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To cite this article: Zhen Wang et al 2013 J. Phys.: Conf. Ser. 419 012044

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Numerical Simulation of the Dynamic Performance of the Ceramic Material Affected by Different Strain Rate and Porosity

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Abstract. Ceramic materials are frequently used in protective armor applications for its low-density, high elastic modulus and high strength. It may be subject to different ballistic impacts in many situations, thus many studies have been carried out to explore the approach to improve the mechanical properties of the ceramic material. However, the materials manufactured in real world are full of defects, which would involve in variable fractures or damage. Therefore, the defects should be taken into account while the simulations are performed. In this paper, the dynamic properties of ceramic materials (Al2O3) affected by different strain rate (500-5000) and porosity (below 5%) are investigated. Foremost, the effect of strain rate was studied by using different load velocities. Then, compression simulations are performed by setting different porosities and random distribution of pores size and location in ceramic materials. Crack extensions and failure modes are observed to describe the dynamic mechanical behavior.

1. Introduction

A number of expressions for the effects of different strain rate and porosity on the mechanical performance of ceramic have been proposed by various investigators. Many of these articles already discussed the influence of porosity and pore size on the compressive strength or fracture properties of porous ceramic materials1-2, which have been widely used in bone replacement, but barely studied the
mechanical properties of a high-density aluminum oxide ceramic (porosity below 5%). This is because all the required factors (e.g., random pore sizes, geometrical shapes and distributions) are not clearly studied in practical ceramic bodies. And also the porosity are not so easy to control when prepare test pieces before experiment\cite{3}. Herein, a numerical simulation was carried out to do the research. The mechanical properties of ceramic with low porosity was studied, especially the dynamic performance.

Several semi-empirical functions have been used to describe the relationship between fracture strength and porosity of ceramic\cite{4-7}. Meanwhile, it has been frequently studied the effect of porosity on Young's modulus. DEAN\cite{8} and SPRIGGS\cite{9} et al. have proposed several empirical relations to fit Young's modulus and porosity.

The effects of strain rate on the mechanical properties of ceramics have been observed in many studies\cite{9-10}. Considering the very comprehensible degree to which both porosity and strain rate influence the dynamic performance of ceramic, there is a remarkable lack of accurate information in the literatures. Furthermore, almost none of the available information deals with the combined effect of these factors on dynamic properties.

In the present study, a numerical simulation has been made (1) to study the dynamic properties of high-density aluminum oxide ceramic in different strain rate and porosity, (2) to observe the situation of damage accumulation and crack propagation, and (3) to provide reference for further engineering application in engineering and other sectors.

2. Numerical simulations

Specimens of alumina ceramic belong to non-strictly axial symmetry. Since pores are separated in specimens randomly, which have small size and few quantities, we reckon that specimens are homogenous, and distributions of stress and strain are axisymmetric. Hence an axisymmetric model was taken to do the research.

Simulations were carried out by different models with porosity of 0, 1%, 3%, 5% and strain rate of 500, 1000, 3000 and 5000 separately. Dynamic mechanical properties of alumina ceramic are studied using models referred before.

2.1. Model and Mesh

Models was constructed by a software ANSYS. Since the pores size is small, if the original model was used in simulation, it generates huge mesh quantity, which means large-scale simulations. Hence the simulation used a tiny cell which is cut out from ceramic panel and has a size of 0.5cm × 0.5cm. Pores are all in the form of circle with diameters ranging from 10nm to 200μm\cite{11} randomly. The porosities are 0%, 1%, 3% and 5% respectively as shown in figure1(a), (b), (c) and (d).
The geometries of computational models are regular and the mesh size is set to 0.002cm, hence the model with no porosity contains 126002 nodes and 62500 elements.

2.2. Constitutive models

Ceramic is a kind of typical brittle material. When ceramic is under impact load, the damage appears in the place of micro-cracks. With the development of cracks, material yields or breaks eventually.

One of the most widely used constitutive model for simulating the response of ceramic materials is the JH-2 model which is also used in simulation and engineering design of glass and cement. This constitutive model does account for strain rate effects and shows the relationship among the pressure, strength and damage of material which can be obtained from figure 3.

**Figure 1.** Models of different porosities

(a) (b) (c) (d)
Figure 2. Description of the JH-2 ceramic model\textsuperscript{[12]}

JH-2 model include a damage parameter that can describe the material from intact to yield which can be used to simulate damage. As in figure 2, damage is controlled by parameter D ranging from 0 to 1. The material is intact when D equals 0, while it is totally damaged, D was set to 1. The parameters of ceramics available for this simulation are cited from other literature\textsuperscript{[13]}.

