JOURNAL OF MATERIALS SCIENCE 28 (1993) 6737–6740

# Measurements of internal friction coefficient of SiC and $Al_2O_3$ powders

R. CORTÉS, M. A. MARTÍNEZ, C. NAVARRO, V. SÁNCHEZ-GÁLVEZ
*Department of Materials Science, E.T.S. de Ingenieros de Caminos, Canales y Puertos, Polytechnic University of Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain*

The frictional strength of the powder of two ballistic materials (SiC and $Al_2O_3$) under low confining pressures has been studied statically and dynamically. In the static tests, the influence of the ceramic fragment size upon the internal friction coefficient value was investigated. In the dynamic tests, the effect of the ceramic fragment size, the relative sliding velocity and the confinement load were studied. It was found in the experimental conditions, that the influence of the fragment size and of the relative sliding velocity upon the internal friction coefficient value of comminuted SiC and $Al_2O_3$ is important.

## 1. Introduction

Ceramic-faced armours backed by metallic or composite plates have proved to be a very efficient arrangement for defeating ballistic projectiles. Strong ceramics are of great practical importance in designing such composite armours, owing to their erosive properties when subjected to highly energetic attack by penetrators.

After impact on a ceramic composite armour, a complex stress state is generated, where compressive stress waves move through the target reflecting at the ceramic/backing plate interface as tensile waves. Thus both tensile and compressive fracture may take place. The fracture of ceramics leads to the formation of a fine powder which may deform non-reversibly by the relative motion of the ceramic fragments. Frictional effects may, therefore, be important and they are a cause of the ability of comminuted ceramic to support deviatoric stresses. The importance of this comminuted ceramic zone ahead of the projectile in ceramic penetration has been pointed out by several authors [1–4]. To study this property of pulverized ceramic, impact experiments at high velocities of tungsten rods on confined ceramic targets have been performed [4]. Thus, for the projectile to advance, it is required that the comminuted ceramic material in front of the penetrator moves away from its path, a conclusion which is confirmed from fractographic observations. Therefore, projectile penetration is mainly controlled in these conditions by the Coulomb frictional forces developed in the comminuted ceramic zone.

In ceramics, most of the research performed in the past refers to intact material, whereas little information dealing with pulverized ceramic is available in the open literature. Attempts have been made to quantitatively determine the properties of granular ceramics by Johnson *et al.* [5], who performed quasistatic tests on comminuted SiC and estimated an internal friction coefficient for this material of 0.46. Klopp and Shockey [6] used a symmetric plate impact technique to study the dynamic behaviour of SiC. By measuring the transverse velocity history, they performed numerical simulations of the experiment, varying the parameter values of the constitutive model employed, until a reasonable agreement with experimental measurements was obtained. On this basis, they concluded that the internal friction coefficient for SiC in such conditions is about one-half to one-fourth of that obtained by Johnson *et al.* [5] under quasistatic conditions.

The behaviour of granular materials has been also the subject of theoretical investigation. Rudnicki and Rice [7] have developed a macroscopic model for the behaviour of granular materials, introducing the concept of an internal friction coefficient, $\mu$. This parameter relates the equivalent shear stress, $\tau$, borne by the material and the hydrostatic pressure, $\sigma$, acting on it by the expression $\tau = \mu\sigma$ [7]. Other authors have attempted statistical descriptions of the behaviour of planar arrays of granular materials [8, 9]. In this manner, it has been possible to relate the value of the internal friction coefficient, $\mu$, for planar assemblies of discs, to the sum of the contributing anisotropy in contact normals and anisotropy in the distribution of average normal and average tangential contact forces [8].

In this work, an experimental study of the ability of silicon carbide and alumina powder to bear shear stresses under low confining pressures was undertaken. Both static and dynamic tests were performed. In this way, the internal friction coefficient, $\mu$, ($= \tau/\sigma$) was determined for different fragment sizes, relative sliding velocities and confinement loads. In the experimental conditions, it was found that both the fragment size and the relative sliding velocity may have an important influence in the internal friction coefficient.

## 2. Experimental procedure

The determination of the internal friction coefficient of the SiC and $Al_2O_3$ ceramic fragmented material, was attempted by use of some techniques originally conceived for application in soil mechanics. A detailed description of such techniques has been given elsewhere [10], and only a brief explanation will be included here.

