JOURNAL DE PHYSIQUE
Colloque C3, Supplément au n°9, Tome 49, septembre 1988 C3-333

STRESS-WAVE-INDUCED DAMAGE IN ALUMINA

L.H.L. LOURO, A. LINDFORS and M.A. MEYERS

Center for Explosives Technology Research, New Mexico Institute of Mining and Technology, Socorro, NM 87801, U.S.A.

Résumé - La fragmentation de l'alumine sous des conditions d'impact a été etudiée. Les paramètres matériaux et de choc ont étés variés pour établir les mécanismes et la cinétique de fragmentation. Les essais ont étés conduits dans un canon à gaz, et les disques d'alumine ont étés confinés dans des capsules de cuivre et d'aluminium, pour produire des tensions de compression et compression suivie de traction, respectivement. Les essais ont démontré que la fragmentation se manifeste à des tensions de compression bien au dessous du limite élastique de Hugoniot. La fragmentation depend aussi de la pureté de l'alumine, de la taille du grain, et de la durée du pulse de tension. L'addition de la zircone partiellement stabilisée ne mène pas à un améliourissement de la résistance à la fragmentation.

Abstract - The fragmentation of alumina under impact conditions has been investigated. Shock and material parameters were varied in order to better understand the mechanisms and kinetics of fragmentation. Impact was carried out in a gas gun, and the alumina disks were confined in copper and aluminum capsules, to produce, respectively, compressive and compressive + tensile pulses in the alumina. It was found that compressive stresses below the Hugoniot elastic limit produce fragmentation. The disks in the aluminum capsules undergo considerably more fragmentation than in copper capsules. Fragmentation is also dependent on alumina purity, grain size, and duration of the stress pulse. The addition of partially stabilized zirconia does not lead to an enhancement in the resistance to fragmentation.

1- INTRODUCTION

Ceramic materials are used, in military applications, as components of armor systems, because of their low density and high dynamic compressive strength. The objective of this work was to investigate the effects of internal and external variables on dynamically loaded alumina, in order to understand its fracture and fragmentation behavior. The dynamic behavior of alumina has been intensively studied in the past years /1-4/. Nevertheless, many uncertainties exist regarding the mechanisms of fragmentation.

2- EXPERIMENTAL PROCEDURES

2.1- MATERIAL CHARACTERIZATION: Three aluminas were used in this investigation: (i) High-Purity Alumina (HP-Alumina); (ii) Low-Purity Alumina (LP-Alumina); (iii) Alumina-Partially Stabilized Zirconia (PSZ-Alumina). Table 1 shows some static properties of the materials studied. The disks (38 mm diameter by 6.35 thickness) were pressed and sintered at 1700 °C. The HP-Alumina was heat treated (1900 °C, 30 min), and its grain was grown from 4 to 24 µm average size. Thus, the effect of grain size could be investigated. The HP-alumina contained approximately 99.4 % alumina, and was prepared by Honeywell, while the low-purity alumina was the Coors AD-85 (85 % alumina). The PSZ-alumina contained 13.45 wt% zirconia partially stabilized with 1 % yttria.

Table 1: Static Properties of Aluminas.

Ceramic	Density (g/cm^3)	Porosity (%)	Grain Size (µm)	K_{IC} (MPa.m$^{1/2}$)
HP-Al_2O_3	3.865	3.14	4.2 and 24	4.0
LP-Al_2O_3	3.410	11.0	6.0	3.4
PSZ-Al_2O_3	4.147	-	-	-

2.2- DYNAMIC TESTS: Planar recovery impact experiments were conducted in a 63.5 mm gas-gun. Impact velocities were measured and ranged between 200 and 1000 m/s. The corresponding stresses were in the range of 3.5 - 10.0 GPa. The pressures and stress durations were predicted by one-dimensional hydrocode (SWAP/5/), as well as by the impedance matching technique using the equations of state for HP and LP-aluminas/1/. A schematic representation of the impact assembly is shown in Figure 1. Special capsules were designed to confine the ceramics and to generate the desired stress states in alumina. Tensile stresses could be separated from compressive stresses by using aluminum and copper as capsule materials. The choice of these capsule materials was based on their relative shock impedance when compared with that of alumina. Figure 2 shows the capsule design and Figure 3 shows SWAP predictions of capsule performance (Cu and Al). A tensile pulse is generated in the alumina by using the Al capsule; no tension is generated with the copper capsule. The flyer plate was attached to the front of a nylatron sabot; the flyer plate and capsule material were the same.

