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Effect of Microstructure on the Ballistic Performance of Alumina

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CONTENTS

ABSTRACT

Results of a study of various dense Al_2O_3 bodies using a 22-caliber fragment simulator are presented showing that there is no significant correlation of ballistic performance to static tensile strength, surface finishes, or effect of single crystal orientation. Grain size appears to have a limited effect while there is a definite lowering of performance by some impurities. The effect of impurities depends on their state and thus on method of addition and thermal history. Results are discussed in terms of possible microplasticity.

PROBLEM STATUS

This is an interim report. Work on this problem is continuing.

AUTHORIZATION

This research was supported by the Naval Air Systems Command of the Department of Defense, Project No. AIR3205 203/652A/IWR0070101, NRL Problem F04-15. Mr. H. J. Boertzel, Jr. is the Project Engineer.

Effects of Microstructure on the Ballistic Performance of Alumina (U)

1. INTRODUCTION

(U) In 1962, armor consisting of a ceramic facing backed with glass reinforced plastic (GRP) was introduced to provide protection from attack by armor piercing projectiles such as 30 and 50 caliber service rounds. Subsequent development has led to increased understanding of the characteristics of materials which influence their performance as an armor. For example, harder materials generally perform better than softer ones. Performance usually decreases with increasing porosity but does not appear to depend significantly on static tensile strength or grain size. However, the effect of porosity, grain size, and other microstructural variables such as the type and distribution of impurities have not been fully explored. This is due in part to the large (6" x 6") size and number of tiles normally required for ballistic testing which sets a practical limit on the range of variables that can be examined.

(U) Ceramic faced armor has been considered also for protection from fragments and other non-armor piercing projectiles. Research on this application has been limited by early indications that such ceramic armor is superior to other materials only with targets which are thick relative to the fragment size. Earlier data suggests a bimodal distribution with different lots of the same alumina bodies falling on either an upper or lower curve.

(U) This work was initiated to explain the effect of microstructure and strength determining factors (e.g. surface finish) on the ballistic performance. It was hoped that such basic information would provide insights into the causes of the differences in the ballistic performance of supposedly identical materials as suggested by earlier data. The fragment simulator was selected for the evaluations rather than armor piercing projectiles for several reasons. The penetration mechanisms for armor piercing projectiles are different from those for fragment simulators; however, the general trends should be similar. Furthermore, effective scaling laws are available to normalize various sizes of fragment simulating projectiles for the class of target materials considered, and, of course, fragment armor data is useful in itself. The use of the much smaller fragment simulating projectile makes it possible to obtain more samples with a given quantity of material and permits investigation of a wider range of microstructural variables.

(U) Alumina was chosen for study since fabrication technology and effects of microstructures are better established for it than for other ceramics. Alumina is generally less expensive than other ceramics used for armor and is useful as a component of layered armor.

II. EXPERIMENTAL PROCEDURE

(U) The method of fabrication, composition, strength and density of the various aluminas tested are shown in Table 1. Tests were performed with 6" x 6", 4" x 4", plates and 1.5 to 2.5 inch diameter disks of alumina. A few fused cast bodies of alumina were rectangular pieces 1.34 x 2.0 inches and the single crystal samples were 1.375 inch diameter disks. The various sample surfaces, were as fired, diamond cut, conventionally ground, or polished.

(U) Ballistic limit velocities were obtained with 22 caliber fragment simulating missiles having a truncated chisel front. The missiles weigh 17 grains and are made of a moderately hard steel, Rockwell "C"-27. The fragment simulators were produced in accordance with specification MIL-P-46593(A).

(U) Alumina densities were determined by Archimedes principle. Static tensile strengths were taken as the modulus of rupture measured in three point bending on a span of one half inch with bars of width at least twice the thickness (e.g. 0.2 x 0.1 inch or 0.15 x 0.07 inch). Grain sizes are the average linear intercept lengths measured on fracture surfaces.

III. RESULTS

(C) A. Alumina Armor Data and Development of Small Target Testing

The ballistic data referred to in the introduction as exhibiting a bimodal distribution were generated by Goodyear Aerospace Corp. (1), Picatinny Arsenal (2) and NRL. The data are given in Table 2 and displayed in Figure 1. All of the data for targets prepared from the commercial aluminas which are normally considered for armor fall very close to either one of the two lines. The separation of the two lines represents a fourteen percent difference in ballistic limit for 3.0 to 5.0 PSF targets or is 500 FPS for 4.5 PSF targets. The probability of data on one curve being from a population represented by the other was less than five percent as determined by the Student t test. The aluminas were obtained from two commercial sources, tested in three laboratories and the purity ranged from 85 to 99.3 percent. About half of the alumina was tested with as-fired surfaces with the balance with ground surfaces. All of the alumina tiles were at least 4 x 4 inches with the majority about 6 x 6 inches; surely an adequate size. In addition the ratio of areal density of the ceramic facing to the GRP backing ranged from 0.55 to 2.7. Neither these variables nor the source of the alumina could be associated with the ballistic performance.

(U) The difference in performance is an example of the variability mentioned earlier and was one of the interests of this study. Unfortunately, samples of the alumina representing the various ballistic test lots represented in Fig. 1 were not available. Therefore, information on the effect of microstructure and physical properties was sought through use of other aluminas including laboratory produced items. Since smaller size ceramic specimens would greatly facilitate such work, disks 1.5 inches in diameter were cut from plates of two different thicknesses of a commercial alumina previously tested in 4 x 4 and 6 x 6 inch plate. The total spread in these limit velocities for a given ceramic thickness was less than 1.5 percent, i.e. about one tenth the separation of the two lines shown in Fig. 1. Additional 1.5 inch diameter disks cut from the commercial plates were lapped on an iron lap with silicon carbide grit (220) and polished with alumina grit. No effect upon ballistic limit was found as a result of this polishing.

