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One-Dimensional Calculations of Shock-Loaded Polycrystalline Beryllium

by

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ONE-DIMENSIONAL CALCULATIONS OF SHOCK-LOADED POLYCRYSTALLINE BERYLLIUM

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ABSTRACT

This report describes a numerical study of the response of polycrystalline beryllium to shock loading. We discuss various methods of incorporating material properties relations to improve the hydrodynamic calculations and propose a treatment whereby the anisotropic, polycrystalline nature of beryllium can be modeled. We present the results of calculations, compare them with experimental data of several investigators, and comment on the applicability of the treatment.

I. INTRODUCTION

Calculation of polycrystalline beryllium response to plate impact experiments has not been successful using the normal technique of hydrodynamic calculations incorporated with an elastic perfectly plastic (EPP) treatment. Calculations of the free-surface velocity profiles of three experiments (Nos. 1-3) indicate that, without assuming a phase change upon shocking, the observed velocity of the rarefaction wave cannot be reproduced. The observed ramped elastic precursor is also not calculated by this method. The results of calculations using the EPP model with a yield strength (Y_o) of 0.15 GPa (1.5 kbar) are compared with the experimental profiles of Taylor* (Expt. Nos. 1 and 2) in Fig. 1.

The experiments shown in Fig. 1 were performed using the same material, target thickness, and driver plate velocity but with different driver plate thicknesses. Therefore, the observed difference between the two experiments in the rise of the profile is not explainable. Christman and Feistmann[1] also noticed such an effect, which was concluded to be real and due to a material effect that would include material properties. No proposed theoretical treatment will produce this difference if identical samples are assumed.

II. DISCUSSION

Certain mechanisms for treating the behavior of polycrystalline beryllium can be considered. One is

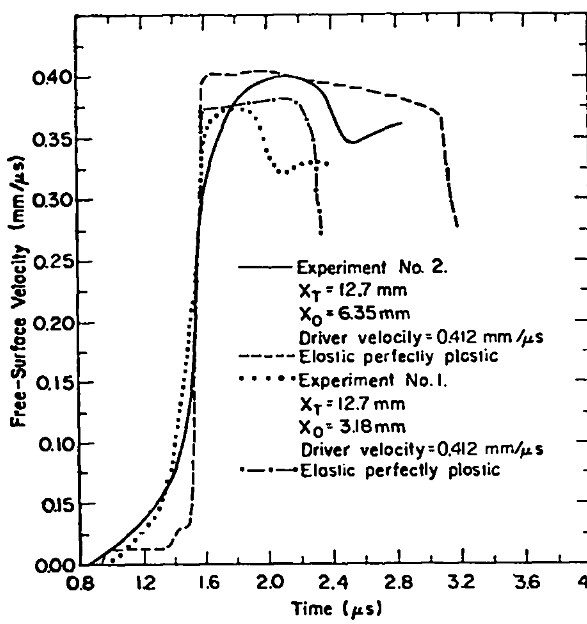

Fig. 1. Experimental and calculated free-surface velocity profiles for polycrystalline plate impact experiments.

*J. W. Taylor, Los Alamos Scientific Laboratory, unpublished data (1967).

the existence of a phase transition upon shock loading which changes the bulk properties of the material. This possibility would not explain the observed ramped profiles and does not seem likely.

Another possibility is to treat the strain hardening properties of the beryllium. Incorporating the strain hardening properties and the Bauschinger effect alters the character and magnitude of the elastic precursor and rarefaction waves and thus shows promise in explaining the observed profiles. We used the strain hardening and Bauschinger effect relations proposed by Read.[2]

$$Y = \begin{cases} Y_o\sqrt{1 + C_o\varepsilon_p} & \text{initial loading} \\ Y_\infty\left[1 - \exp\left(- C_1\sqrt{\varepsilon_p^{max} - \varepsilon_p}\right)\right] & \text{reverse loading} \end{cases}$$

Y = yield strength,

Y_o = initial yield strength,

Y_∞ = asymptotic value on reverse loading,

C_0, C_1 = coefficients selected to fit quasi-static data,

ε_p = equivalent plastic strain, and

ε_p^{max} = maximum plastic strain attained during initial loading.

