EFFECT OF POROSITY ON FRACTURE TOUGHNESS OF BRITTLE POWDER MATERIALS

A.A. Sotnik, A.D. Vasilev, S.A. Firstov, I.G. Slis, L.I. Chernychov*

The dependencies of fracture toughness and strength of powder materials on porosity are considered. It is shown that the course of those dependencies are determined by fracture mechanisms. Under brittle interpartial fracture, fracture toughness decreases monotonously when porosity increases. Under cleavage this dependence is non-monotonous with a significant growth of fracture toughness when pores form connected structure.

INTRODUCTION

In modern physics of fracture, one of the main problems is the adequate description of the effect of structural parameters on energy of fracture of polycrystalline solids. The important part of this problem lies in investigation of influence of porosity on fracture toughness and strength of sintered powder materials.

In accordance with the Griffith's theory (1) energy of fracture or effective surface energy is a function of modulus of elasticity and fracture stress. It is required to analyse the influence of porosity first at all on elastic constant of material. The dependence of modulus of elasticity on porosity has been studied by numerous authors both experimentally and theoretically. It is known from work by Springgs (2), Carniglia (3) and Dean (4). The most developed is Balshin's model, given in his book (5). Balshin has found the correlation between elastic properties and the critical size of the least contact section of a porous material. A variation of modulus of elasticity resulting from an increase of porosity may

* Frantsevich Institute for Problems of Materials Science,
Krjijanovskogo str., 3, Kiev 252680, U.S.S.R.

be described by either power or exponential functions of the following type:

$$E = E_o \exp\{-bP\} \qquad (1)$$

Similar dependencies were found for energy of fracture and fracture stress:

$$\gamma = \gamma_o \exp\{-bP\}, \qquad (2)$$

$$\sigma = \sigma_o \exp\{-bP\} \qquad (3)$$

A direct measurement of the dependence of fracture toughness on porosity carried out on ceramic materials by Phani and Niyogi (6) has demonstrated a good correlation between the experiment and the formula

$$K_{Ic} = K_{Ic}^{o} \exp\{-bP\} \qquad (4)$$

The observed deviations, especially at low values of porosity, have been interpreted as effect of some chemical feathures of specimens used. May be seen that K_{Ic} decreases non-monotonously with increasing porosity.

Analyzing a number of data of mechanical tests of porous materials, available in literature and our own ones, it has to note that cited investigations lack in control of failure mechanisms of tested specimens and particularly in keeping single mechanism of fracture over all interval of porosity under study. As was shown by Coppola and Bradt (7) on ceramics, where such control has been done, the mixed nature of failure is noted, the change from cleavage fracture to intercrystalline takes place as the total porosity of material increases. Metallic powder materials, in particular powder iron, reveal also the change of fracture mechanisms. Drachinsky et al (8) showed that fracture mechanism changes from cleavage to dimple fracture with increasing porosity. The change takes place at about porosity of 6%. Strictly speaking, since the proposed dependences (1), (2) and (3) have been based on the model of the contact section of material, they are true only in case of interpartial (intercrystalline) failure mechanism.

Thus, the consideration of effect of porosity on fracture toughness and strength keeping single fracture mechanism in a wide range of porosity is actual. For brittle sintered powder materials the following two failure mechanisms are valid: interpartial or intercrystalline fracture and cleavage one.

MATERIALS AND METHODS

As powder material failed by brittle interpartial mechanism, sintered molybdenum was chosen with particles size about 100 μm. Material has porosity changing from 10 up to 80%. As sintered materials, that fail by cleavage in all interval of porosity from non-porous to 50 %, powder chromium was chosen. Size of particles was about 50 mkm. Fracture toughness was estimated as K_{1c} parameter or impact toughness of notched samples under three-point bend at room temperature. Fracture mechanism were controlled by scanning electron microscopes "SuperProbe-733" and JSM-T20 (JEOL).

RESULTS AND THEIR DISCUSSION

Brittle intercrystalline fracture. Dependence of fracture toughness on porosity for intercrystalline fracturing materials is shown in Figure 2a.It may be seen that this dependence is monotonous without any features. That confirms the theoretical dependence of fracture toughness on porosity (4). The obtained experimental dependences of the modulus of elasticity, fracture stress and fracture toughness on porosity may be adequately approximated by formulae (1),(3),(4).

Values of measurement strength and fracture toughness are controlled by the area of intercrystalline contacts. Pores are placed on particle bondaries that make easier the run of brittle cracks along their interfaces and, thus, the role of interpartial pores consists only in decreasing contact section of a specimen. Values of fracture toughness and strength of a material failing by brittle intercrystalline mechanism do not depend on size and shape of pores.

Cleavage. The dependence of fracture toughness of sintered chromium on porosity (Fig. 2b) is in, contrast to above discussed, obviously non-monotonous. It has the maximum which is located within the 25 % porosity, while the behavior of modulus of elasticity with increasing porosity may be described by the function $E=E_0\exp\{-4P\}$.

The reason of the maximum on the fracture toughness vs porosity curve may be explaned in terms of the growth of fracture resistence of a rather porous material as a result of interaction between the crack and pores, the role of which varies qulitatively with increasing their quantity. Indeed, with low pore contents (<10 %), when the total porosity mainly consist of isolated pores, the interaction between a running sharp crack that is a cleavage crack and pores is practically absent. The most significant result of a possible interaction may consist in the formation of "tails" behind the pores, that results from the change of a cleavage plane. Scheme of crack propagation in material with isolated pores is shown in Fig. 1c. Within this porosity range, a monotonous decrease of fracture toughness and strength is observed, and features of crack propagation are like those for non-porous polycrystalline materials. An additional evidence of the absence of significant interaction between the crack and pores may consists in the equality between the fraction of pores visible on the fracture surface and their volumetric content.