B. Effect of Microstructural and other Strength Variables

(U) Most of the targets used for the work covered in subsequent descriptions consisted of 1.5 inch diameter disk of alumina bonded to GRP* with a 0.020 inch thick layer of Proseal 890 resin (a polysulfide resin).

*GRP panels were 12" x 12", irrespective.

The ceramics used are described in Tables 1 and 3. The ballistic data points generally fell on or between the two curves of Fig. 1. The data are shown in Fig. 2 with the curves from Fig. 1 drawn in. Small numbers of samples (e.g. 4-5) were used for most of the ballistic evaluations of the hot pressed bodies and the fusion cast material. Testing of many targets would undoubtedly result in moderate revisions of the ballistic limit velocities and an occasional significant change, particularly for highly inhomogeneous material. Increasing the number of samples used for grain size determination and/or modification of the techniques for grain size determination would cause some changes, however, the range covered is about one thousand to one; so again the changes would be of little consequences for present purposes.

(U) In order to explicitly evaluate the effect of grain size, purity and other ceramic characteristics, a normalization of the ballistic data was made. This resulted in an expected or normalized ballistic limit for targets having an areal density of 4.5 PSF.

(U) The areal density of most of the targets fell between 4.0 and 4.8 PSF thus the normalization did not result in a large extrapolation of observed data. The normalization was based upon the assumption that the difference between the lower line of Fig. 1 and the observed ballistic limit velocity for a given areal density would be the same for a 4.5 PSF target. An objective was to seek trends and indications of factors having a significant effect on ballistic performance.

(U) Two sets of values for the hot pressed Linde A alumina were obtained using as hot pressed bodies and the same material after annealing. Annealing increased the grain size by a factor of about 5 and the flexure strength decreased about forty percent yet there was not a significant change in the performance in the ballistic tests. The use of 2 W/O LiF in hot pressing Linde A powder did not result in a significant change in average grain size. The flexure strength was reduced by more than fifty percent, but there was no change in the ballistic performance. Annealing of this material doubled both the grain size and flexural strength (due to reduction in impurity and additive content). The ballistic limit decreased by only about six percent.

(U) All of the oxide additions to alumina tested in the hot pressed or hot pressed plus annealed condition resulted in low ballistic performance. Hot pressed and annealed specimens of Linde A powder with TiO_2 added, and as hot pressed specimens containing both LiF and TiO_2 resulted in the poorest performance of any of the experimental bodies although the flexure strength was higher and the grain size smaller than for other bodies. This suggests that specific impurities may be responsible for low performance and this may account for the low performances of some commercial materials.

(U) In Fig. 3 the resulting normalized data, for hot pressed bodies made at NRL and sintered alumina obtained from commercial producers, are plotted against the inverse square root of the grain size as has been done in other recent studies of ceramics, (3). Also included is a single data point for results obtained on targets made from Czochralski grown single crystals having surfaces intersecting at 0°, 30°, 60°, or 9C° to the crystal (c) axis. The total spread in ballistic limit velocity for 4.5 PSF targets commercial sintered aluminas (see Fig. 1) was almost the same as shown for all of the experimental materials used in this study. Table 3 includes values of the inverse square root of the grain size and the ballistic limit velocities normalized to 4.5 PSF in order that individual data values may be identified in Fig. 3. These data show that as groups (1) high purity sintered bodies and hot pressed aluminas without oxide additives, are superior to (2) low purity sintered items and the hot pressed bodies containing oxides additives. For each group there is a trend of decreasing ballistic performance with increasing grain size. The trend lines representing this dependence in Fig. 3 are least square fit of a straight line to the respective data groups.

(U) Impurities appeared to have a much greater effect on ballistic performance than microstructure. Impurities are present in the commercial bodies, and their distribution can be effected by rates of cooling. Specimens were heated in air to 1500°C for approximately 16 hours, lowered as fast as possible,(i.e. in a few seconds) from a commercial bottom loading furnace and moved rapidly from their lowered position (approximately three feet below the furnace). The specimens were 2 x 2 inch squares of AD-94 alumina held by about one half inch of one corner being inserted into slots in a fire brick. The samples were spaced at least two inches apart with their faces at a substantial angle to one another in order to accomplish a high rate of cooling. Fragment simulator tests of these fast cooled bodies resulted in a ballistic limit velocity about five percent higher than for an as-fired commercial production lot from which the specimens were taken for the quenching experiment. Restricting consideration to NRL ballistic data for sintered aluminas produced by commercial manufacturers (not all commercial products, however) resulted in an increase in ballistic limit of about 14 percent in going from about 94 to greater than 99 percent alumina, Fig. 4.

(C) A comparable effect of purity of ceramic has been observed for titanium diboride-GRP targets tested with the 14.5 mm BS-41 projectiles, (4).