Where

Y_o = 0.135 GPa,

Y_∞ = 0.220 kbar,

C_0 = 74, and

C_1 = 17.

The incorporation of these relations produced the velocity profiles shown in Fig. 2. We used the SIN code described in Ref. 3 to perform calculations in this report. The technique for incorporating strain hardening models in the SIN code is given in Ref. 4. Obviously, the strain hardening prescription as presented (that is, as determined from quasi-static experiments) does not reproduce the data. However, the prescription could be refined by assuming different hardening behavior at high strain rates to match the observed profiles. For example,

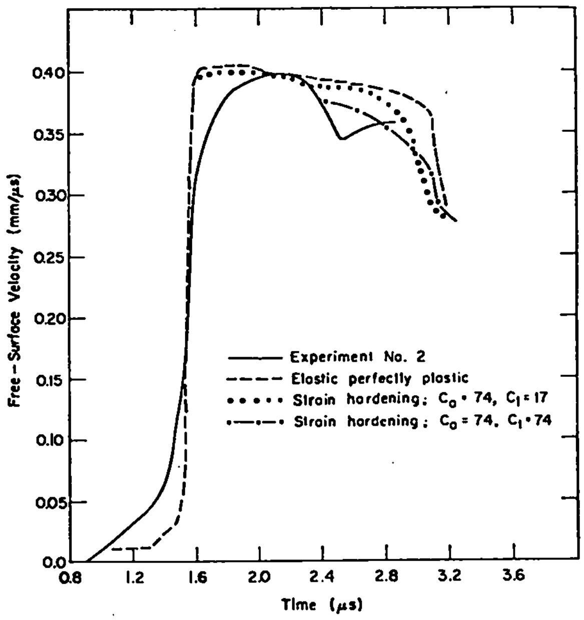

Fig. 2. Experimental and calculated free-surface velocities of a 12.7-mm beryllium plate driven by a 6.35-mm beryllium plate initially traveling at 0.412 mm/μs.

to produce the calculated profile shown as the dash-dot line in Fig. 2, we increased the value of C_1 to simulate increased hardening or reverse loading. Certainly strain hardening properties should be considered in a complete treatment. We think that the polycrystalline nature of beryllium should also be a primary consideration.

Pope and Johnson[5] and Pope and Stevens[6] reported on wave propagation in single-crystal beryllium. They studied the free-surface velocity profiles of the single crystals which were subjected to planar shock loading along various directions with respect to the crystal planes. Their data showed that the elastic precursor was well defined and not ramped as observed in polycrystalline beryllium experiments. They made the interesting conclusion that the response of the polycrystalline beryllium is a consequence of the grains in aggregate rather than a consequence of some intrinsic property of the beryllium.

Stevens and Pope[7] performed experiments on hot pressed polycrystalline beryllium after the texture of the samples was varied by rolling. The effect of rolling was to increase the concentration of basal planes nominally parallel to the rolling direction (normal to the shock propagation direction). They describe the texturing of the as-pressed material as having random R intensity and measured the texture in three rolled samples as having intensities of 3R, 5R, and 8R relative to the as-pressed material. The wave profiles observed in these experiments are shown in Fig. 3a along with an elastic perfectly plastic calculation of the response. They also measured sound speeds in the samples and concluded that, as texturing increased, the number of C-axes parallel to the wave propagation direction increased and therefore the speed was weighted toward the higher value of sound speed observed in the direction of the C-axis in single crystal samples. This resulted in a higher (13.79 mm/μs) sound speed measured in the highly textured (8R) material as compared to the sound speed (13.44 mm/μs) measured in the 1R material. This phenomenon is a result of the orientation of the grains in the polycrystalline material. Stevens and Pope proposed a model for unrelaxed thermal microstresses to explain the observed ramping (supressing of the elastic precursor) in the as-pressed material.

