t_\infty)$ [℃]
t_w = averaged wall temperature [℃]
t_∞ = main stream temperature [℃]
l = characteristic length [m]

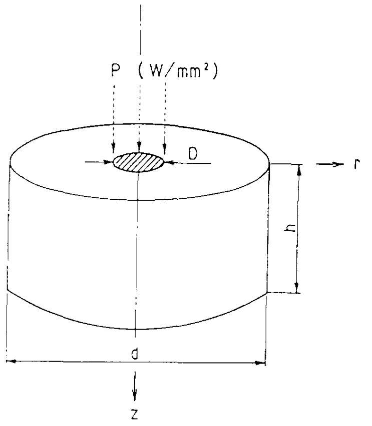

Fig. 1 A model analyzed by the finite-element method

The temperature distributions on the irradiated surface in the radial direction are shown in Fig. 3 for the power density of 1 W/mm^2 and the irradiation period of 1 second. The temperatures drop suddenly at the boundary of the laser spot. But when the spot diameter is larger than 10 mm, the temperature distributions are high and constant inside the spot diameter, and the maximum temperature does not increase with the spot diameter of the laser irradiation.

The temperature distributions in the direction of depth along the center line are shown in Fig. 4. The temperatures decrease suddenly within about 5 mm in depth, but under that depth they do not change very much.

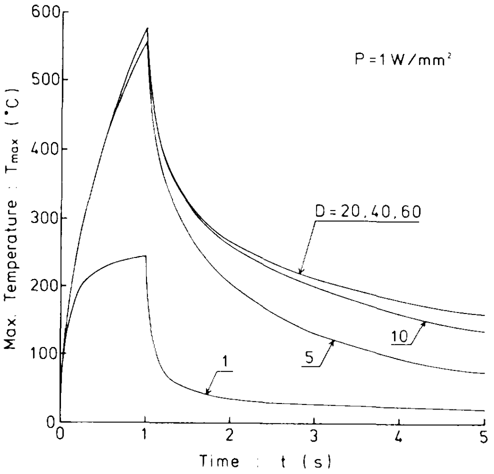

Fig. 2 Time histories of maximum temperatures

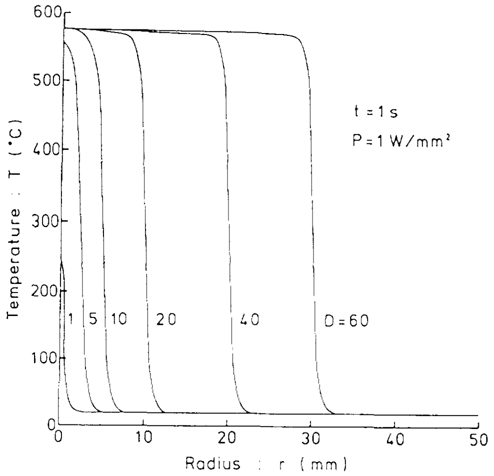

Fig. 3 Temperature distributions in radial direction on irradiated surface

4. Thermoelastic Stress Analyses

Using the temperature distributions obtained by heat conduction computations, the thermoelastic stresses were analyzed by the FEM.

The distributions of the radial stresses σ_r and the hoop stresses σ_θ along the radius on the irradiated surface are shown in Figs. 5 and 6. The radial stresses σ_r have a large compression in the center and are constant within the spot circle, and converge to zero with increasing radius. Meanwhile, the hoop stresses σ_θ show several tens of MPa of tensile stress just outside the periphery of the spot circle, and their maximum values occur within about 6 mm out of the spot diameter. This tensile stress may cause thermal stress fractures in some ceramics.

The distributions of the radial stresses along the depth on the center line are shown in Fig. 7. The compressive stresses vary suddenly within several mm in depth, and beyond this range, tensile stresses of several tens of MPa occur, which gradually converge to zero.