(U) Four sets of targets made from fusion cast alumina were included. The samples were sawn from fusion cast brick and the as-sawn pieces were used for targets. The materials are described in Table 3 and the ballistic data are shown in Figure 5. Three of these fusion cast materials, which have the lowest flexural strength and the largest grain size of any of the bodies, were among the best as judged by the ballistic test used. The fusion cast brick contained porous sections and some macroscopic voids and cracks. Slabs selected to avoid the macroscopic defects were used in the ballistic tests, however, the presence of internal voids, microscopic porosity, etc., may have affected the density and strength determinations. One of the fusion cast brick contained Ti_2O_3 yet the ballistic limit was not significantly different from high purity fusion cast alumina. The hot pressed NRL samples with oxide additives exhibited decreases in ballistic limit when compared to the high purity controls. These results suggest that the state and/or distribution of the impurity is also important. The different fabrication temperatures and quenching rates for the two types of production would be expected to change the form and distribution of the impurities.

(U) The fusion cast material containing visual cracks performed well in these ballistic tests. Impact of the projectile on surface areas containing visual cracks was avoided. The fragment simulating missile undergoes large amounts of deformation for the test conditions (hard ceramic armor, soft projectile and high initial forces for these target areal densities). The deformation results in an increased loading area for the missile on the backing material. Both factors contribute to defeat of the projectile and may not be affected appreciably by cracks in the ceramic. The defeat of other types of projectiles, i.e. 30 caliber AP projectiles, is accomplished by different mechanisms. Wilkins, et al (5) have shown in their analysis of the physical process in penetration of alumina faced armor by a hard conical nosed projectile that the ballistic limit should increase appreciably by maintaining the ceramic integrity for two additional microseconds. Fusion cast alumina containing cracks would not be expected to perform as well as sintered homogeneous material in ballistic tests using armor piercing projectiles.

IV. DISCUSSION

A. The Effect of Impurities and Grain Size

(U) The data shows only a moderate sensitivity of the ballistic performance to the various material parameters. The data of Figs. 3 and 4 shows that the most pronounced effect is the presence of certain impurities.

(U) As noted above, the data appeared to show an effect of purity and further inspection of purity groups suggested a limited decrease in ballistic performance with increasing grain size. This trend is clearer if one limits the population to the hot pressed doped specimens and the lower purity commercial aluminas. The trend toward increasing hardness with decreasing grain size, (6) as well as the indicated mechanism of failure and possible correlations to compression strengths (which are discussed later) would also indicate decreasing performance with increasing grain size.

B. The Mechanism of Failure

(U) Since the forces generated in stopping a projectile are proportional to the change in momentum, the ordinate of Fig. 3 is proportional to the stress. This means that the ballistic limit, and hence ballistic forces are obeying an equation of the form of:

$$F = F_o + KG^{-\frac{1}{2}} \quad (1)$$

where F_o and K are constants and G is the grain size. Clearly F_o and K are dependent on either system (e.g. missile and backing) or material (e.g. hardness) parameters or both. While a final separation of these cannot be made, the above equation may indicate that microplastic processes are important in ceramic armor as follows. F_o is clearly the major factor in determining F. Since F is significantly different for materials of different hardness or bodies of different porosity, material parameters are very important. The system parameters were fixed in this study and since materials variables are important in F and hence F_o, the material may be obeying the Petch equation:

$$\sigma_f = \sigma_o + KG^{\frac{1}{2}} \quad (2)$$

where σ_f is related to a dynamic fracture stress, σ_o = the stress to activate microplastic process, K = a constant, and G = the grain size, and each of these especially σ_f and σ_o are factors in the corresponding terms in equation 1.

(U) This suggestion of microplastic behavior is consistent with other results. Recently Palmour et al (7) have shown direct evidence of microplasticity in ballistically damaged Al_2O_3. Further, Gilman (8) has shown that the hardness and Hugoniot elastic limit of hard ceramics tested for armor purposes are directly correlated. Since Rice (6) has shown that hardness is essentially a measure of microplastic yielding of ceramics, Gilman's results also imply that microplastic effects are important in ballistic behavior, and F_o in particular.

(U) Rice (6) has shown that the yield stress (Y = H/3) of ceramics is the upper limit of static compressive strengths of ceramics, thus suggesting a general correlation of compressive strength and ballistic behavior. However, the correlation will often not be very close since a variety of factors change from static to shock wave conditions, where the stresses are respectively long range and short range (across the shock front will be narrower than many grains. However, some effect is still expected, and is thus consistent with the trend in Fig. 3.

(U) The observed effects of impurities and of quenching are consistent with a microplastic mechanism of ballistic behavior. Some inhibition of slip and twinning by additives or impurities could increase the hardness and dynamic yield stress. This may be the case in some of the fusion cast materials. However, too much hardening could reduce microplasticity to the point where little or no dynamic yielding occurs, which means less energy is absorbed, penetration probably proceeds faster, and more brittle fracture occurs (as appears to be the case here with the doped and lower purity commercial bodies). Because of the high stresses involved several systems of slip and twinning can be expected, so crystal orientation and surface finish effects should be minimized as was observed in these tests.

(U) If one proposes a microplastic mechanism of failure, then the question of why macroscopic ductility is not observed must be answered. Three reasons can be given for this. First, deformation may not occur on enough different systems to produce a general plastic deformation without cracking. Second, even if enough slip systems are activated, they probably cannot interpenetrate to product the homogeneity required for ductility. Third, very high stresses are required for extensive slip in these hard materials. Thus, microplasticity is probably localized spatially under the area of impact and at any one time around the shock front.

V. SUMMARY AND CONCLUSIONS

(U) Ballistic performance appears to follow a Petch type equation with a limited effect of the grain size term and hence of grain size. Since tensile (or flexural) strength depends substantially on grain size the correlation between tensile strength and ballistic limit is poor. Impurities can have a substantially greater effect on ballistic performance but this depends on the type and state of the additive. This also would be consistent with cooling rate effects and hence with variability between different lots of materials. Different mechanical finishes and different single crystal orientations were found to have no effect on ballistic performance. All of these appear to be consistent with a microplastic process.