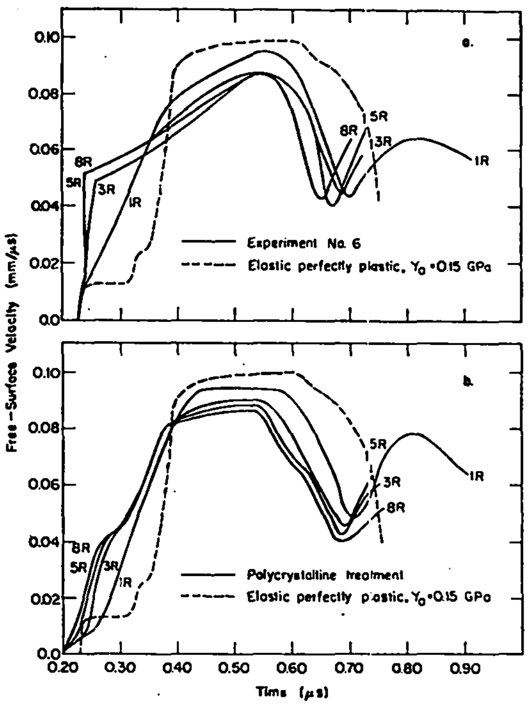

Fig. 3. a. Experimental and calculated free-surface velocities of a 3.00-mm beryllium plate driven by a 1.00-mm fuzed quartz plate initially traveling at 0.120 mm/μs where the texturing of the beryllium was varied.
b. Calculated profiles of the same experiment using the polycrystalline treatment.

III. CALCULATIONAL MODEL

Facts such as those discussed above lead to the conclusion that a proper method for calculating the response of beryllium should treat the anisotropic, polycrystalline nature of the material in hydrodynamic computer codes. We considered individual beryllium cells in the calculation as representing grains oriented in separate directions and assigned the cells different yield values since the phenomenon of different yield strengths along different crystal directions is observed.[5,8] We call the method described below the polycrystalline treatment.

In the crudest sense, consider a slab of beryllium with two types of grain orientations distributed randomly with respect to the planar shock propagation direction. One group of cells (the even ones) is oriented such that the yield strength is small (Y_0 = 0.075 GPa) and the other group (the odd cells) is oriented such that the yield strength is 0.4 GPa. For this case, the code treats the even and odd cells as shown in the Pressure-Specific Volume diagram of Fig. 4a. The response of the

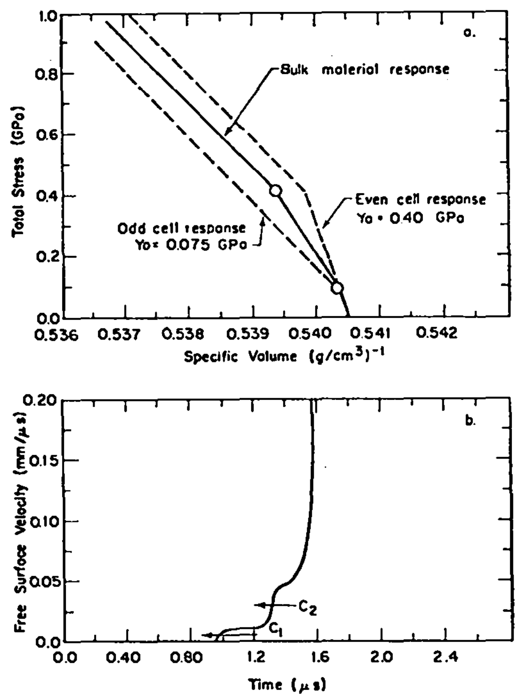

Fig. 4. Representation of the response of a material assumed to have two different yield strengths evenly distributed among the cells.

the aggregate material is represented by the average response shown by the solid line. If the ratio of higher yield values to lower yield values was changed, the average response would be weighted accordingly. Likewise, if more than two different yields were assigned, the response of the aggregate material would be represented by more than one change of slope of the solid line. The solid line Hugoniot in the figure predicts two waves traveling at constant velocities (C_1 and C_2) represented by the slopes of the line segments. Then two "elastic" precursors with velocities C_1 and C_2 and stress magnitudes given by $\sigma_1 = \frac{\nu}{1 - 2\nu} Y_1$ and $\sigma_2 = \frac{\nu}{1 - 2\nu} Y_2$ (ν is Poisson's ratio) are propagated as shown in Fig. 4b. Similar behavior is also exhibited by the elastic components of the rarefaction, the first rarefaction wave travels at velocity C_1 and the second at velocity C_2. Figure 5 shows the calculated pressure profiles in the material as the wave propagates.

