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Low strain rate compressive failure mechanism of coarse grain alumina

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ABSTRACT

The present work reports the dynamic compressive strength (σ_c) of a dense (~95%) coarse grain (~20 µm) alumina measured at ~30 °C as a function of strain rates ($\dot{\varepsilon}$) ranging from 10^{-5} to $5 \times 10^{-1}\ s^{-1}$. The results showed a unique 40% enhancement of (σ_c) with the increase in ($\dot{\varepsilon}$). Extensive post mortem examination of fracture fragments obtained from the compressive failure tests by FESEM, TEM and HRTEM confirmed the formation of micro-cracks, shear bands, nanoscale cleavages and dislocations whose recurrence had increased with strain rate. Both shear induced microplasticity and nanoscale cleavages as well as dislocations had occurred concurrently yet independently during compressive fracture of coarse grain alumina even at very low strain rates. Based on these evidences a new compressive failure mechanism of alumina was proposed.

1. Introduction

The recent resurgence in intense research activities in alumina [1–10], one of the oldest structural ceramics is certainly linked to the most innovative fascinating advanced applications in the forefront of developmental areas. The major advanced applications of alumina include microstructurally tailored porous gas permeation membrane for nanofiltration [1], thin film catalyst support [2], toxic methyl orange dye adsorbing nanofibres [3], advanced dielectric gate material for low voltage transparent FET device [4], and self aggregated nanowire bundles forming broadband and ultrahigh optical haze thin films for photovoltaic applications [5]. The more conventional major structural applications continue to include wear resistant inserts [6], bone implants [7], corrosion resistant coatings [8], and thin films [9]. Further, the most important strategic application of alumina continues to be in the domain of armors [10]. For all of the aforesaid applications in general and for application as armors it is needed to be taken into consideration that as a classical brittle ceramic, alumina is susceptible to strain rate dependent brittle failure [10–20]. Hence, the strain rate dependent compressive failure of alumina continues to remain and blossom out as an area of extraordinary research importance [11–20]. In spite of the huge existing knowledgebase [11–20], however, the finer details of the compressive failure of particularly coarse grain sized alumina are still far from well understood [21–23]. Therefore, keeping in view the above mentioned factors, the detailed analysis on the compressive strength behavior of alumina is depicted in Table 1.

The compressive strength of hot pressed and subsequently hot-isostatically pressed (HPed plus HIPed) alumina [11,12], vacuum hot pressed alumina [12,13], Lucalox alumina pressureless sintered without [14–16] or with [18] MgO doping depended on the relative density, residual porosity, presence or absence of a brittle or tough grain boundary phase, processing conditions as well as on grain size. The compressive strength of these alumina samples [18] generally was strain rate insensitive in the typical low to intermediate strain rate range of 10^{-5} to $10^{-1}\ s^{-1}$ but increased to different extents with strain rate in the typical intermediate to high strain rate regime of 10^{-1} to $10^{4}\ s^{-1}$ (Fig. 1). It was the subcritical growth of axial micro-cracks that controlled the strain rate sensitivity of compressive strength in the low to intermediate strain rate regime of about $10^{-6}\ s^{-1} \le \dot{\varepsilon} \le 10^{-1}\ s^{-1}$ [18]. However, for intermediate to high strain rate regime of about $10^{-1}\ s^{-1} \le \dot{\varepsilon} \le 10^{5}\ s^{-1}$ the control of the compressive strength in alumina was exercised by the crack inertia [18].

It is also evident from Fig. 1 that most of the data reported in literature were for alumina of fine grain sizes [11–13] e.g., 1.45, 1.5 and 3.9 µm and only occasionally for alumina of relatively coarser grain sizes [12,14,18] e.g., 17 and 25 µm. The other striking fact that emerged from Fig. 1 was that generally for alumina in the low strain rate regime of about $10^{-6}\ s^{-1} \le \dot{\varepsilon} \le 10^{-1}\ s^{-1}$ measurements of compressive strength at only two or at the most three strain rates were available [11–14,18]. This information

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Table 1
Literature survey on the compressive strength and deformation mechanisms of different varieties of alumina.