ACKNOWLEDGMENTS

(U) The assistance of Mr. J. R. Spann in hot pressing the doped bodies and Mr. D. P. McGogney for ballistic testing is gratefully acknowledged.

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TABLE I: Types and Characteristics of Alumina Samples

Type of Alumina	Designation or Description	Source of Body	% Al_2O_3	Density gm/cc	Grain Size	Flexural Strength (23°C)
			Exceeds		μm	$X10^{-3}$ PSI
HOT PRESSED	Linde A Powder as H.P.	NRL	99.9	3.92	2	65
	Linde A Powder H.P. + Anneal	NRL			10	40
	Linde A Powder + 2% Lif as H.P.(1)	NRL	99.0	3.89	2	27
	Linde A Powder + 2% Lif H.P. + Anneal	NRL	99.5	3.84	4	52
	Linde A Powder + 2% LiF + 2% TiO_2 as H.P.	NRL	97.0	3.91	2	48
	Linde A Powder + 2% TiO_2 as H.P.	NRL	97.9	3.81	4	24
	Linde A Powder + 2% La_2O_3 as H.P.	NRL	97.9	3.87	1	55
	Linde A Powder + 2% Cr_2O_3 as H.P.	NRL	97.9	3.86	1	68
SINTERED	High Purity Polycrystalline Bodies	American Lava Corp.	99.9	3.96	3	70
	G McB-352	Int. Pipe & Ceramics Corp.	99.3	3.81	15	
	Lucalox	G.E., Lamp Div.	99.9	3.98	60	35
	AD-94	Coors Porcelain Co.	94.0	3.60	20	51
	AD-85	Coors Porcelain Co.	85.0	3.40	10	46
FUSED	Czochralski grown Single Crystals	Union Carbide	99.9	3.[illegible]		60
	Fused Castings*	The Carborundum Co.	99.3	3.76(2)	300-1000	15
	Monofrax A	"	94.5	3.41(2)	250	[illegible]
	Monofrax M	"	99.1	3.72(2)	20	20
	Al_2O_3 + .4% deadburned Magnesia		96.5	3.94	1000	15
	Al_2O_3 + Ti_2O_3					

*courtesy of Dr. R. LaBar

(1) Most of the LiF is lost during hot pressing and therefore it does not represent an impurity of this amount in the ceramic body.

(2) A significant factor in these lower densities are small (e.g. min. size) cavities which were inhomogeneously distributed. Testing was in areas with few or none of these.

TABLE II: Ballistic Test. of Commercial Aluminas by Three Laboratories

Ballistic Tests Performed by:	Alumina Manufacturer(1)	Percent Alumina	Backing Material(2)	Ratio of Facing to Backing Areal Density	Target Areal Density(3) PSF	Ballistic Limit Velocity (Vp50) FPS
Goodyear Aerospace Corp.	A	85	R	2.66	2.60	1729
	"	"	R	2.54	3.82	2656
	"	"	R	1.38	4.02	2779
	"	"	R	1.93	5.32	3737
Picatinny Arsenal(4)	A	85	R	.9	2.30	1755
	"	"	R	1.22	2.92	2305
	"	"	R	1.48	3.12	2435
	"	"	R	.45	3.58	2520
	"	"	R	1.16	3.98	2840
	"	"	R	.67	4.19	3000
	"	"	R	.73	4.45	3075
Naval Research Laboratory	A	94	D	.54	1.31	[illegible]
	"	94	D	----	2.16	1379
	"	94	D	----	2.52	1640
	B	99.3	D	1.13	4.00	3090
	A	94	R	2.32	4.31	2996
	A	94	R	2.32	4.31	3051
	B	99.3	D	.87	4.55	3683
	A	94	D	2.00	5.21	3739

(1) A - Coors Porcelain Co.; B- International Pipe and Ceramics Corp.
(2) R - Resin bonded glass fiber woven roving; D (Doron) - resin bonded glass fiber fabric.
(3) Target areal density as used here is for the ceramic facing and backing laminate and does NOT include the resin which amounts to one eight pound per square foot for a 0.020 thickness.
(4) Data were presented in graphical form with type, thickness and density of alumina given. The areal density ratios were computed by the authors from that information.

TABLE III: Ballistic Data for Various Aluminas

Type of Alumina	Designation or Description	Source of Body	Alumina Geometry	Areal Density of Targets PSF	Ballistic Limit Velocity FPS	Ballistic Limit Normalized to 4.5 PSF FPS	$\frac{1}{\sqrt{G.S.}}$
HOT PRESSED	Linde A Powder as H.P.	NRL	1.5 inch dia disk	4.82	3852	3610	32
	Linde A Powder H.P. + Anneal	NRL	1.5 inch dia disk	4.82	3809	3567	71
	Linde A Powder + 2% LiF as H.P.	NRL	1.5 inch dia disk	4.53	3659	3637	71
	Linde A Powder + 2% LiF H.P. + Anneal	NRL	1.5 inch dia disk	4.53	3466	3444	45-50
	Linde A Powder + 2% LiF + 2% TiO_2 as H.P.	NRL	1.5 inch dia disk	3.57	2502	3206	50
	Linde A Powder + 2% TiO_2 as H.P.	NRL	1.5 inch dia disk	3.63	2572	3231	71
	Linde A Powder + 2% La_2O_3 as H.P.	NRL	1.5 inch dia disk	4.07	3065	3391	100
	Linde A Powder + 2% Cr_2O_3 as H.P.	NRL	1.5 inch dia disk	4.18	3138	3370	100
SINTERED	High Purity Polycrystalline Bodies	American Lava Corp.	2.5 inch dia disk	4.08	3328	3646	58
				3.63	2934	3593	58
	G McB-352	Int.Pipe and Ceramics Corp.	5.5 inch plates	4.00	3090	3469	29
				4.55	3683	3645	29
	Lucalox	G.E.,Lamp Div.	2 inch dia disk	4.28	3295	3462	13
	AD-94	Coors Porcelain Co.	1.5 inch dia disk	2.72	1857	3204	22
				4.76	3310	3114	22
		"	"	4.74	3202	3020	22
		"	"	2.62	1667	3090	22
		"	4x4 inch plates	4.31	2996	3140	22
		"		4.31	3051	3195	22
		"	"	2.52	1640	3146	22
		"	5.75x5.75 plates	5.21	3739	3202	22
	AD-85	"	2.75x2.75 inch plates	3.73	2517	3100	32
				4.86	3411	3139	32

