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AN EXAMINATION AND SENSITIVITY STUDY OF THE
KOVEC CONSTITUTIVE MODEL FOR BERYLLIUM

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AN EXAMINATION AND SENSITIVITY STUDY OF THE
KOVEC CONSTITUTIVE MODEL FOR BERYLLIUM

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ABSTRACT

We have checked the consistency of the KOVEC constitutive model for beryllium with experimental data, by examining work hardening, the temperature dependence of the yield strength, strain-rate effects, and the Hugoniot ($U_s - U_p$) relations. We have examined the sensitivity of simulations of uniaxial strain plate impact experiments, in which beryllium was used, to changes in the beryllium constitutive model. We also discuss the non-uniqueness of constitutive models.

INTRODUCTION

This report is divided into two parts. In the first part, we check the consistency of the KOVEC constitutive model for beryllium with experimental data, by examining work hardening, the temperature dependence of the yield strength, strain rate effects, and the Hugoniot ($U_s - U_p$) relations. In the second part, we determine which constitutive model parameters are important for simulating uniaxial strain plate impact experiments. (Constitutive model sensitivity studies for converging flows are in progress.) We focus on the sensitivity of numerical simulations of the experiments to changes in the constitutive model for beryllium, which was the target material in the plate impact experiments. We use KOVEC and the material models that are common to our 1- and 2-D hydrodynamic codes to simulate the experiments. This "multi-dimensional" or "basic" model consists of:

$$P(\rho, E)$$

$$Y(e^P, P, T) = Y_1(e^P) Y_2(P, T)$$

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von Mises yield criterion, $J_2' - 1/3 Y^2 = 0$
 isotropic hardening
 Prandtl-Reuss flow rule
 $G(P, T)$,

where P , ρ , E , Y , e^P , J_2' , T , and G are the pressure, density, specific internal energy, yield strength (true stress), equivalent plastic strain (true strain $[\int \sqrt{(2/3)} de_{ij}^P de_{ij}^P]$, second invariant of the stress deviator tensor $[(1/2) S_{ij} S_{ij}]$, temperature, and shear modulus. The KOVEC Bauschinger and viscoplastic models are not considered, because they are available only in the 1-D codes.

EXPERIMENTAL DATA

In this section we discuss recent experimental data that can be used to construct a constitutive model for beryllium. We compare these data with the current KOVEC model and note where improvements can be made, within the framework of the current KOVEC model.

Types of Beryllium

Specifications for the different types of beryllium [Corle, 1978; Froula, 1968; Green and Schierloh, 1968] discussed in this report are shown in Table 1. The berylliums are all polycrystalline and are fabricated similarly: beryllium ore is refined to pebbles, then cast into a billet, then powdered, and hot pressed into billets, from which specimens are machined. The table shows that the specification tolerances can be large. For example, the S200E material received by Christman and Feistmann [1972] has significantly different properties than the listed specifications. At low pressures and strain-rates, these large tolerances can create large discrepancies between specific experimental data and the constitutive model predictions, because the constitutive model parameters are obtained from the average behavior of the material. However, at high pressures and strain-rates, the effects of specimen-to-specimen variations are very small.

We will show data from many of the types of beryllium that are listed in the table, however, we are interested primarily in 1162A and 1319B, because they have been weaponized. We note that the current KOVEC model is constructed mainly from 1162A data.

Work Hardening in Beryllium

Figure 1 shows uniaxial stress data [Green & Schierloh, 1968; Christman and Feistmann, 1972; Breithaupt, 1981] plotted as a function of equivalent plastic strain, for different kinds of beryllium. In uniaxial stress, the von Mises yield condition reduces to $\sigma = Y$, thus the ordinate in Fig. 1 is either stress or yield strength, and is a direct measure of work hardening. The S200E data [Christman and Feistmann, 1972] at constant strain-rates of 0.2/sec and 0.002/sec. The S200D data [Green and Schierloh, 1968] are at strain-rates of 1200, 10, 0.05, and 0.005/sec. The 1200/sec data were compiled from many split Hopkinson bar tests (compressive split Hopkinson bar tests are not constant strain-rate tests), whereas, their other strain-rate data were obtained from constant strain-rate experiments. Although S200D and S200E are supposed to have identical mechanical properties [Brush Wellman Corp., private communication, 1982], the figure shows there are differences: the behavior of S200D at 1200/sec is the same as S200E at 0.2/sec. This can probably be attributed to the deviations of the true mechanical properties from the specifications, as noted in the previous section.

Compressive split Hopkinson bar data [Breithaupt, 1981] for 1162A and 1319B beryllium are also shown in the figure. The strain-rate varies from approximately 1000 to 100, as the plastic strain increases. The data were obtained from cylindrical specimens whose symmetry axes were either parallel or perpendicular to the pressing direction, to examine isotropy. The figure shows that the work hardening behavior of 1162A and 1319B is independent of orientation, because the data yielded one curve for each material.