5. Critical Fracture Curve in Thermal Shock

The ceramics used in this study have a lower compressive fracture strength. Furthermore, the computational results show that the maximum tensile stress is only 60% of the tensile strength of this material. Based on these characteristics it may be considered that the material fracture may be caused by the large compressive stresses.

The relationships between maximum compressive stresses and spot diameter with 0.6~3.0 W/mm^2 in power density are shown in Fig. 8. Under the above fracture assumption and the relationships with the compressive strength of 343 MPa of the material, the fracture curve is obtained in Fig. 9 (as expressed by the symbol □). Therefore, this curve defines the critical fracture curve of the machinable ceramic (MACOR) in thermal shock, and the zone above the curve is that of fracture. Thus, the curve may define the critical power density which specifies the power density in the case of fracture. Further, it is considered that the machinable ceramics may be fractured with a constant power density above the spot diame-

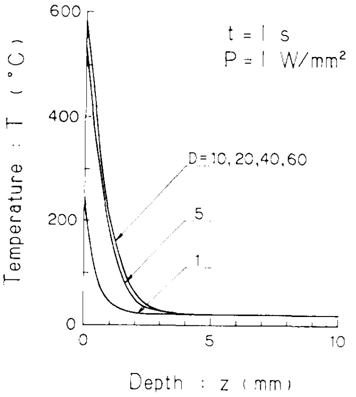

Fig. 4 Temperature distributions in direction of depth along center line

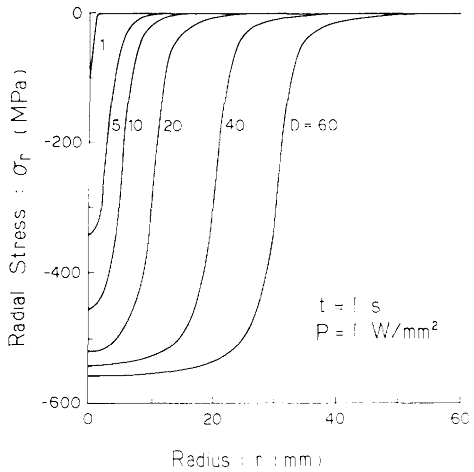

Fig. 5 Radial stress distributions σ_r along radius on irradiated surface

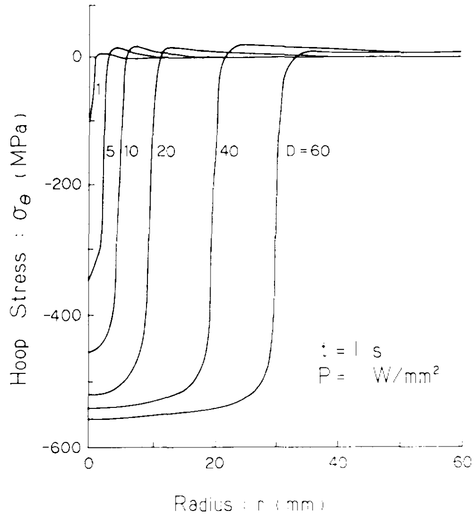

Fig. 6 Hoop stress distributions σ_θ along radius on irradiated surface

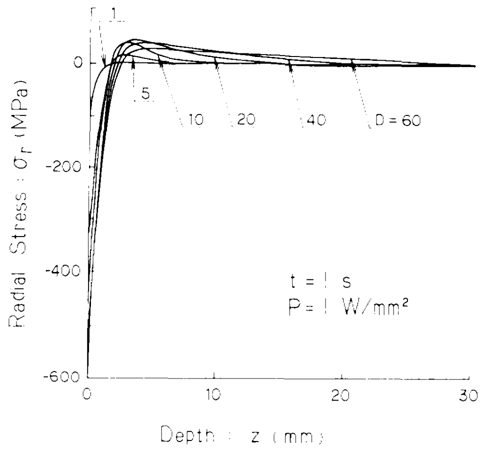

Fig. 7 Radial stress distributions σ_r along center line

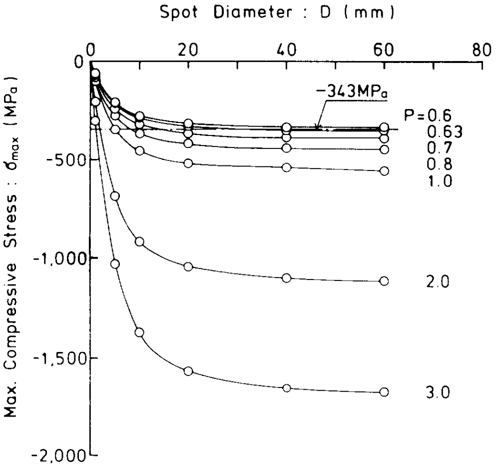

Fig. 8 Relationships between maximum compressive stresses and spot diameters

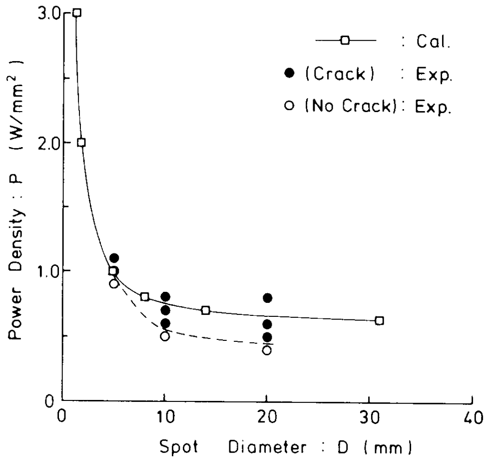

Fig. 9 Critical fracture curve in thermal shock

ter of 10 mm, but the critical power density increases sharply as the spot diameter decreases. Considering the experimental reproducibility, the experiment should be done at a rather large spot diameter so that this method may be established as a standard thermal shock test.