TABLE III: Ballistic Data for Various Aluminas - Continued

Type of Alumina	Designation or Description	Source of Body	Alumina Geometry	Areal Density of Targets PSF	Ballistic Limit Velocity FPS	Ballistic Limit Normalized to 4.5 PSF FPS	$\frac{1}{G.S.}$
FUSED	Czochralski grown Single Crystals	Union Carbide	≈1.5 inch dia disk	4.09	3015	3326	0
	Fused Castings* Monofrax A	The Carborundum Co.	≈2x2 inch	4.08	3191	3509	4.5
	Monofrax M	"	≈2x2 inch	3.50	2623	3380	6
	Al_2O_3 + .4% dead-burned Magnesia	"	≈2x2 inch	4.52	3669	3654	8
	Al_2O_3 + Ti_2O_3	"	≈2x2 inch	4.38	3445	3536	3

*courtesy of Dr. R. LaBar

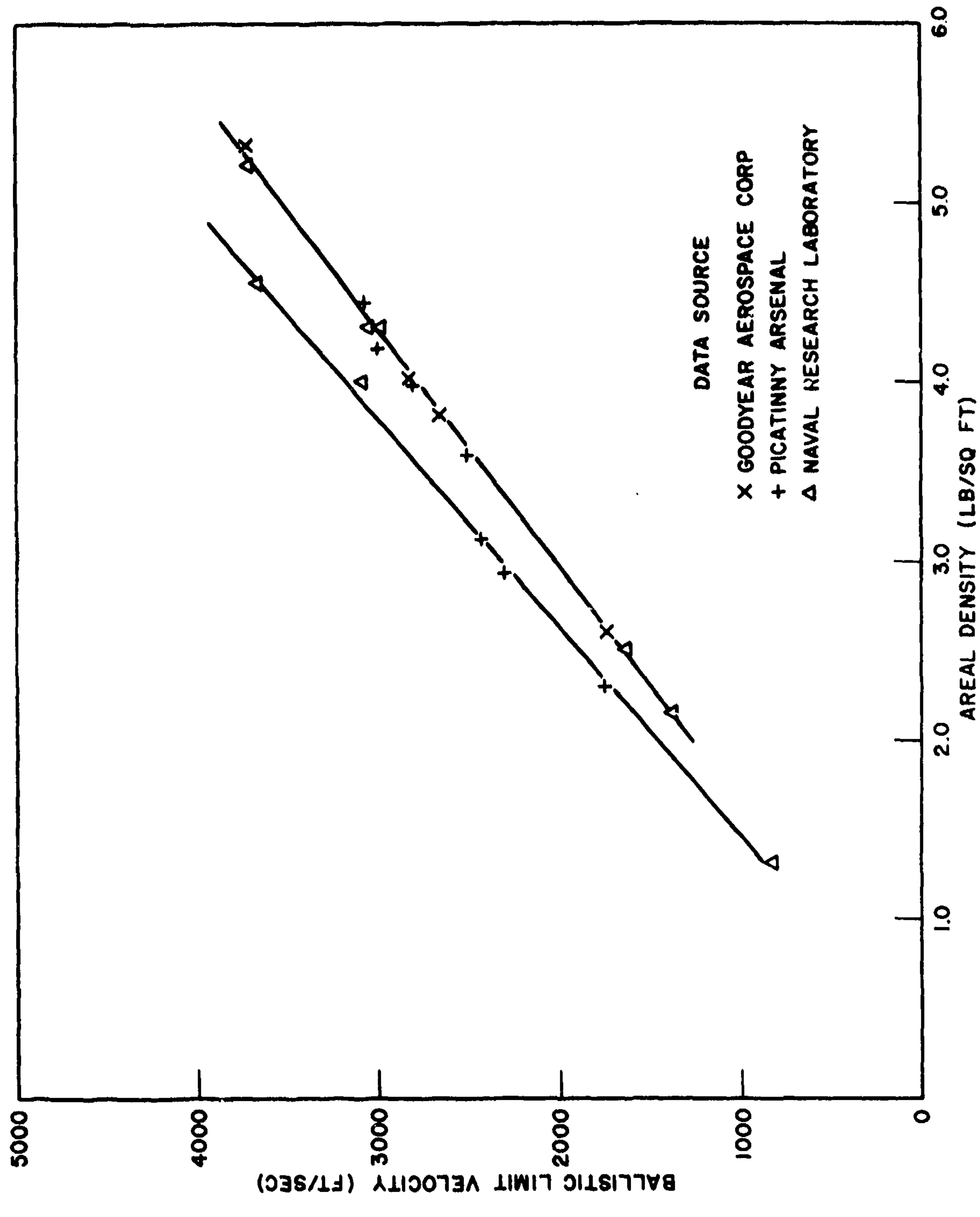

Fig. 1 (C) - Ballistic data for commercial aluminas

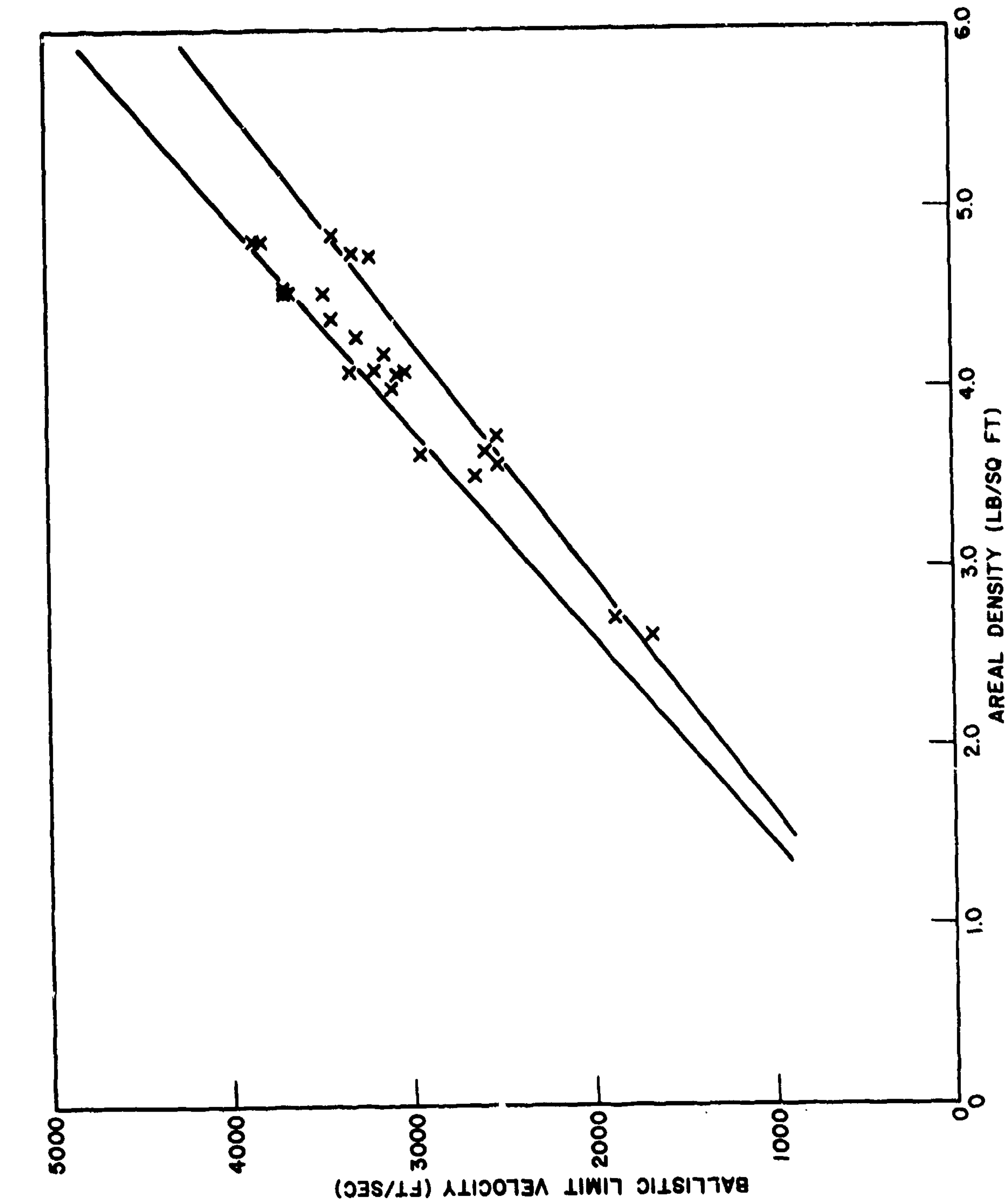

Fig. 2 (C) - Ballistic data for experimental aluminas

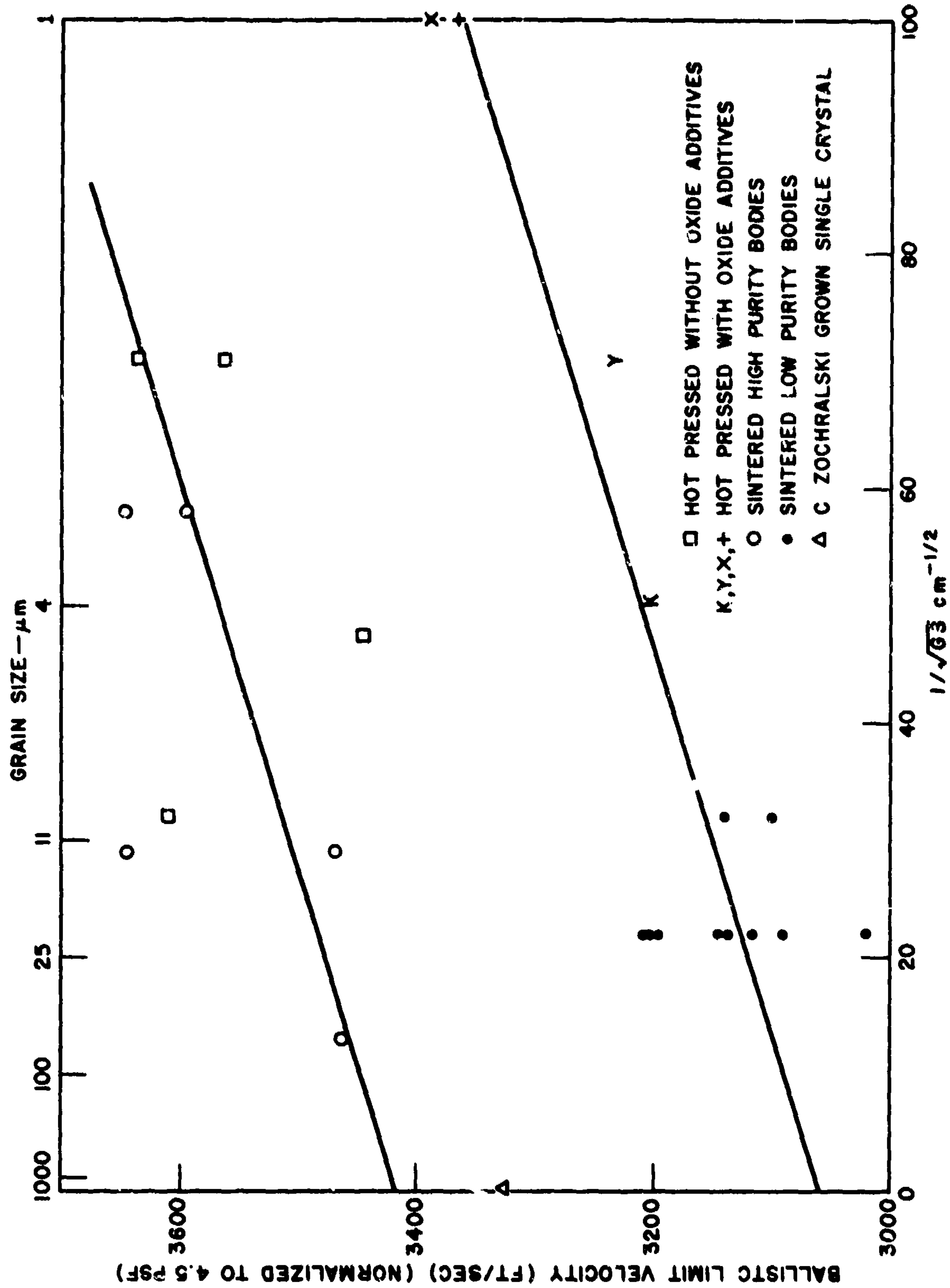

Fig. 3 (C) - Effect of grain size on ballistic performance

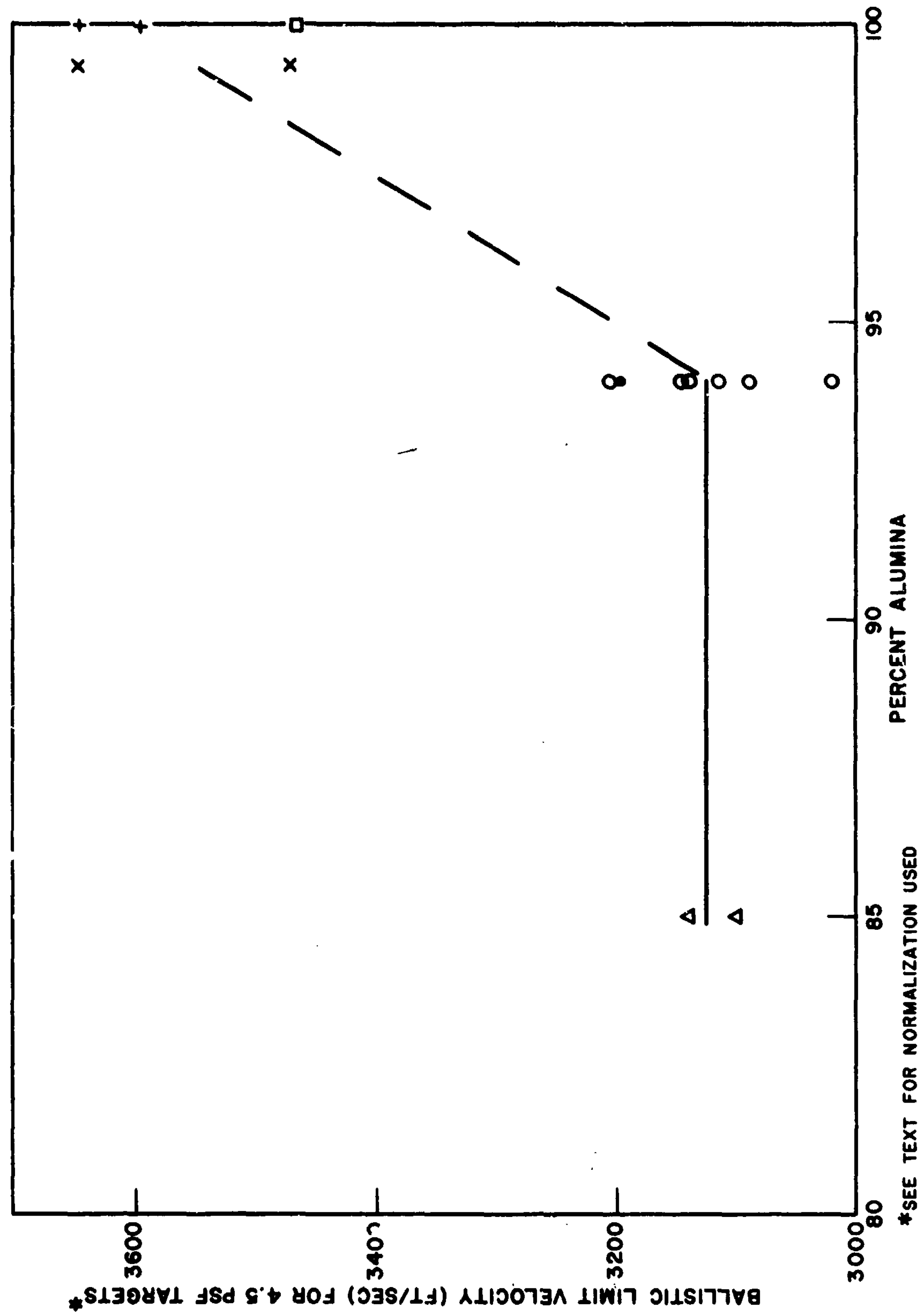