The determination of the static internal friction coefficient was attempted in two different ways. The first one consisted of pouring the ceramic powder on a funnel and thus giving rise to the formation of a conical-like volume of material as the falling powder is deposited on a horizontal plane. From a well-established result of soil mechanics, it is known that the value of the angle with respect to the horizontal of the generatrix of the above conical-like volume, coincides with the internal friction angle of the material [10]. The second method consisted of filling a box with transparent walls with the ceramic powder, and then suddenly removing one of the walls. The final angle of inclination of the surface of the ceramic fragmented material with respect to the horizontal coincided again with the internal friction angle of the material [10]. In practice, both methods gave very similar results, and the results obtained with both methods were averaged to estimate the final static internal friction coefficient value corresponding to each case.

The dynamic estimation of the internal friction angle was attempted by use of the arrangement depicted in Fig. 1, and further described elsewhere [10]. In such an arrangement the ceramic fragmented material is placed between two boxes, having a cross-sectional area of 34.77 $cm^2$. Then, the powder is confined by the application of a compressive load. A relative oscillatory motion between the boxes is imposed by a vibrator, and the friction force developed in the powder is recorded. Then, the internal friction coefficient, $\mu$, is simply computed as the quotient between the friction force developed in the ceramic powder and the total applied compressive load [10].

## 3. Results

Static internal friction coefficient values for SiC and $Al_2O_3$ as a function of the average fragment size are plotted in Fig. 2. It is observed in this figure that for both materials the internal friction coefficient first decreases with increasing fragment size, and then begins to increase slightly with increasing fragment size.

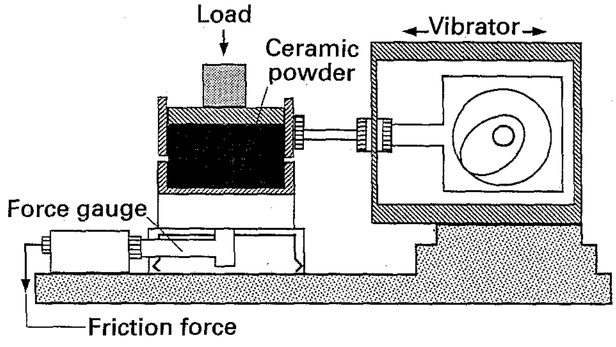


*Figure 1* Arrangement employed in the dynamic estimation of the internal friction coefficient.

Fig. 3 shows the typical shape of the frictional force versus time curves obtained in the dynamic tests. For the two cases shown, the force initially increases and after a small peak it continues to increase up to the instant when the frictional force stabilizes. This latter stabilized value was employed to compute the internal friction coefficient in each case, by taking as a reference the value of the frictional force measured in the absence of ceramic powder. Fig. 4 shows the dynamic internal friction coefficient for SiC and $Al_2O_3$ as a function of the fragment size, for a relative sliding velocity of 40 $mm\,s^{-1}$ and a confinement load of 52 N. We see that the initial tendency of the friction coefficient to decrease with increasing fragment size is enhanced compared with the static case. There is a similar tendency for this parameter to increase after reaching a minimum in the $\mu$ versus fragment size curve.

Fig. 5 shows the internal friction coefficient value for SiC and $Al_2O_3$ as a function of the confinement load, for a relative sliding velocity of 40 $mm\,s^{-1}$ and the indicated values of fragment size. For alumina, a marked increase in the friction coefficient is initially observed, followed by a region of relative stabilization of its value. For SiC, only a slight tendency to increase

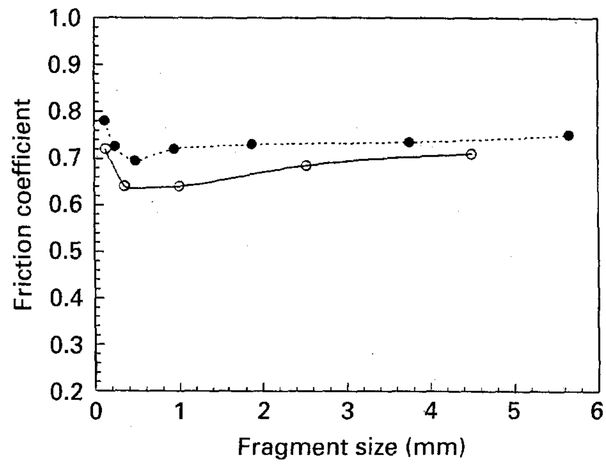


*Figure 2* Static internal friction coefficient values for (—O—) SiC and (---●---) $Al_2O_3$, as a function of the ceramic fragments size.