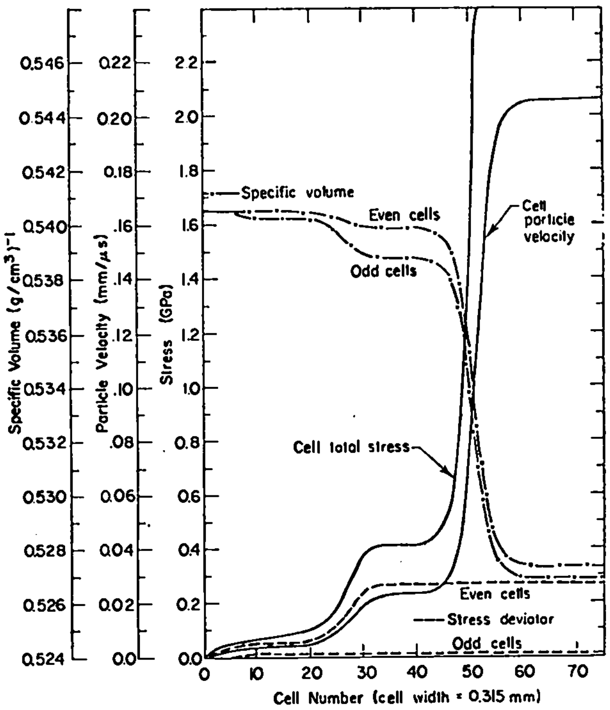

Fig. 6. Total stress, particle velocity, stress deviator, and specific volume profile as calculated using the polycrystalline treatment.

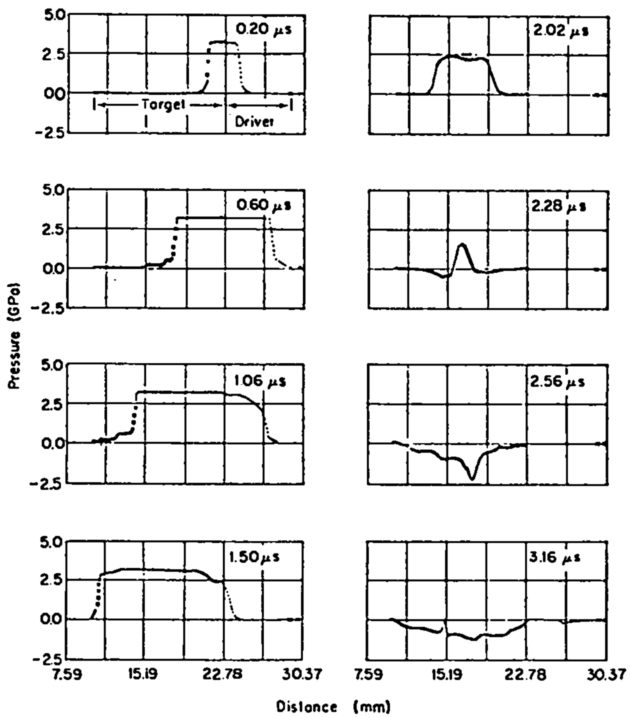

Fig. 5. Computed pressure-distance profiles for experiment No. 2. The driver plate is shown as a light line, and the target plate as a heavy line.

Figure 6 shows how the code treats such a situation. Plotted are the total stress, particle velocity, stress deviator, and specific volume profiles in the beryllium as the compressive waves propagate. Note that the pressure and particle velocity are continuous since they are matched from cell to cell. The discontinuous nature of the yield strength is compensated for by the discontinuity in the compression. This method has proven to be independent of mesh size.

By varying the distribution of cells and their yield strength, a large variety of profiles can be produced. Increasing the number of one yield strength over another has the effect of "texturing" the sample. Figure 7 shows typical calculations performed during a parameter study where the magnitudes and wave speeds of the elastic components of the waves vary as the yields and distribution of the cells are varied.

