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SHEAR STRENGTH OF ALUMINUM OXYNITRIDE

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Abstract. Aluminum oxynitride (AlON) is a polycrystalline transparent ceramic. It is an attractive material as a high strength window material. In this work we analyze the results of four sets of plane shock wave experiments reported to determine the shear strength of AlON. Our analysis indicates that the compression of AlON appears to undergo a shift around 16-20 GPa becoming relatively more compressible. However, AlON continues to retain shear strength at higher stresses. The reason for the observed shift remains to be understood and explained satisfactorily.

Keywords: Aluminum Oxynitride, ceramic, Elastic constants, Hugoniot, shear strength.
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INTRODUCTION

Aluminum oxynitride (AlON) is one of the three important materials in Al_2O_3 and AlN system, the other two being the end members Al_2O_3 and AlN. When the ratio of Al_2O_3 and AlN is 9:5, it has a cubic structure and its composition is $Al_{23}O_{27}N_5$ (35.7 mole% AlN). The cubic phase AlON persists between 28-40 mole% of AlN and its density varies with the mole% of AlN. The ideal density with 35.7 mole% of AlN is 3.711 Mg/m^3 [1]. It is also transparent and retains its transparency even when porosity 1-2.6% by volume is present in the material. The density of a transparent AlON varies between 3.60 and 3.67 Mg/m^3. It has excellent mechanical properties similar to Al_2O_3. It is thus a viable material for applications requiring high hardness, mechanical strength, and broad electromagnetic transparency. The elastic properties of polycrystalline AlON and their dependence on pressure and temperature were measured by Graham et. al. [2]. The mole% of AlON in their material varied between 30 and 35.7. The density of their AlON material varied between 3.604 and 3.649 Mg/m^3 for the material with 30 mole% of AlN. AlON material used in Ref. 2 had porosity varying between 2.6 and 1.8%. Their 35.7 mole% AlN material had a density of 3.644±0.004 Mg/m^3 implying a porosity of 1.9% in AlON. The measured values of elastic constants of the four polycrystalline AlON materials reported in Ref. 2 are given in Table 1. The pressure and temperature derivatives of the elastic constants were measured only for two of the four AlON materials.

Potential application of AlON required that its behavior be studied under dynamic loading conditions. The results of dynamic impact experiments performed [3-4] showed AlON to be potentially a viable material as an alternative to single crystal sapphire in impact related environment. This motivated four independent investigations [5-8] to determine shock wave response of AlON. Densities of AlON materials used in Ref. 5-8 varied from 3.51 to 3.67 Mg/m^3. The lower density materials were not transparent. The primary aim of the current study is to use the results of these four shock wave investigations to examine whether or not AlON retains shear strength under plane shock wave

Table 1. Properties of AlON.

Property	Unit	Graham et al.[2]	Graham et al.[2]	Graham et al.[2]	Graham et al.[2]	Cazamias et al.[5]	Cazamias et al.[5]	Vaughan et. al.[6]	ARL [9]
Density	Mg/m^3	3.604	3.631	3.649	3.644	3.51	3.68	3.59	3.67
Elastic wave velocity									
Longitudinal	km/s	10.13	10.26	10.20	10.29	10.30	10.50	10.27	10.25
Shear	km/s	5.83	5.90	5.87	5.93	5.91	5.91	5.91	5.88
Bulk	km/s	7.57	7.68	7.62	7.68	7.71	7.98	7.67	7.68
Elastic Modulus									
Bulk	GPa	206.5	214.0	212.1	214.7	208.9	234.3	211.5	215.8
Shear	GPa	122.6	126.3	125.6	128.1	122.6	128.5	125.4	126.5
Poisson's ratio	none	0.251	0.254	0.253	0.251	0.255	0.268	0.252	0.255
Pressure derivative									
Bulk modulus		4.5±0.5			4.2±0.5				
Shear modulus		0.85±0.02			0.95±0.09				

Propagation since shear strength of a material is considered to be important for its performance under impact loading condition.

EXPERIMENTS AND MATERIAL

The natures of four plane shock wave studies on AlON are indicated in Table 2. The details of experiments performed in these studies are given in Ref. 5-8. Therefore, the details of these four sets of experiments are not provided here. The density and elastic properties of AlON materials used in these studies are given in Table 1. The material used in Ref. 7 and 8 were provided by Army Research Laboratory (ARL). The properties of ARL material are given in the last column of Table 1.