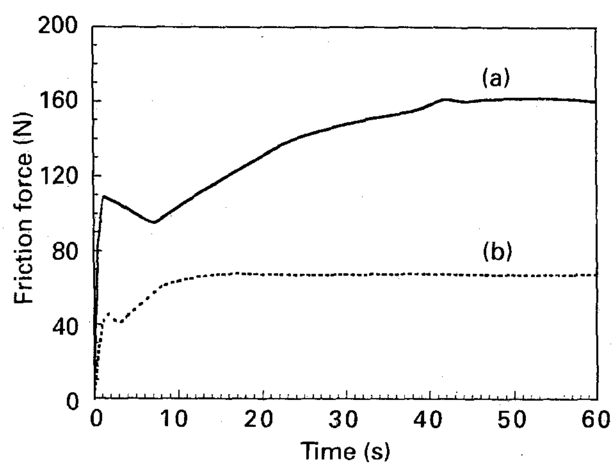


*Figure 3* Typical friction force versus time curves corresponding to the dynamic tests for $Al_2O_3$. (a) Fragment size 0.47 mm, $V = 40\ mm\,s^{-1}$, $F_N = 250$ N. (b) Fragment size 3.75 mm, $V = 40\ mm\,s^{-1}$, $F_N = 52$ N.

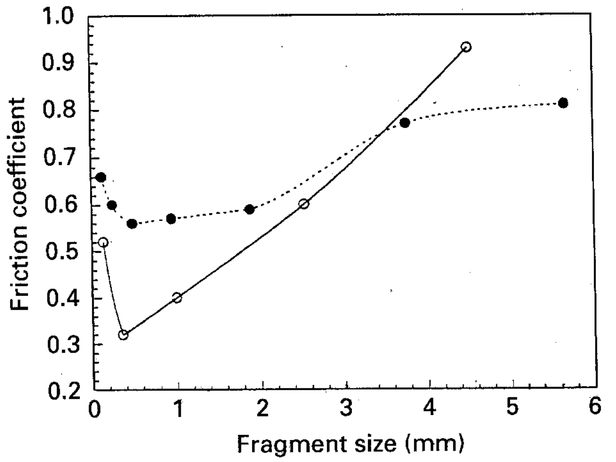


*Figure 4* Dynamic internal friction coefficient for (—○—) SiC and (---●---) $Al_2O_3$, as a function of the fragment size, for a sliding velocity of 40 mm $s^{-1}$ and a confinement load of 52 N.

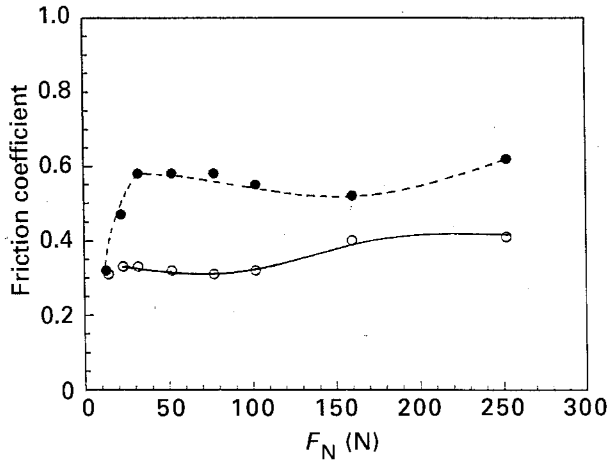


*Figure 5* Dynamic friction coefficient for (○) SiC (fragments size 0.35 mm) and (●) $Al_2O_3$ (fragments size 0.47 mm), as a function of the confinement load for a sliding velocity of 40 mm $s^{-1}$.

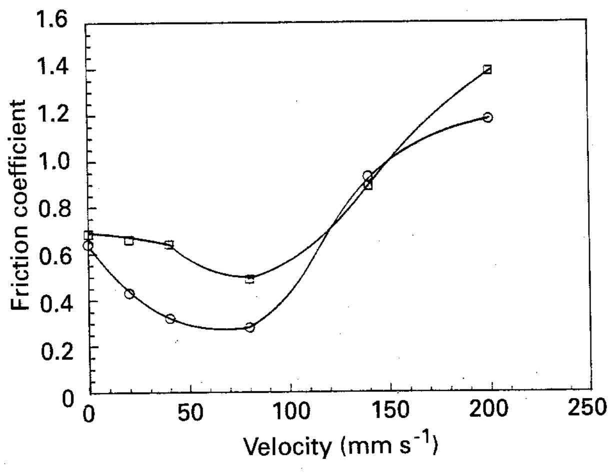


*Figure 6* Dynamic friction coefficient value for SiC, as a function of the relative sliding velocity, for a confinement load of 52 N and fragment sizes of (○) 0.35 mm and (□) 2.52 mm.