2.3 Loading methods and boundary conditions
In order to achieve loading at different strain rates, the loading methods and boundary conditions are set as follows:

Figure 4. Load and boundary conditions

The interfacial effect of models under loading is ignored. The bottom is constrained in displacement to fix the model, while the top is loaded by different speed of displacement to simulate impact loading. The left and right sides are set as nonreflecting boundary conditions.

3. Results and discussion
It is evident that the strain rate and porosity do have some influence on the performance of ceramic material due to the result analyzed below.

3.1 the effect of porosity
Since the effect of porosity was discussed, here we take a fixed strain rate (500) as an example. The fracture strengths are 8.84GPa, 3.63GPa, 2.74GPa and 2.32GPa with the increase of porosity, respectively for 0%, 1%, 3% and 5% when strain rate is set to 500, shown in figure 5(a).
The strength decreased with the porosity increased, which is in good accordance with the literature. The strength of ceramic for porosity 0% (8.84GPa) is much higher than others, mainly because porosity 0% means ‘ideal material’—there are no pros in the ceramic body, which is impractical to obtain that kind of material during production process. In a word, it's only an ideal value. That's the reason why we never got such a high strength through experiments.

![Stress-strain curve of different porosities under different strain rates](image)

Figure 5. Stress-strain curve of different porosities under different strain rates

when strain rate is set to 5000 as in figure5(b), the issue was turned into a high strain rate situation which should take impact effect into consideration. Since the shock wave propagation is complex, transmission and reflection in material caused fluctuation in the curve. So the stress-strain curve of figure5(a) is smoother than that of (b).

| Porosity | E (GPa) | ΔE | σ (GPa) | Δσ |
|----------|---------|----|---------|----|
| 0%       | 442.1   | /  | 8.84    | /  |
| 1%       | 423.7   | 18.5 | 3.63   | 5.21 |
| 3%       | 415.6   | 8.1  | 2.74   | 0.89 |
| 5%       | 377.8   | 37.8 | 2.32   | 0.42 |

Table 1 shows material properties for ceramic at strain rate 500. Two fitting functions can be obtained from the data listed.

\[ E = 441.9e^{-2.88P} \]  
\[ \Delta\sigma = 0.003P^{-1.57} \]

Those two expressions are in good accordance with the result of KNUDSEN \[^9\] (in form of \( E = E_0e^{-bP} \), where \( E \) is the Elastic Modulus with porosity, \( E_0 \) is the Elastic Modulus of non-porous ceramic, \( b \) is a fitting parameter, \( P \) is porosity) and Dunn \[^6\] (in form of \( \Delta\sigma = aP^b \), where \( \Delta\sigma \) is stress difference, \( P \) is porosity, and \( a > 0 > b \)) under lower porosity. Meanwhile, the value of \( E_0 \) obtained by fitting is 441.9GPa, which is in good accordance with the result 442.1GPa gained by this simulation. But the fitting function of stress difference \( \Delta\sigma \) is not so agreed with the results Dunn obtained. That's because there are only three data used to fit the function which brings the unusual margins of error. Generally, the strength has decreased 5.21GPa since the porosity increased from 0% to 1%; 0.89GPa since the
porosity increased from 1% to 3%; and 0.42GPa since the porosity increased from 3% to 5%. That means the decrease of strength slows down with the increase of porosity.

The Elastic Modulus and failure strength calculated from the simulation decreased with porosity increased when strain rate is 500, which is in good accordance with the literature\(^9\), and validate the simulation method at the same time.

### 3.2. The effect of strain rate

The computational results from the comparison analysis shows the stress-strain curves of ceramic model under different strain rate for porosity 0%, 1%, 3% and 5% respectively. Discrepancy can be easily observed from the figures. When porosity was set to 0%, shown in figure 6(a), the fracture strengths of ceramic are 8.84GPa, 9.02GPa, 8.89GPa and 6.57GPa with the corresponding strain rate 500, 1000, 3000 and 5000 respectively. The ‘ideal ceramic’ has lower fracture strength when strain rate reaches 5000 which reveals the impact performance at high strain rate are unsatisfactory. When loading at low strain rate, Stress is well-distributed in material, so the fracture strength shows the load bearing capacity of the material; but when loading at high strain rate, damage initially emerged at the load end, thus the current material strength represents the load bearing capacity after local fracture, not what the material really has.
Models with pores have the similar conclusion: larger strength comes with higher strain rate, which lead to a better impact performance than ceramic with no pores.

