Dynamic yield and tensile strengths of spark plasma sintered alumina

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Abstract. Fully dense alumina samples with 0.6-µm grain size were produced from alumina powder using Spark Plasma Sintering and tested in two types of VISAR-instrumented planar impact tests. In the tests of the first type the samples of 0.28 to 6-mm thickness were loaded by 1-mm tungsten impactors accelerated up to a velocity of about 1 km/s. These tests were aimed to study the Hugoniot elastic limit (HEL) of the SPS-processed alumina and the decay of the elastic precursor wave with propagation distance. In the second type of test the samples of ~3-mm thickness were loaded by 1-mm copper impactors accelerated up to velocities 100-1000 m/s. These tests were aimed to study the dynamic tensile (spall) strength of the alumina. The data on tensile fracture of the alumina demonstrate a monotonic decline of the spall strength with the amplitude of the loading stress pulse. The data on the decay of the elastic precursor wave allows for determining the rates of the irreversible (inelastic) strains in the SPS-processed alumina at the initial stages of shock-induced inelastic deformation and, thus, to derive some conclusions concerning the mechanisms responsible of the deformation.

1. Introduction
During the last five decades the impact response of aluminum oxide ceramics (\textit{Al}_{2}\textit{O}_{3}, alumina) has been the subject of multiple studies. As a result, the impact response of different aluminas is defined well, and the influence of the structural features such as porosity or purity on dynamic mechanical properties is well established [1, 2]. At the same time the mode, either ductile or brittle, of inelastic deformation of alumina shock-loaded above its Hugoniot elastic limit (HEL) is still unclear. An experimental technique which is capable of providing information about the character of the elastic-inelastic transition in a given material is measurements of the decay of the elastic precursor wave with propagation distance [3]. In the acoustic approximation [4], the decay of shear stress at the HEL is related to the plastic strain rate $\dot{\gamma}$ as:

$$\frac{d\tau_{\text{HEL}}}{dh} = -\frac{4}{3} \frac{G^2 \dot{\gamma}}{E' c_l}$$

(1)
where \( h \) is the Lagrangian coordinate, \( \rho_0 \) is the initial material density, and \( E' = \rho_0 c_t' \) and \( G = \rho_0 c_s' \) are, respectively, the material longitudinal and shear moduli. Availability of the material strain rate function \( \tau_{HEL} = \tau_{HEL}(\dot{\gamma}) \) makes it possible to derive some conclusions about the mode of the material behavior at the onset of inelastic deformation.

Respectively, the purpose of the present study was to characterize the dynamic response of an alumina ceramic produced by Spark Plasma Sintering (SPS) [5]. This was done by measuring the yield and spall strengths and the decay of the elastic precursor wave.

2. Material and Experiments

The samples of SPS alumina were produced from 0.4-µm powder of Al₂O₃ of 99.99-% purity. The sintering of alumina disks of 30-mm diameter an 6 and 3 mm nominal thickness was performed at 1300 °C with a holding time of 20 min. under 65-MPa pressure. The average density, longitudinal and shear speeds of sound of the SPS alumina are equal to \( \rho_c = 3.947 \pm 0.006 \) g/cc, \( c_t = 10.90 \pm 0.03 \) km/s, and \( c_s = 6.42 \pm 0.02 \) km/s, respectively. The 3 and 6-mm samples were ground to 0.1 mrad plane parallelism. A portion of the 3-mm samples were ground down to nominal thicknesses of 1, 0.5, and 0.25 mm. In order to enhance reflectivity a 1-µm gold layer was vapor deposited on the rear surfaces of the samples. The yield strength and decay of the elastic precursor wave in the SPS alumina were studied in the planar impact tests with 1-mm W impactors accelerated in a 25-mm smooth bore gun up to velocities of about 1 km/s. In these tests the velocity of either free sample surface or of the sample/window interface (5.8-mm PMMA) was monitored by VISAR [6]. The spall strength of 6 and 3-mm alumina was studied in a series of planar impact tests with 1-mm Cu impactors having velocities between 150 and 1000 m/s. These tests were performed with the PMMA windows.

3. Experimental results

Typical free surface and interface velocity histories recorded in the HEL-oriented tests on samples of different thicknesses are shown in figure 1. In all the tests the samples were loaded by 1-mm tungsten impactors accelerated up to the velocity of about 1 km/s. All the waveforms contain an elastic precursor wave followed by an inelastic compression wave. The amplitude of the elastic precursor wave (HEL) is observed to decay with propagation distance (shown in figure 2).