In the current KOVEC work hardening model, the compressive yield strength, Y (true stress), is expressed as a function of the equivalent plastic strain, e^P (true strain):

$$Y = \text{Min} (Y_0 [1 + \beta (e^P + e_0^P)]^\eta, Y_{\text{max}}) \quad (1)$$

where Y_0 , β , e_0^P , η , and Y_{max} are determined from experimental data. The parameters for beryllium are: $Y_0 = 3.3$ kb, $\beta = 26.0$, $e_0^P = 0.0$, $\eta = 0.78$, and $Y_{\text{max}} = 13.1$ kb. Y_0 was obtained from low strain rate ($\dot{e} \sim 0.001$) uniaxial stress data [Christman and Feistmann, 1972], whereas, the other parameters were obtained from split Hopkinson bar ($\dot{e} \sim 1000$, uniaxial stress) experiments [Breithaupt, 1981]. The split Hopkinson bar data for 1162A and 1319B beryllium and the numerical fit to the data [Steinberg, 1981] are shown in Fig. 2. Care must be taken when interpreting these data, because beryllium is brittle and can fracture in uniaxial compression. We must confirm that only plastic flow is occurring, in order to use Eq. (1) as a general (1-, 2-, or 3-D) description of plasticity in beryllium. Three of the specimens that were used to obtain the data in Fig. 2 were cut parallel to the specimen axis (loading and pressing direction), to examine the mode of deformation. An undeformed specimen was also sectioned parallel to the pressing direction, and is shown in Fig. 3a. The "dark spots" in the micrographs are inclusions. There are no cracks or voids in the unstrained material. Figure 3b shows optical micrographs of a specimen that was strained to $e^P \sim 0.14$ ($Y \sim 11$ kb). There is little evidence of cracking. Figure 3c shows optical micrographs of a specimen that was strained to $e^P \sim 0.16$ ($Y \sim 12$ kb). As compared to Figs. 3a and 3b, many cracks and voids have nucleated. Figure 3d shows optical micrographs of a specimen that was strained to $e^P > 0.24$ ($Y > 12$ kb). Macroscopic cracks and voids are pervasive, indicating that brittle failure, not plastic flow has occurred. Although some cracking may have occurred by rarefaction waves, which unload the specimen and end the experiment, cracking also occurred during loading, because the yield strength was decreasing before the rarefaction arrived [Breithaupt, private communication, 1982]. It is difficult to determine precisely when void growth and crack formation become the dominant deformation mechanisms in uniaxial stress. Nevertheless, Fig. 3 suggests that plastic flow dominates when $e^P \leq 0.16$. Consequently, these uniaxial stress data probably should not be used to deduce yield strength information when $e^P > 0.16$, because the beryllium is undergoing brittle failure.

An extrapolation of Breithaupt's [1981] data to $e^P = 0$, indicate that the value of Y_0 should be reduced to 2.3 kb. However, this small change in Y_0 has virtually no effect on numerical simulations of plate impacts.

Simulations that used this work hardening model for beryllium and whose results are sensitive to the work hardening parameters should be re-examined. For example, there are specific systems which are more sensitive to the properties of beryllium. An example of this is a hydro shot fired in 1976, but which was not simulated successfully (radius-time plots of the innermost shell) until very recently, using the work hardening model just discussed [Larson, 1982]. The simulation is sensitive to the choice of work hardening parameters, and depends critically on the maximum value of the work hardening (13.1 kb). Calculations using 15.0 kb give poor results [Larson, 1982]. The "successful" calculation of this hydro may be fortuitious, because the work hardening model (representative of plastic flow) was constructed from data that represented brittle fracture, not plastic flow.

Beryllium Hugoniot

Figure 4 shows shock velocity, as a function of particle velocity for various grades of beryllium [Froula, 1968; Isbell, 1968; McQueen et al., 1970; Christman and Feistmann, 1972; Wise et al., 1981]. Hugoniot pressures are also shown on the horizontal axis. The data ($U_p > 0$) were obtained from uniaxial strain plate impact experiments. The $U_p = 0$ data were obtained from acoustic measurements. The difference between the two Christman and Feistmann [1972] data points represents measurements made parallel and perpendicular to the pressing direction, which yielded $U_p = 0.78$ and 0.74 cm/ μ sec, respectively. The dashed line in the figure, $U_s = 0.776 + 1.4 U_p$, was used by Steinberg and Sharp [1981] to simulate the data obtained by Christman and Feistmann [1972]. The data of McQueen et al. [1970] for an unknown grade of beryllium, are identical to the data obtained by Wise et al. [1981], for 1162A beryllium. The solid line drawn through the 1162A data, $U_s = 0.80 + 1.124 U_p$, represents the U_s - U_p relation for beryllium that is used in KOVEC.

Temperature Dependence of Beryllium Yield Strength

As the temperature increases, the yield strength decreases. Table 2 shows high temperature yield strength data (uniaxial stress) that were obtained for S200D [Green and Schierloh, 1968] and 1319B [Mayville, 1980] beryllium. To remove strain-rate effects, the high temperature and the room temperature yield strengths were both measured at approximately the same strain-rates, which are listed in the table. The table also shows the predictions of the KOVEC model. These data indicate that the temperature dependence of the KOVEC yield strength model may be too small.