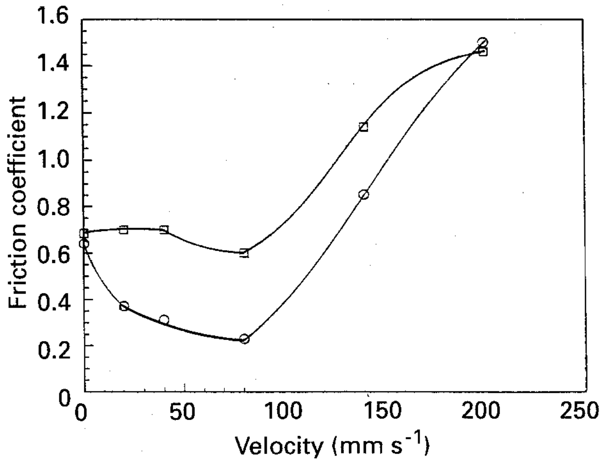


*Figure 7* Dynamic friction coefficient value for SiC, as a function of the relative sliding velocity, for a confinement load of 77 N and fragment sizes of (○) 0.35 mm and (□) 2.52 mm.

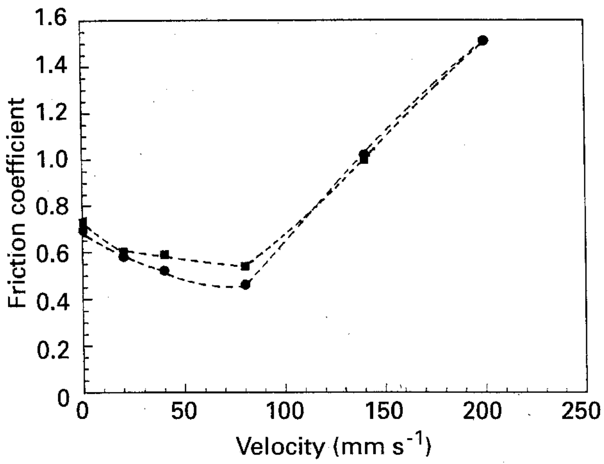


*Figure 8* Dynamic friction coefficient value for $Al_2O_3$, as a function of the relative sliding velocity, for a confinement load of 52 N and fragment sizes of (●) 0.47 mm and (■) 1.87 mm.

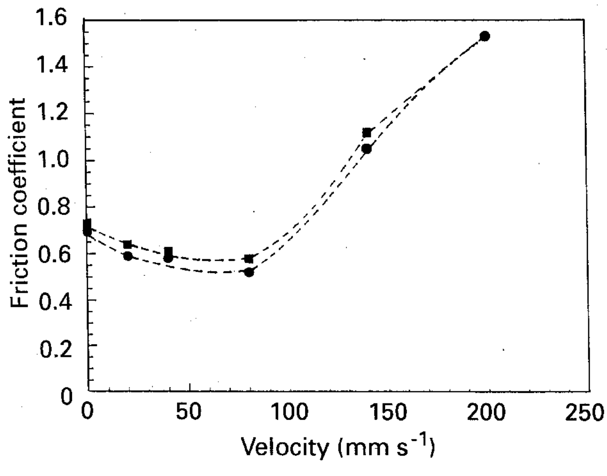


*Figure 9* Dynamic friction coefficient value for $Al_2O_3$, as a function of the relative sliding velocity, for a confinement load of 77 N and fragment sizes of (●) 0.47 mm and (■) 1.87 mm.

of the internal friction coefficient value with increasing applied load is detected. Figs 6 and 7 show the friction coefficient values of SiC as a function of relative sliding velocity, for fragment sizes 0.35 and 2.52 mm, and for confinement loads of 52 and 77 N, respectively. Figs 8 and 9 show the friction coefficient values of $Al_2O_3$ as a function of the relative sliding velocity and for fragment sizes of 0.47 and 1.87 mm, and for confinement loads of 52 and 77 N, respectively. We appreciate that for both materials, there is an important influence of sliding velocity on the friction coefficient value, which reaches values larger than unity for the largest velocities tested. Moreover, from Figs 6 and 7 it is apparent that an increase in the fragment size of silicon carbide powder tends to cause an increase in the internal friction coefficient, especially in the low-velocity range. This effect is much less marked for alumina (see Figs 8 and 9).