![Figure 1. Velocity histories recorded after tests with SPS alumina samples of different thickness (in mm near the waveform). Dashed curves correspond to the tests with PMMA window.](image1)

![Figure 2. Amplitudes of elastic precursor waves in SPS alumina obtained in the tests without (circles) and with (triangles) window as a function of propagation distance.](image2)
Based on the recorded velocity histories of the HEL stress, \( \sigma_{\text{HEL}} \), may be found as
\[
\sigma_{\text{HEL}} = \frac{1}{2} \rho_0 c_{\text{HEL}} \text{ or } \sigma_{\text{HEL}} = \frac{1}{2} (\rho_0 c_{\text{HEL}} + \rho_{\text{PMMADPMMA}} D_{\text{PMMADPMMA}}) u_{\text{HEL}} \]  
while the test is performed without and with the PMMA window, respectively. The PMMA Hugoniot data [7] were used for determination of the shock impedance \( \rho_{\text{PMMADPMMA}} D_{\text{PMMADPMMA}} \). Amplitudes of the elastic precursor waves in the SPS alumina are shown in figure 2 as a function of the propagation distance.

Typical interface velocity histories recorded in the spall oriented tests with the SPS alumina are shown in figure 3. The spall strength of the SPS alumina was determined based on the interface velocity values marked in figure 3 as \( u_2 \) and \( u_3 \) [8]:
\[
\sigma_{\text{sp}} = \frac{1}{2} \left[ (u_1 - u_2) Z_{\text{cer}} - (\sigma_1 + \sigma_2) \right] \quad (2)
\]
\[
\sigma_{\text{sp}} = \frac{1}{2} \left[ (u_3 - u_2) Z_{\text{cer}} + (\sigma_3 - \sigma_2) \right] \quad (2a)
\]
where \( \sigma_1 \), \( \sigma_2 \), and \( \sigma_3 \) are the stress states of the PMMA window after loading \( (u_1) \), unloading \( (u_2) \), and reloading \( (u_3) \), respectively, and \( Z_{\text{cer}} \) is the impedance of the alumina. As previously, for estimating both of the spall strength and of the peak impact stress \( \sigma_{\text{peak}} \) the PMMA Hugoniot [7] was used.

![Figure 3](image_url)

**Figure 3.** Typical interface velocity histories recorded in spall-oriented tests with the SPS alumina. The arrows show the velocity values employed in the calculations of the spall strength.

![Figure 4](image_url)

**Figure 4.** Spall strength of 3-mm (circles) and 6-mm (triangles) samples of the SPS alumina as a function of the peak impact stress.

While the peak impact stress does not exceed the alumina HEL the spall strength estimates (equations (2) and (2a)) give similar results. As soon as the HEL value is exceeded the \( \sigma_{\text{sp}} \) estimates based on equation (2) become unreasonably high. Respectively, the spall strength of the SPS alumina shown in figure 4 as a function of the peak stress was calculated with aids of equation (2a). The difference between the two estimates is considered as uncertainty of the spall measurements. As apparent from figure 4 the spall strength of the SPS alumina declines monotonically with increasing \( \sigma_{\text{peak}} \) and vanishes at \( \sigma_{\text{peak}} \approx 2 \sigma_{\text{HEL}} \).

4. Discussion

The power function \( \Delta \sigma_{\text{HEL}} = \sigma_{\text{HEL}} - \sigma_\infty = \Delta \sigma_0 (h/h_0)^\alpha \) with two fitting parameters \( \sigma_0 \) and \( \alpha \) and \( h_0 = 1 \) mm fits reasonably well the experimental values of \( \sigma_{\text{HEL}} \) obtained with the samples of different thickness, figure 5. The value of \( \sigma_\infty = 5.47 \) GPa corresponding to the infinitesimal inelastic strain rate was based on the compressive strength of Metoxit Al 999-05x alumina \( \sigma_\infty = 3.8 \) GPa and Poisson's ratio \( \nu = 0.234 \) of the presently studied SPS alumina. The fitting parameters for the SPS alumina are \( \Delta \sigma_0 = 10.42 \) GPa and \( \alpha = 0.3 \). The power law describing the alumina's \( \sigma_{\text{HEL}} (h) \) together with equation
(1) yields the relation between the shear stress excess $\Delta \tau_{\text{HEL}} = \tau_{\text{HEL}} - \tau_\infty$ and the initial rate of the inelastic deformation $\dot{\gamma}$

$$\Delta \tau_{\text{HEL}} = \Delta \sigma_0 \left( \frac{c_L^2}{c_T^2} \right) \frac{4h_i G \dot{\gamma}^2}{3\alpha c_\Delta \Delta \sigma_0} = A \dot{\gamma}^m$$