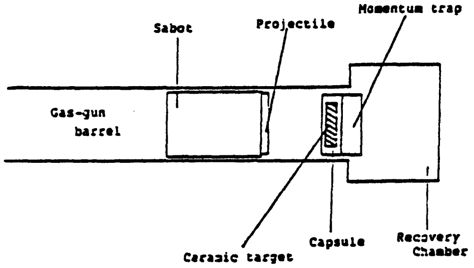

Fig. 1 - Schematic representation of gas-gun assembly.

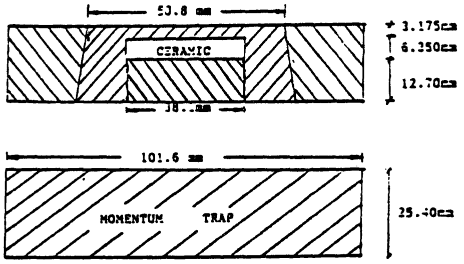

Fig. 2 - Capsule for confinement of ceramic surrounded by spall disk and backed by momentum trap.

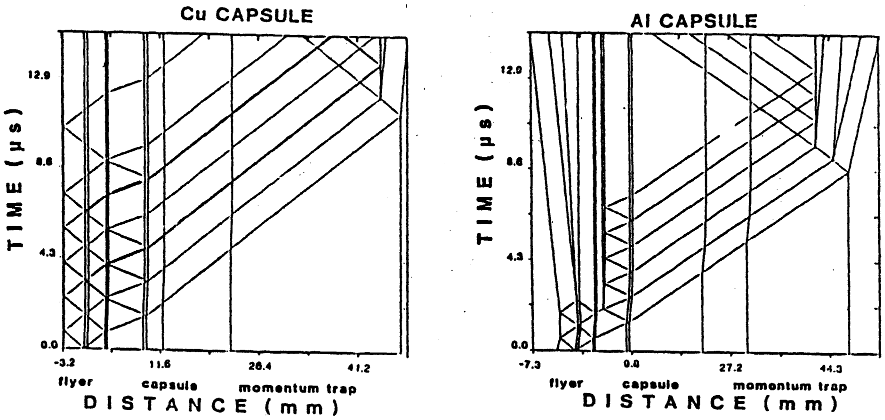

Fig. 3 - SWAP code predictions of stresses for aluminum and copper capsules.

2.3- PARAMETERS INVESTIGATED: Two groups of parameters were investigated, and Table 2 summarizes the variables studied.

Table 2: Parameters Investigated.

Parameter	Variable	Variable Range
Internal	Grain Size	4 µm and 24 µm.
	Purity	85% and 99.4% of Alumina.
	2nd Phase	HP-Alumina and PSZ-Alumina.
External	Pressure	3.5, 4.6, 7.5, 10.0 GPa.
	Pulse Duration	0.5, 1.0, 1.6 µs.
	Stress State	Compressive and Compressive + Tensile stresses.

Internal parameters were intended at investigating the microstrutural effects on alumina fragmentation. External parameters were concerned with particular conditions to which the alumina can be submitted. Pressure was changed by varying the impact velocity, and pulse duration was varied by changing the flyer plate thickness.

2.4- POST-IMPACT CHARACTERIZATION: After impact, the recovered capsules were opened and the ceramics were cut in a direction parallel to the impact direction. Then, a black-colored resin was introduced into the impact-generated cracks, by using a vacuum furnace, in order to highlight the crack paths. Optical micrographs were obtained, and from them macrocrack measurements were done, using the line intercept method of quantitative metallography. Scanning electron fractography was performed on the cracks generated in the spall regions of the aluminas. Transmission electron microscopy samples were prepared to identify internal damage produced by shock in the ceramics. Optical microscopy at higher magnifications (200 - 400 X) was done by preparing thin slices by standard petrographic techniques.

3- RESULTS AND DISCUSSION

3.1- EFFECT OF GRAIN SIZE ON ALUMINA FRAGMENTATION: The effect of grain size on alumina fragmentation is shown in Figure 4, which shows the amount of fragmentation, at two pressure levels, occurring in 4 and 24 µm grain sizes. Sv gives the macroscopic surface area per unit volume, and it provides a quantitative value of alumina fragmentation. The fragmentation decreases significantly as the grain size increases. Scanning electron fractography revealed a predominant intergranular fracture in alumina, as illustrated in Figure 5. It is an expected fracture behavior since alumina exhibits an anisotropic hexagonal structure, which causes tensile regions along its grain facets. Considering the fragmentation process as a sequence of nucleation, growth, and coalescence of cracks, and that the grain boundaries are the main sources for crack nucleation, the number of crack nuclei will be smaller for the alumina with larger grain, leading to less fragmentation, as was observed.