3.3. Damage accumulation and fracture
The colored areas in figure 7 represent the damaged area, and when the color turns into red, that means this part of material is entirely ineffective.

![Figure 7. Damage contour of ceramic when porosity sets 0%](image)

Under compressive loading, damage begins to accumulate when the deviator stress exceeds a critical value. It can be seen clearly in figure 7, the damage generate initially at the direction of \( \pm 45^\circ \) plane which shear failure occurred due to the shear stress reaches its limit. As we all know, the strength of compressive is greater than shear for ceramic materials, so the results displayed that the fracture of ceramic material did agree with the maximum shear stress criterion.

![Figure 8. Damage contour of ceramic when porosity sets 1%](image)
when pores exist in ceramic material, take porosity 1% as an example, figure 8 shows the damage propagation and fracture situation: in normal conditions, damage generate initially at the place of more dense pores, larger pore size or the vicinity of the boundary which form stress concentration easily along with the impact loading. Thus it can be seen instantaneous damage occurred at a larger pore size close to the bottom surface, after that failure emerged near the left boundary due to the damage accumulation, ultimately an increment in damage leads to material bulking.

Figure 9 shows the fracture of ceramic without pores (0%) were controlled by shear stress when compression. But the ceramic with pores fractured in other way—varies from different distribution, size and shape of pores.

4. Conclusions

It should be emphasized that the present results refer to specific ideal material, and should be expected to predict the ‘dynamic property’ at given porosity and strain rate in ceramics. The results presented here should not be expected to apply directly to substantially different types of porosity.

Meanwhile, fitted curves of $E$-porosity and fracture strength-porosity show great acceptance with literature. With the increase of porosity, elastic modulus and strength of ceramic both decreased. And the decrease of strength slows down with the increase of porosity.

High-density alumina ceramic (porosity below 5%) is analyzed among different porosities. The fracture strength increased as the strain rate raised from 500 to 5000 when pros exit in ceramic material, but it went to the opposite direction when there are no pros in ceramic body during simulation. From that it can be concluded the dynamic property of ceramic with pros (porosity below 5%) performed better than without it. But it has been noted that the strain rate effects are typically secondary compared to the porosity effects.

Lastly, the fracture pattern of ceramic without pores is totally different from that with pores: the fracture of ceramic without pores acts as normal brittle material—shear stress reaches its limit; the process of damage is different from ceramic with pores, which involved local damage course by
stress concentration. With the accumulation of damage in the formation of micro-cracks, micro-crack propagation and eventually cross throughout the entire material, then came the material failure.

Reference:
[1] Rice R W 1996 *J Mater Sci.* **31** 1969-83
[2] Michael AM, James YY and Carlos GL 2001 *J Am Ceram Soc.* **84** 2594-602
[3] DEANM L 1997 *J Mater Sci Mater Med.* **8** 227-32
[4] David E D, Lester J L and Robert EJ 1973 *J. Geophys. Res.* **78** 2403-17
[5] KNUDSENFP 1959 *J Am Ceram Soc.* **42** 376-87
[6] Thomas JA, Gust W Hand and Royce E B 1968 *J. Appl. Phys.* **39** 4610-6
[7] Wagh A S Singh J P and Poeppehl R B 1993 *J Mater Sci.* **28** 3589-93
[8] DEAN E A and LOPEZ J A 1983 *J Am Ceram Soc.* **66** 366-70
[9] SPRIGGS R M 1961 *J Am Ceram Soc.* **44** 628-9
[10] Weitao Y A, Tabie 2002 Strain Rate Dependent Micro-Mechanical Composite Material Model for Finite Element Impact Simulation. 7th Int. LS-DYNA Users Conf. (Detroit: Materials) p 16-5
[11] Le Huec J C, Schaeverbeke T and Clement D 1995 *Biomaterials.* **16** 1113-8
[12] Holmquist J, Templeton W and Bishnoi D 2001 *Int J Impact Eng.* **25** 211-31
[13] Khahn Bui Duane S. Cronin 2003 Implementation and Validation of the Johnson-Holmquist Ceramic Material in Ls-Dyna 4th European LS-DYNA Users Conf. (Ulm: Materials) p 53
[14] KNUDSEN F P 1962 *J Am Ceram Soc.* **45** 94-5