Fig. 4 (C) - Effect of alumina purity upon ballistic limit velocity

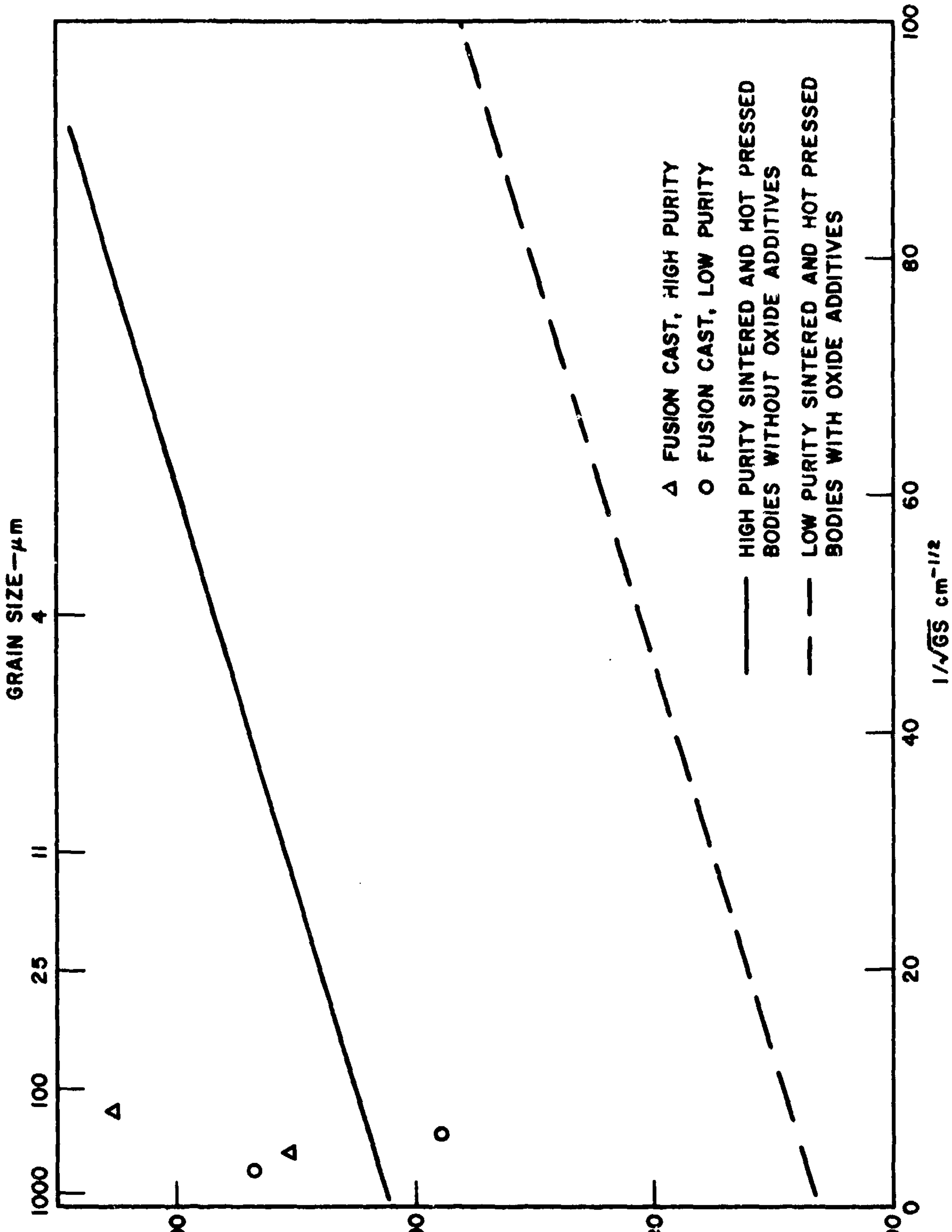

Fig. 5 (C) - Ballistic performance of fusion cast alumina

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13. ABSTRACT (UNCLASSIFIED)

Results of a study of various dense Al_2O_3 bodies using a 22-caliber fragment simulator are presented showing that there is no significant correlation of ballistic performance to static tensile strength, surface finishes, or effect of single crystal orientation. Grain size appears to have a limited effect while there is a definite lowering of performance by some impurities. The effect of impurities depends on their state and thus on method of addition and thermal history. Results are discussed in terms of possible microplasticity.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Armor Alumina Microstructure Strength Microplasticity						

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