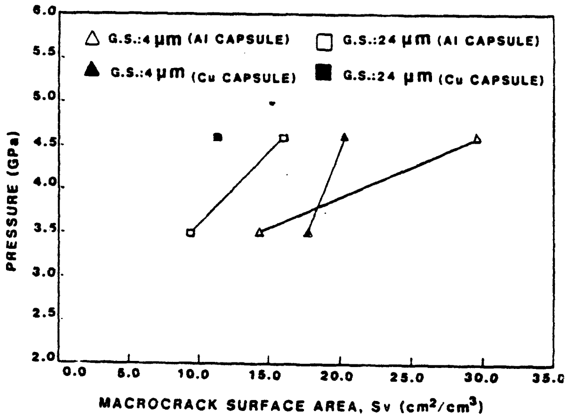

Fig. 4 - Influence of grain size on alumina fragmentation.

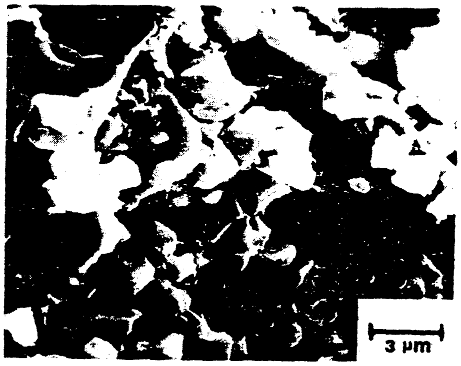

Fig. 5 - Scanning electron micrograph of spall surface.

3.2- EFFECT OF PURITY ON ALUMINA FRAGMENTATION: The effect of purity is illustrated in Figure 6. Under compressive stresses (Cu capsule), fragmentation was about the same both in HP-Alumina and LP-Alumina (AD-85) at the pressure level of 3.5 GPa; much more fragmentation was observed in AD-85 at the higher pressure level of 4.6 GPa. Since the degree of porosity in alumina increases as the purity decreases, the greater porosity in AD-85 (see Table 1) is probably responsible for the fragmentation behavior under compressive stresses. When a pore is uniaxially compressed, it deforms and stresses are generated at its ends. Cracks generated in this fashion are usually oriented perpendicular to the direction of compression/6/. Figure 7 shows optical micrograph where this crack orientation tendency was observed. Conversely, cracks parallel to the direction of propagation of the compressive pulse are generated by Griffith's mechanism/7/. On the other hand, under tensile stresses (Al capsule), more fragmentation was observed in HP-Alumina. It is probably due to larger shock impedance of HP-Alumina, which provides a larger tensile release wave, as compared with AD-85. For instance, by compressing both aluminas at 4.6 GPa, a tensile stress of 1.7 GPa was generated in HP-Alumina, while only 0.96 GPa was produced in AD-85. Larger tensile stress means larger number of crack nuclei, and, hence, more fragmentation.

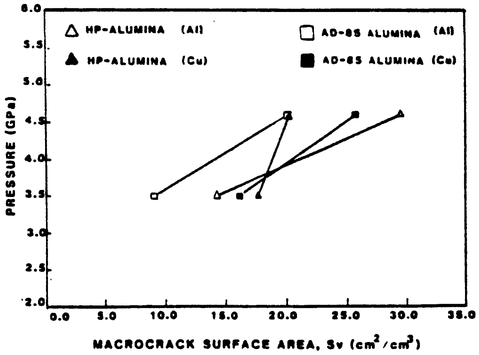

Fig. 6 - Influence of purity on alumina fragmentation.

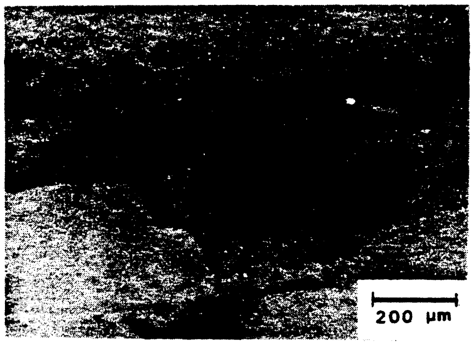

Fig. 7 - Perpendicular grid of cracks generated by compressive stresses.