Table 2. Nature of shock wave studies.

Studies	Diagnostics	Information	Stress (GPa)
Cazamias et. al. [5]	Manganin gages and VISAR	Longitudinal, lateral, and spall stresses.	15
Vaughan et al. [6]	Manganin gages	Longitudinal, and lateral stresses.	21
Sekine et al. [7]	Inclined mirror	Shock and mass velocity.	61-180
Thornhill et al [8]	VISAR	Longitudinal, and spall stresses, and refractive index.	5-89

The values of elastic wave velocities do not appear to vary significantly from one another due to variation in density except for the longitudinal wave velocity reported for the highest density material 3.68 Mg/m^3 used by Cazamias et al. [5]. This yields higher values of bulk modulus and Poisson's ratio for this material compared to the rest of AlON material in Table 1. Since only one shock compression experiment at 4.7 GPa was performed in this high density AlON in Ref. 5, the results of this particular experiment is not included in the present work.

RESULTS

The results of these experiments on AlON may be described as follows.

The magnitudes of the HEL are found to vary from 10.5 to 12.1 GPa. This variation does not show a systematic dependence of the HEL on the initial density of AlON. The authors of Ref. 5 and 6 reported the HEL of magnitudes 10.5-10.9 GPa, and 10.7 GPa, respectively. Sekine et. al. [7] report a relatively higher value of the HEL i.e., 11.2-12.1 GPa compared to 8.7-10.7 GPa reported by Thornhill et. al. [8] although AlON material were of the same density. The values of yield (Y) and shear (τ) stresses calculated from the values of the respective HEL and Poisson's ratios vary from 6.6 to 7.9 GPa, and 3.3 to 3.9 GPa, respectively. τ is one-half of Y. These values are not different from the values of yield stress and shear stress near the HEL i.e., 9.9 GPa obtained from the measurements of Vaughan et. al. [6]. Table 3. gives their measured values of longitudinal, $\sigma(x)$, lateral, $\sigma(y)$, and calculated values of mean, $<\sigma>$, stresses and shear, (τ), stress for AlON. The uncertainties in the values of $\sigma(x)$, $\sigma(y)$, τ, and $<\sigma>$ are 1%, 2%, 6%, and 3%, respectively.

Table 3. Summary of shock data from Ref. 6.

$\sigma(x)$	V/V_0	$\sigma(y)$	$\tau(y)$	$<\sigma>$
5.4	0.988	1.3	2.0	2.6
9.9	0.976	2.4	3.8	4.9
13.9	0.962	7.1	3.4	9.4
16.5	0.946	10.4	3.0	12.4
20.6	0.934	12.3	4.1	15.1

Shock response of AlON reported by Sekine et. al. [7] and Thornhill et. al. [8] is summarized in Table 4. The inelastic deformation of AlON above the HEL are represented through the relationship between the shock velocity (U_S) and particle velocity (u_P) obtained in these two studies.

Table 4. Results of shock response of AlON.

Reference	[7]	[8]
Density (Mg/m^3)	3.67	3.67
HEL (GPa)	11.2-12.1	10.0±0.7
Y (GPa)	7.4-7.9	6.6±0.5
τ (GPa)	3.7-3.9	3.3±0.0.2
Inelastic deformation : $U_s=C_0+s.u_P$		
C_0 (km/s)	8.08 (7.31)	7.60
s	0.761 (0.972)	0.779
K_0 (GPa)	239 (196)	211
$(\partial K/\partial P)$ at P=0	2.04 (2.88)	2.11