For convenience we use the following notation to indicate the yield strength values used for the polycrystalline model.

$$Y_o = [Y_1, Y_2, \ldots, Y_n] \text{ GPa, meaning}$$

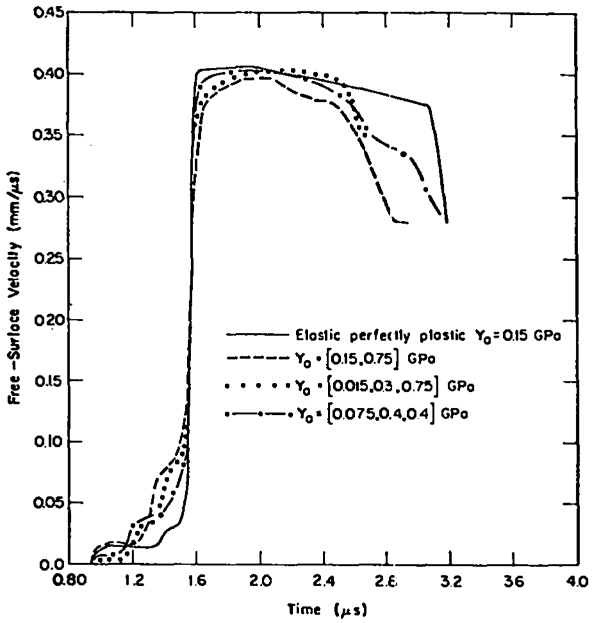

Fig. 7. Calculated free-surface velocities of a 12.7-mm beryllium plate driven by a 6.35-mm beryllium plate initially traveling at 0.412 mm/μs.

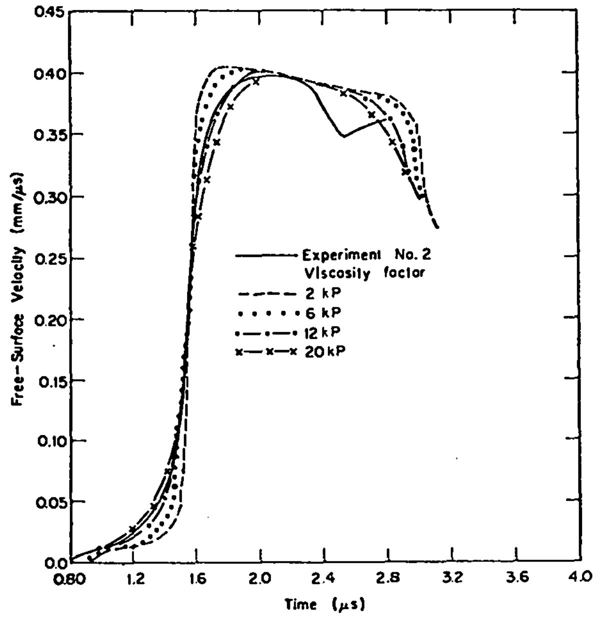

Fig. 8. Experimental and calculated free-surface velocities of a 12.7-mm beryllium plate driven by a 6.35-mm beryllium plate initially traveling at 0.412 mm/μs.

$Y_o = Y_1$ GPa every first cell of a block of n cells

$Y_o = Y_2$ GPa every second cell

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$Y_o = Y_n$ GPa every n^{th} cell.

For example, in Fig. 7, the notation Y_o = [0.75, 0.15] GPa indicates that all the odd numbered cells were assigned a value of Y_o = 0.75 GPa and the even numbered cells were assigned a value of Y_o = 0.15 GPa.

Of course, in polycrystalline beryllium the grains are oriented in an extremely complicated, three-dimensional way and the interactions between the individual grains are also complicated. We attempted to indicate the effects of such randomness by averaging the effects of the crude polycrystalline treatment using a real viscosity factor. Certainly, we could incorporate enough viscosity to smear out and obscure the effect of the treatment. Figure 8 shows a parameter study of the effect of real viscosity on calculations of beryllium impact experiments. A viscosity factor of 2 kP was found to reasonably describe the response of aluminum during plate impact experiments for shock pressures of 2.0 to 10.0 GPa.[4] Thus we do not consider a viscosity factor of 3 kP an unreasonable value for beryllium. We used the one-dimensional hydrodynamic code SIN[3] to perform the calculations. We treated the spalling observed in Expt. No. 6 by using the pressure gradient spall model[3] with a Spall A constant of 8.5×10^{-4} $(\text{GPa}\cdot\text{mm})^{1/2}$ = 0.027 $(\text{Mbar}\cdot\text{cm})^{1/2}$. The results of calculations are compared with experimentally determined wave profiles in Section V.