The shear stress excess $\Delta \tau_{\text{HEL}}$ is the part of shear stress directly responsible of the increment of the inelastic deformation. While the main carriers of the inelastic deformation are lattice dislocations the shear stress $\tau_\infty$ corresponds to the Peierls stress. If such carriers are the micro-cracks the stress $\tau_\infty$ corresponds to the compressive cracking threshold. Based on average values of the alumina elastic constants the factor $A$ in equation (3) is equal to 0.197 (stress units are GPa, strain rate units are s$^{-1}$). The exponent of the inelastic strain rate is equal to $m = 0.23$. The dependence $\sigma_c = 2\Delta \tau_{\text{HEL}}(\dot{\gamma})$ found for the SPS alumina is shown in figure 6 together with Lankford data for Lucalox alumina [9].

![Figure 5. Stress excess as a function of the propagation distance.](image)

![Figure 6. Strength of the alumina as a function of inelastic strain rate (circles and line) and strength values of Lucalox ceramic from [9] (triangles).](image)

The exponent $m$ in equation (3) may be considered as a strain rate sensitivity (hardening) exponent. Based on general energy consideration Grady with coworkers suggested that either for compressive or tensile brittle failure $m = 1/3$ and is independent of the type of brittle material [10, 11]. The values of $m$ derived from micromechanical modeling of brittle failure may vary between 0.25 and 0.3 [12]. Experimentally determined values of $m$ for different brittle ceramics are varying between 0.263 in SiC [13] and 0.287 in AlN [14]. Taken with the presently determined value $m = 0.23$, this allows one to assume that the onset of inelastic deformation in shock loaded SPS alumina is more brittle-like than ductile.

5. Conclusion
Fully dense high strength SPS processed alumina is characterized in a series of VISAR-instrumented planar impact experiments. It is found that the elastic precursor wave in the alumina decays with propagation distance and that the shear stress excess at HEL $\Delta \tau_{\text{HEL}}$ is related to the initial inelastic strain rate $\dot{\gamma}$ as $\Delta \tau_{\text{HEL}}[\text{GPa}] = 0.197 \dot{\gamma}^{0.23}$. The value $m = 0.23$ of the exponent suggests that the mode of the initial inelastic deformation in the alumina is rather brittle than ductile. The spall strength of the
studied alumina declines with loading and vanishes while the peak compressive stress approaches twice the HEL.

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References
[1] Murray N H, Bourne N K, Rosenberg Z and Field J E, 1998 J. Appl. Phys. 84 02 734
[2] Murray N H, Bourne N K and Rosenberg Z, 1998 J. Appl. Phys. 84 09 4866
[3] Zaretsky E B and Kanel G I., 2012 J. Appl. Phys. 112 073504
[4] Duvall G E, 1964 In: Stress Waves in Anelastic Solids, edited by H. Kolsky and W. Prager, Springer-Verlag, Berlin, 20
[5] Zhijian Shen, Johnson M, Zhe Zhao and Nygren M 2002 J. Amer. Ceram. Soc. 85 08 1921
[6] Barker L M and Hollenbach R E 1972 J. Appl. Phys. 43 11 4669
[7] Barker L M and Hollenbach R E 1970 J. Appl. Phys. 41 10 4208
[8] Dandekar D P and Bartkowski P 1994 AIP Conf. Proc. 309 733
[9] Lankford J 1981 J. Mater. Sci. 16 567
[10] Grady D E and Kipp M E 1979 Int. J. Rock Mech. Min. 16 293
[11] Grady D E and Lipkin J 1980 Geoph. Res. Lett. 7 255
[12] Ravichandran G and Subhash G 1995 Int. J. Solids Struct. 32 2627
[13] Lankford J 1981 Comm. of Amer. Cer. Soc. February C-33
[14] Subhash G and Ravichandran G 1998 J. Mater. Sci. 33 1933