Sekine et. al. included the data of Ref. 5 in obtaining their U_s-u_P linear relationship. Since the density of the material used in Ref. 5 i.e., 3.51 Mg/m^3, much less than the density of AlON used in Ref. 7 and if it is excluded in determining the U_s-u_P linear relationship the values of parameters C_0 and s would become 7.86 km/s and 0.834, respectively instead of 8.08 and 0.761 shown in Table 4. The values of C_0 and s given in the parenthesis are those obtained from the data of experiments showing propagation of a single wave i.e., 125 GPa and beyond. The two values of K_0 obtained in the above manner are 227 and 196 GPa. The value of K_0 obtained by Thornhill et. al. [8] is 211 GPa, i.e., close to the value of the bulk modulus of AlON and very different from those of Ref. 7. These indicate that compression curve of AlON obtained in Ref. 7 is stiffer than the one obtained in Ref. 8. Both studies yield the pressure derivative of bulk modulus to be almost half the value obtained by Graham et. al. [2] i.e., 4.5. This suggests that even though the shock wave velocity following the elastic precursor is traveling with a magnitude equal to or greater than the bulk wave velocity in AlON, it is much more compressible than would be expected from the results of high pressure ultrasonic wave velocity measurements reported in Ref. 2. This is illustrated in Fig.1.

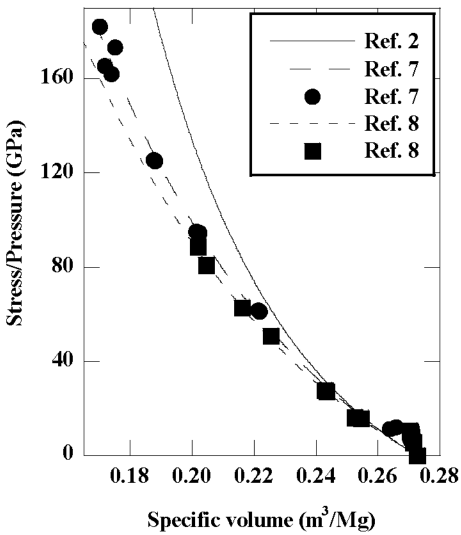

Figure 1. Compression of AlON.

The data of Vaughan et. al. [6] indicates that AlON retains shear strength of magnitude between 3 and 4 GPa above the HEL.

Graham and Brooks [10] showed that high pressure shock wave data can be used to give an explicit measure of shear offset under the assumption that the offset is constant and that no phase changes have occurred. This implies that the volume offset at zero stress obtained from extrapolation of high pressure shock data permits one to calculate the shear stress sustained. Applying this procedure to the data above 16 or 27 GPa in Ref. 8, yielded volume offset values between 0.020 and 0.028. Shear stress offset is given by the product of these and the bulk modulus. The calculated values of shear stress are 4.4 and 6.0 GPa. The data of Ref. 7 did not yield a credible value possibly because of the suggested phase transition in AlON at higher pressures.

Fig. 2 shows compression of low density AlON shock from Ref. 5 and 6, and a few low stress data from Ref. 8. It shows that Shock wave data below 16 GPa irrespective of density tend to maintain a finite offset from the hydrostat of AlON generated from the ultrasonic data [2]. Further, the values of mean stress obtained from the data of Vaughan et al. [6] lie on the hydrostat but begins to deviate from it when stressed beyond 16.5 GPa. Thus it appears that AlON begins to be more compressible when shocked around 16 GPa and above while retaining shear strength as discussed earlier.

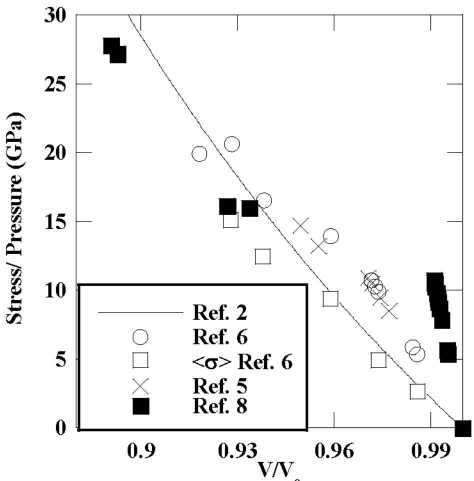

Figure 2. Compression of AlON to 30 GPa.

At this time, there is no plausible explanation that can be put forward for the observed softening of the compression of AlON above 16 GPa. The data of Ref. 8 do not show any evidence of phase transformation nor for that matter an unambiguous evidence for the suggested transformation by Sekine et. al. [7]

CONCLUSIONS

There is a need to conduct further studies to determine the underlying causes for the observed unusual shock response of AlON

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