The equation-of-state parameters used in the SIN code to describe the response of the materials considered are listed below. The nomenclature and units are identical to those used in Ref. 3 and are described in detail there. We treated the fuzed quartz (FQ) as an elastic material for the stress ranges experienced by the quartz in the experiments studied.

Beryllium

C	7.975	-01
S	1.091	+00
F_S	2.07189823068	+00
G_S	-2.90125259335	+01
H_S	-7.55281579097	+01

I_S	-7.78921352738	+01
J_S	-2.62045226172	+01
γ_S	1.1	+00
C_V	4.74	-01
α	1.233	-05
V_o	5.40540540541	-01
μ	1.615	+00

Polytetrafluoro-ethylene (PTFE)

C	1.022	-01
S	1.834	+00
F_S		
G_S		
H_S		
I_S		
J_S		
γ_S	6.8	-01
C_V	3.0	-01
α	1.0	-05
V_o	4.76190476200	-01
μ		

Fuzed Quartz (FQ)

C	4.075	-01
S	1.5	+00
F_S		
G_S		
H_S		
I_S		
J_S		
γ_S	2.0	+00
C_V	1.8	-01
α	5.5	-07
V_o	4.54338936800	-01
μ	3.09	-01

IV. EXPERIMENTAL DATA

A summary of the experiments studied in this report is given in Table I. Experiments 1 and 2 were performed by J. W. Taylor* who impacted target plates of polycrystalline beryllium with beryllium driver plates and monitored the time-resolved free-surface velocity of the rear surface using the d-c capacitor technique.

Experiment No. 3 was performed by P. Fuller of the Atomic Weapons Research Establishment, Aldermaston, England.** He monitored the pressure in a polycrystalline I 400 beryllium target with a pressure gauge imbedded 12.7 mm from the impact surface.

*J. W. Taylor, Los Alamos Scientific Laboratory, unpublished data (1967).

TABLE I

SUMMARY OF EXPERIMENTS

Expt. No.	Driver Velocity (mm/μs)	Driver (mm)		Target (mm)		Target Backing
1	0.412	3.18	Be	12.7	Be	Free surface
2	0.412	6.35	Be	12.7	Be	Free surface
3	1.25	6.3	Be	12.7	Be[a]	
4	0.351	1.509	FQ	6.203	Be	FQ
5	0.346	1.524	FQ	9.149	Be	FQ
6	0.120	1.00	FQ	3.00	Be	Free surface

[a]Manganin gauge imbedded in PTFE 12.7 mm from impact plane.

Christman and Feistmann[1] tested S-200E, Type 1, hot pressed block Brush beryllium extensively. Experiments Nos. 4 and 5 are the results of two of their plate impact experiments. They monitored the particle velocity at the beryllium-quartz window interface using the interferometric quartz window technique. The shock propagation direction was parallel to the pressing direction. They noted little evidence of structure or texturing in the samples. However, they did observe some elastic anisotropy which implies a crystallographic anisotropy.

Experiment No. 6 is actually a series of several shots performed by Stevens and Pope[7] where the texturing of the beryllium was varied as discussed in Section II. They used Kawecki-Berylco hot pressed HP-10 beryllium and annealed the samples prior to texturing. The laser interferometric technique was used to monitor the free-surface velocity during the plate impact experiments.

The lack of knowledge of the texturing and prior treatment of the beryllium used for most of the experiments studied makes it difficult to relate the results of different test series to each other.

V. RESULTS

The comparison of experimental and calculated results is shown in Fig. 3 and Figs. 9-13. We

**Unpublished data.

qualitatively simulated the effect of texturing of the beryllium by changing the ratio of yield strengths, thus texturing the material in the calculations as discussed in Section III. Figures 3a and 3b compare the results of calculation and experiment.

In Figs. 9-11, the treatment is shown to better reproduce the ramped elastic precursor and velocity of the elastic component of the rarefaction. However, the agreement is still not satisfactory. For Expt. No. 3 (Fig. 11) the beryllium experiences over 10.0 GPa (100 kbar). Under these conditions, the occurrence of a phase change on shocking is a greater possibility.

Figures 12 and 13 illustrate the difficulty of determining parameters from one set of experiments and applying them to experiments where beryllium with different treatment history and texturing is used. For these two experiments we were unable to match both the observed behavior of the elastic precursor and rarefaction waves without considering effects outside the scope of this report.