3.3- EFFECT OF 2nd PHASE IN ALUMINA: The presence of PSZ in alumina did not lead to an enhancement in the resistance to fragmentation, as can be seen in Figure 8. X-ray analysis prior to and after shock of PSZ-Alumina revealed that tetragonal zirconia does not transform to monoclinic. Because the toughening benefit of zirconia phase transformation could not be explored, PSZ-Alumina dynamically loaded did not provide a decrease in alumina fragmentation.

3.4- EFFECT OF PRESSURE LEVEL: This effect is illustrated in Figure 9. The larger the pressure, the greater is the corresponding fragmentation. It is believed to be caused by the activation of larger number of crack nuclei at higher pressure levels.

3.5- EFFECT OF PULSE DURATION: Pulse duration was varied at the pressure level of 4.6 GPa. The result is shown in Figure 10, which shows that the fragmentation of alumina increases strongly when the pulse duration is increased. Since crack nucleation is time dependent, more cracks nucleate and grow at longer times, leading to an increase in fragmentation.

3.6- EFFECT OF STRESS STATE: Copper capsules, generating a compressive pulse, caused less fragmentation than aluminum capsules, which generate compressive and tensile pulses. Since cracks are driven by tensile stresses, and they are more effective in Al capsules, more fragmentation was observed in this type of capsule, as illustrated in Figure 9.

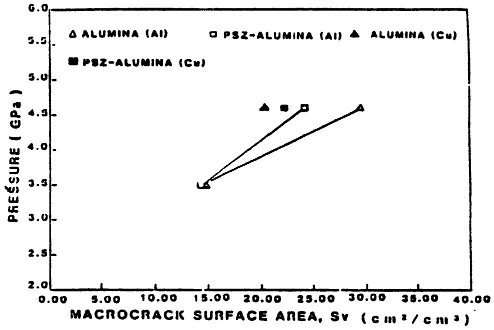

Fig. 8 - Influence of second phase on alumina fragmentation.

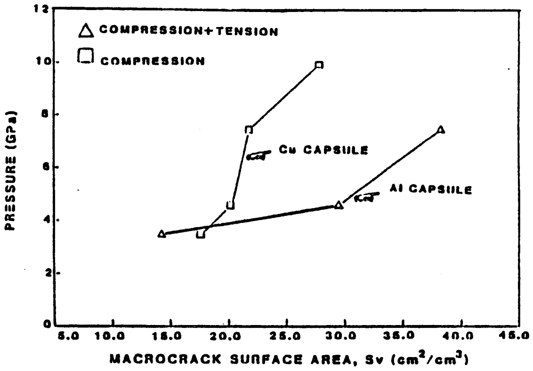

Fig. 9 - Influence of pressure on alumina fragmentation.

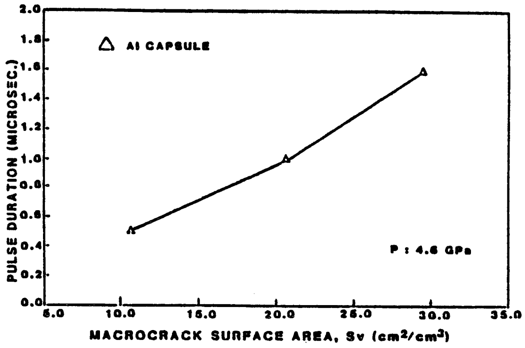

Fig. 10 - Influence of pulse duration on alumina fragmentation.

4- CONCLUSIONS

Alumina fragmentation has been shown to be very sensitive to stress state, pressure, pulse duration, as well as the microstructural parameters, of grain size, and purity. Partially stabilized zirconia did not improve the dynamic fracture toughness of alumina. Considerable fragmentation was obtained by compressive stresses substantially lower than the Hugoniot elastic limit.

REFERENCES

/1/ Yaziv, D., "Shock Fracture and Recompaction of Ceramics", Ph. D. Thesis, U. of Dayton, Ohio, July 1985.
/2/ Yeshurun, Y. and Brandon, D. G., Proc. IMPACT 87, DGM, W. Germany, in press, 1988.
/3/ Longy, F. and Cagnoux, J., Proc. IMPACT 87, DGM, W. Germany, in press, 1988.
/4/ Brusso, J. A., Mikkola, D. E., Flynn, J. E. and Kelsey, P. V., Scripta Met., 22 (1988) 47.
/5/ Barker, L. M., "SWAP-7: A Stress Wave Analyzing Program", Res. Rep. SC-RR-67 143, Sandia National Laboratories, NM, 1967.
/6/ Nemat Nasser, S. and Hori, M., J. Appl. Phys. 62 (1987) 2746.
/7/ Griffith, A. A., Philos. Trans. R. Soc. London., A221 (1920) 275.