## 4. Discussion

An outstanding result of the present investigation is the marked dependency, under dynamic conditions, of the internal friction coefficient of fragmented SiC and $Al_2O_3$ on factors such as the fragment size and the relative sliding velocity. In effect, whereas under static conditions the internal friction coefficient for both materials with increasing fragment size tends to vary little (see Fig. 2), the variations in the value of $\mu$ under dynamic conditions are greatly enhanced (see Fig. 4), causing an important increase in the internal friction coefficient value with the fragment size after the minima of the curves shown in Fig. 4 are surpassed. A similar effect is observed if the relative sliding velocity exceeds a value of, say, $120\ \mathrm{mm\,s^{-1}}$ (see Figs 6–9), where an abrupt increment in the internal friction coefficient with the relative sliding velocity takes place. On the contrary, it seems that, for the values of sliding velocity and fragment size specified in Fig. 5, if the confinement load reaches a critical value, a relatively stable compaction state is reached under dynamic conditions, in such a manner that the internal friction coefficient varies little if the confinement load is increased further.

The above results suggest than when an impacting projectile penetrates a ceramic plate, the friction coefficient of the ceramic fragments generated by the impact will be greatly affected by the size of the fragments and by the relative sliding velocities between them. From the present work, there is insufficient information to estimate the influence of the confinement pressures on $\mu$ in the range of high confining pressures developed during impact. Also, it seems that very high $\mu$ values (even larger than unity) may be developed in the fragmented ceramic, both for silicon carbide and alumina, for sufficiently large relative sliding velocities. This may suggest that, under certain conditions, fragmented ceramic may retain at least a fraction of the ballistic efficiency of undamaged ceramic.

## 5. Conclusions

The internal friction coefficient values of two ballistic ceramics, SiC and $Al_2O_3$ have been determined, statically and dynamically. The influence of factors such as fragment size, confinement load and relative sliding velocity on the internal friction coefficient values has been assessed. Under the experimental conditions, factors such as fragment size and relative sliding velocity were found to have an important influence on the dynamic internal friction coefficient value for both SiC and $Al_2O_3$. This fact is of great importance with regards to the understanding of the ballistic performance of ceramic-faced armours, as well as in the numerical simulation of impact on ceramics.

## References


1. J. MESCALL and C. TRACY, "Improved Modelling of Fracture in Ceramic Armour", in Proceedings of the 1986 Army Science Conference, US Military Academy, West Point (1986).
2. J. MESCALL and V. WEISS, "Materials Behaviour Under High Stress and Ultrahigh Loading Rates–Part II", in Proceedings of the 29th Sagamore Army Conference, Army Materials and Mechanics Research Center, Watertown, MA, (1984).
3. D. R. CURRAN, L. SEAMAN and T. COOPER, "Micromechanical Model for Comminution and Granular Flow of Brittle Material Under High Pressure and High Strain Rate; Application of Penetration of Ceramic Plates", Progress Report of SRI to the Office of Naval Research, Contract no N00013-88-C-0734 (1991).
4. D. A. SHOCKEY, A. H. MARCHAND, S. R. SKAGGS, G. E. CORT, M. W. BURKETT and R. PARKER, *Int. J. Impact Eng.* **9** (1990) 263.
5. G. R. JOHNSON, T. J. HOLMQUIST, J. LANKFORD, C. E. ANDERSON and J. WALKER, "A Computational Constitutive Model and Test Data for Ceramics Subjected to Large Strains, High Strain Rates and High Pressures", Final Technical Report on Optional Task I, Department of Energy Contract DE-AC04-87AL-42550 (1990).
6. R. W. KLOPP and D. A. SHOCKEY, *J. Appl. Phys.* **70** (1991) 7318.
7. J. W. RUDNICKI and J. R. RICE, *J. Mech. Phys. Solids* **23** (1975) 371.
8. R. BATHURST and L. ROTHENBURG, *Mech. Mater.* **9** (1990) 65.
9. G. SUBHASH, S. NEMAT-NASSER, M. MEHRABADI and H. SHODJA, *ibid.* **11** (1991) 87.
10. M. A. MARTÍNEZ, R. CORTÉS, V. SÁNCHEZ-GÁLVEZ and C. NAVARRO, *J. Test. Eval.* **21** (1993) 494.



*Received 27 January*
*and accepted 7 May 1993*