VI. CONCLUSION

Obviously, more work must be done to properly characterize the response of polycrystalline beryllium. This report demonstrates that the polycrystalline treatment can be used to reproduce certain aspects of the observed response. It should be considered when effects such as strain hardening and rate dependence (e.g., real viscosity) are studied.

ACKNOWLEDGMENTS

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This work was performed in the Theoretical Division of the Los Alamos Scientific Laboratory.

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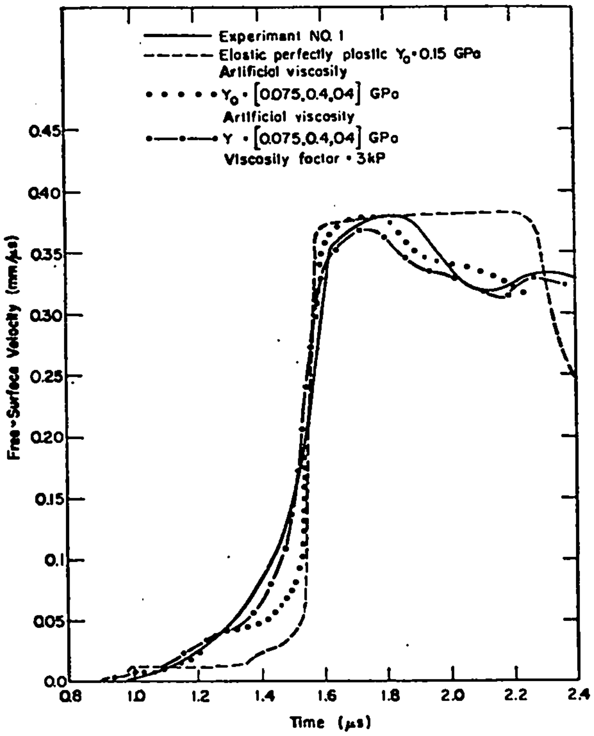

Fig. 9. Experimental and calculated free-surface velocities of a 12.7-mm beryllium plate driven by a 3.18-mm beryllium plate initially traveling at 0.412 mm/μs.

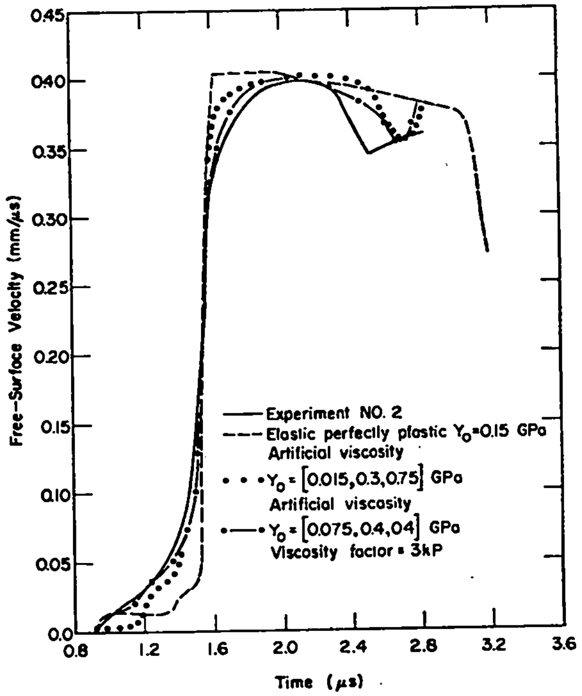

Fig. 10. Experimental and calculated free-surface velocities of a 12.7-mm beryllium plate driven by a 6.35-mm beryllium plate initially traveling at 0.412 mm/μs.