With porosity above 10 %, the coalescence of separate pores and the formation of conglomerates begin. Next step is the formation of a branched porous structure whose degree of branching is characterized by value of connectedness of structure. In other words, the transition from a material with defects to a two-phase composite materials where pores play of the second phase, occurs.

In a material with connected porosity, an efficient braking of the crack by pores, due to blunting its tip following its reinitiation at interfaces, takes place. Scheme of crack propagation in material with connected pores is shown in Fig. 1d. This results in additional cracking, and the change of crack orientation with respect to applied loads. The above processes are reflected in an increase of roughness of a relief of fracture surface, the change of orientation of cleavage facets relative to the direction of propagation of the main crack, an increase of porosity opened by crack. The fracture surface of such materials consists of isolated cleavage facets which are separated by pores (Fig. 1d) whose part in the fracture surface may reach 70 % while the values of measured porosity is 25 %.

Calculations of efficiency of the blunting of crack tip by pores, carried out by Shchurov et al and cited in (9), confirm the presence of maximum of fracture toughness of brittle porous materials with the porosity of 25 %. The dependence obtained by Shchurov et al describes rather accurately the course of fracture toughness within the range of porosities above 20 %, that evidences the critical role of the above process.

The finded maximum of fracture toughness correlates well with stereological parameters of a porous structure, and particularly with the connectedness of pores. Saltykov (10) has shown that transition from isolated pores to connected ones is completed when porosity equals about 20-25 %. This fact also confirms the correctness of the carried out analysis.

Thus, the fracture mechanism determines the type of dependence of fracture toughness of brittle powder material on porosity. Material fracturing intergranularly has monotonously decreasing fracture toughness vs increasing porosity. In that time, material fracturing by cleavage has non-monotonously changing dependence with the maximum when the connectedness of porous structure becames equal 1.

The competition of processes of reducing braking by pores with growing porosity controls the course of the curve of dependence of fracture toughness of brittle materials on porosity. At the same time, an increase of K_{IC} with a growth of porosity is of the greatest interest since it opens ways to the development of materials with high fracture toughness.

SYMBOLS USED

P = porosity (%)

b = constant

K^o_{Ic}, K_{Ic} = fracture toughness of non-porous and porous material respectively

E_o, E = elastic modulus of non-porous and porous materials respectively

σ_o, σ = strength of non-porous and porous materials respectively

γ_o, γ = surface energies of non-porous and porous materials respectively

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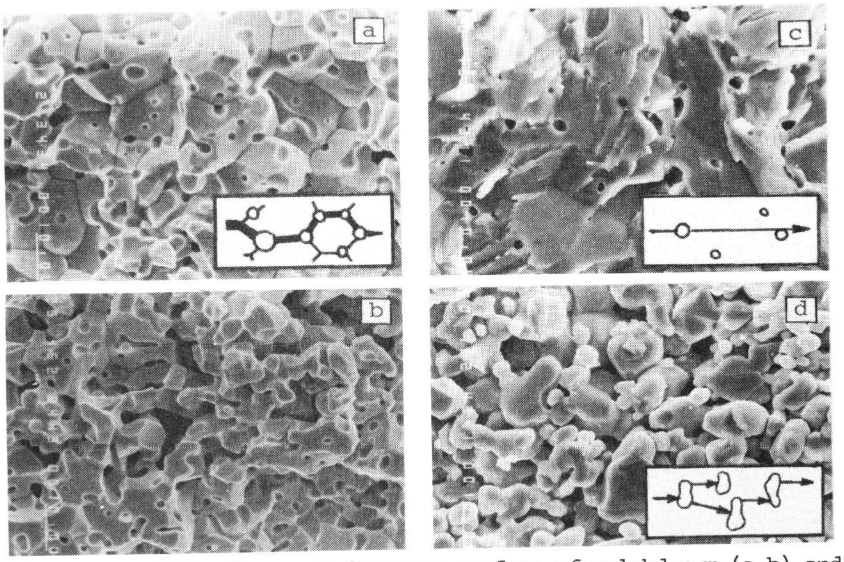
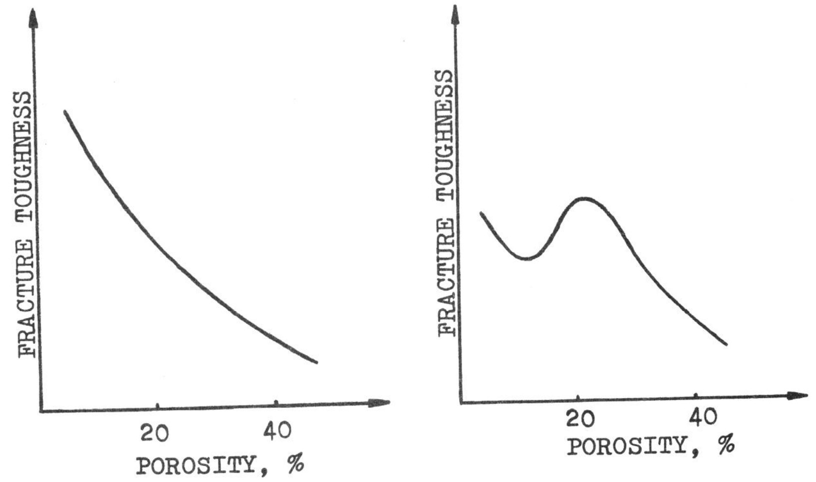


Figure 1. SEM views of fracture surface of molybdenum (a,b) and chromium (c,d) with different porosity: a-10%, b-30%, c-7%, d-25 %.



a

b

Figure 2. Dependencies of fracture toughness of sintered molybdenum (a) and chromium (b) on porosity.