The results of the experiments are shown in Fig. 9. The symbol ● indicates cracked and the symbol ○ indicates noncracked samples. The critical power densities of the experiments are slightly lower than the values obtained from the theoretical calculations. However, they agree considerably well qualitatively. These differences are supposed to indicate that the compressive strength criteria used in these theoretical calculations were obtained by the uniaxial test; however, on the other hand, these experimental stress fields are under multiaxes stress conditions. Judging from the fracture criteria used here, we should adopt the multiaxes fracture conditions; however, no fracture curve data are obtained for this material under the multiaxes stress condition.

6. Conclusions

The quasi-stationary thermoelastic stresses for machinable ceramic (MACOR) heated by CO_2 laser beams were analyzed under uncoupled assumption by the finite-element method. Experiments on thermal shock with a CO_2 laser were performed, and the results obtained are summarized as follows:

(1) The radial stresses and the hoop stresses irradiated by laser beams are mainly compressive stresses inside the spot circle, and they have the maximum value in the center of the spot diameter. The maximum tensile stresses occur within about 6 mm outside the spot diameter.

(2) The maximum radial stresses and the maximum hoop stresses increase abruptly with spot diameters for fixed power densities, and are almost constant at larger than 20 mm in spot diameter.

(3) Under the assumption that the ceramic is fractured by the compressive stress, a critical fracture curve in thermal shock was obtained from the relationships between the maximum compressive stresses and spot diameters. In the range of larger spot diameter, this ceramic is nearly fractured at a constant power density, but the critical power density suddenly increases as the spot diameter becomes smaller. Therefore, it is recommended that a rather large spot diameter should be used to evaluate the thermal shock strength of the materials.

The period of laser pulse used in this study is 1 second and relatively longer, and so it is considered that the dynamic effects are not influenced much by it. However, the influence of dynamic effects on thermal stresses caused by irradiation of the laser beams is a problem that should be elucidated. Thus, we should like to research this in the future.

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