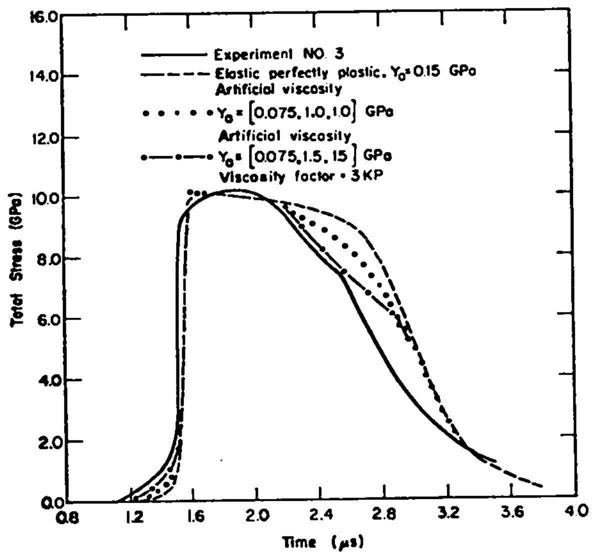

Fig. 11. Experimental and calculated stress profiles of a 38-mm beryllium plate (0.25-mm PTFE with an imbedded manganin gauge 12.7 mm from the impact surface) driven by a 6.3-mm beryllium plate initially traveling at 1.25 mm/μs.

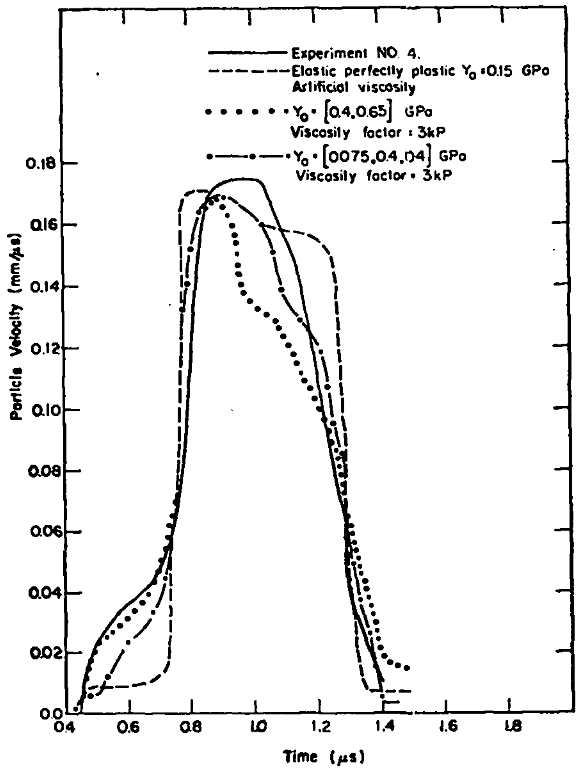

Fig. 12. Experimental and calculated particle velocity at the beryllium-quartz window interface of a 6.203-mm beryllium plate driven by a 1.509-fuzed quartz plate initially traveling at 0.351 mm/μs.

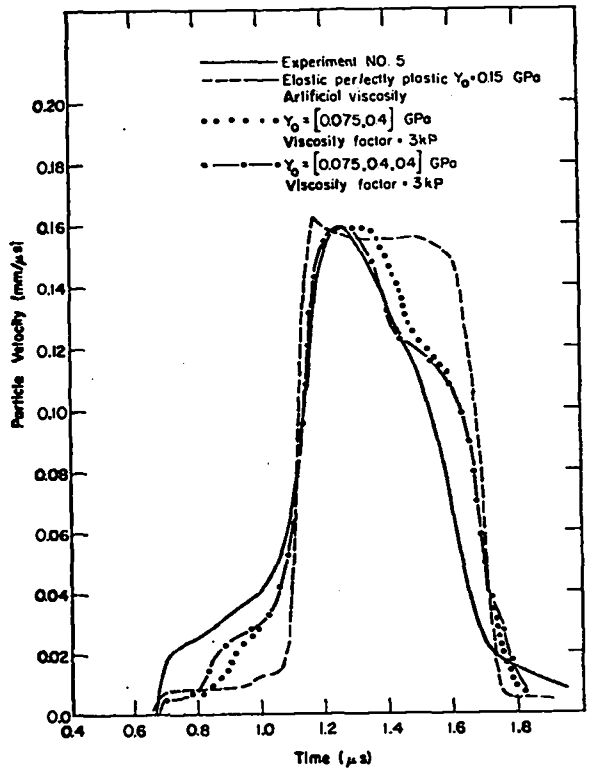

Fig. 13. Experimental and calculated particle velocity at the beryllium-quartz window interface of a 9.149-mm beryllium plate driven by a 1.524-mm fuzed quartz plate initially traveling at 0.346 mm/μs.