Processing details and/alumina type	GS (μm)	$\dot{\varepsilon}$ (s^{-1})	σ_s (GPa)	Power law exponent (n)	Deformation mechanism	Ref. no
HP+HIP	1.45	10^{-4} to 10^{5}	6–9	0.055(at 10^{-4} to 10^{-1} s^{-1}) 0.016 (at 10^{0} to 10^{5} s^{-1})	Dislocations on single or multiple slip planes and their pile up at the GB	[11]
(1) AD995: VHP (2) JSI: VHP+HIP (3) JSII: VHP	(1) 17 (2) 1.45 (3) 3.9	7×10^{-5} to 10^{5}	(1) 3.8–9 (2) 6–9 (3) 1.2–5	(1) 0.04 (at 7×10^{-5} to 2×10^{3} s^{-1}) (2) 0.055 (at 5×10^{-4} to 5×10^{-2} s^{-1}) 0.017 (at 10^{0} to 10^{5} s^{-1}) (3) 1.23 (at 5×10^{-4} to 10^{0} s^{-1}) 10.23 (at 10^{0} to 10^{5} s^{-1})	(a) Dislocation pileup (b) Nucleation of MC ahead of dislocation pile up (c) Generation of MC, especially in coarse grain alumina, at stress levels much lower than that required to cause plasticity	[12]
(1) VHP+HIP (2) Cerver (3) Lucalox	(1) 1.5 (2) – (3) –	(1) 5×10^{-4} to 5×10^{3} (2) do (3) 5×10^{-5} to 2×10^{3}	(1) 5.5–8.3 (2) 2.5–4 (3) 3–3.5	(1) 0.014 (at 5×10^{-4} to 10^{0} s^{-1}) 0.034 (at 10^{0} to 5×10^{3} s^{-1}) (2) 0.029 (at 5×10^{-4} to 5×10^{3} s^{-1}) (3) 0.009 (at 5×10^{-5} to 2×10^{3} s^{-1})	Presence or absence of a glassy GB phase	[13]
Lucalox	25	6×10^{-5} to 2×10^{3}	3–3.8	0.01 (at 6×10^{-5} to 2×10^{3} s^{-1})	MC generation due to twin GB interaction	[14]
Lucalox	–	10^{-4} to 10^{4}	3–3.5	0.008 (at 10^{-4} to 10^{4} s^{-1})	Formation of axial MC	[15]
Lucalox	20–30	–	–	–	Growth of thermally activated subcritical TC, nucleated athermally by twins formed over a characteristic stress range	[16]
Monolithic	–	5×10^{-6} to 10^{3}	2.5–3.3	0.024 (at 5×10^{-6} to 5×10^{-1} s^{-1})	–	[17]
Lucalox with MgO doped	25	7×10^{-5} to 1×10^{4}	2.5–5.8	0.029 (at 7×10^{-5} to 5×10^{-1} s^{-1}) 0.3 (at 1×10^{3} to 1×10^{4} s^{-1})	Athermal nucleation of MC at intrinsic flaws	[18]
PS	5	0.9×10^{3}	3	–	Grain localized microcleavages, plasticity, intragranular MC and SG formation	[19]
–	–	10^{-5} to 2×10^{3}	2–3	120 (at $< 10^{2}$ s^{-1}) 0.327 (at 10^{2} to 2×10^{3} s^{-1})	Nucleation, growth and coalescence of a large number of compression- induced, interacting and tensile MC	[20]

GS: Grain Size, $\dot{\varepsilon}$: Strain rate, σ_s: Compressive strength, HP: Hot pressed, HIP: Hot isostatically pressed, VHP: Vacuum hot pressed, PS: Pressureless sintered, GB: Grain boundary, MC: Micro-cracking, TC: Transgranular crack, SG: Sub- grain, -: Not given in literature.