Viscoplasticity in Beryllium

Figure 1 shows that at strain-rates less than 1000, the yield strength of beryllium is strain-rate dependent. However, at strain-rates greater than 10^5 , which are typical of shock loading, experimental data indicate that the strain-rate dependence of the yield strength of beryllium is very small, as is shown below.

A nonlinear material response causes a compressive wave to steepen and "shock up", while dissipative processes in the shock tend to smear it out. The dissipative processes can be characterized by a shock viscosity. When a shock wave is steady ("shock up" balances dissipation, or equivalently, the wave does not change shape as it moves through the material) it is possible to calculate the shock viscosity, and then compute a relaxation time for the viscous (strain-rate) effects [Chhabildas and Asay, 1979]. Asay et al. [1981] produced steady waves in 1162A beryllium, at pressures of 100, 170, and 250 kb. Figure 5 shows the effective viscosities from these data, as a function of peak strain-rate. Christman and Feistmann's [1972] data are also shown in the figure. These data yield a maximum relaxation time, $\tau = 0.6$ nsec, where the relaxation time equals one-half the viscosity divided by the shear modulus [Chhabildas and Asay, 1979]. This relaxation time is too small (the beryllium relaxes too quickly) to affect the simulations, in which response times were of the order of microseconds. Thus, the data do not support the use of a viscoplastic constitutive model for shock loaded beryllium.

SENSITIVITY STUDY

In this section, we determine which constitutive model parameters are important for simulating uniaxial strain plate impact experiments. First we discuss the experiments we have chosen to simulate, and then we discuss the effects of work hardening, Hugoniot, and computational zone size on simulating the experimental data. We conclude with a discussion of the uniqueness of constitutive models, where we show that a constitutive model for beryllium that is different than the basic KOVEC model, and is based on different assumptions, can simulate the uniaxial strain data as well as the basic KOVEC model.

Uniaxial Strain Plate Impact Experiments

We have simulated the three uniaxial strain plate impact experiments shown in Fig. 6, which we refer to as, the Compression, Reshock, and Release experiments. These experiments cover a broad range of uniaxial strain behavior. In the Compression experiment [Christman and Feistmann, 1972], a fused quartz (FQ) flyer plate impacts (24 kb) a Be (S200E)/FQ target. The 24 kb compression wave travels through the target and is followed by a rarefaction wave that is generated at the free end of the flyer. In the Reshock experiment [Wise et al., 1981], a WC/Cu flyer plate impacts (250 kb) a Be (1162A)/LiF target. The copper and the beryllium are shocked initially to 250 kb. The high impedance of the WC (as compared to copper) reflects a "reshock" back through the copper and the target. The magnitude of the reshock in the beryllium is 50 kb. In the Release experiment [Wise et al., 1981], a PMMA/WC flyer plate impacts (350 kb) a Be (1162A)/LiF target. When the 350 kb shock reaches the PMMA/WC interface, the low impedance of the PMMA (as compared to WC) generates a rarefaction wave that travels back through the WC and the target. The beryllium does not go into tension.

The data obtained from these experiments are particle velocity vs time records, at the right boundary of the beryllium (see Fig. 6). Numerical simulations of these experiments attempt to reproduce these particle velocity vs time records.

We used KOVEC and the material models that are common to our 1- and 2-D hydrodynamic codes to simulate the experiments. This multidimensional or basic constitutive model is described in the introduction. We did the sensitivity study by varying only the beryllium parameters.

Numerical Simulations of the Experimental Data using the Basic KOVEC Constitutive Model

The comparisons between the experimental data and the numerical simulations using the basic KOVEC constitutive model are shown in Figs. 7-9, showing the Compression, Reshock, and Release experiments, respectively. The basic model generates a sharp elastic wave followed by a sharp plastic wave, as shown in the figures. The experimental data show the elastic precursor ramps smoothly into the plastic wave. Thus, elastic-plastic loading is not simulated well by the basic model. The reshock precursor in Fig. 8 also cannot be simulated by the basic model. Release phenomena, which are responsible for the peaked shape and smooth fall-off of the Compression and Release data are not simulated well by the basic model. Although the KOVEC Bauschinger model simulates these release phenomena well, it is available only in the 1-D codes. The basic KOVEC model, which is being studied here, is the one that is used in the 2-D codes.

We note that the compression experiment is a low pressure experiment, as compared to the Reshock and Release experiments. The horizontal dashed lines at $0.015 \text{ cm}/\mu\text{s}$ in Figs. 8 and 9 represent the peak particle velocity in the compression experiment.

Work Hardening Sensitivity

The effects of work hardening on simulating the experimental data are shown in Figs. 10-12. The figures show the experimental data and simulations using the basic model, which has work hardening (Eq. 1), and the basic model without a work hardening yield strength in beryllium. The simulations show that a constant yield strength (elastic perfectly plastic) in beryllium fits these uniaxial strain data as well as simulations with a work hardening yield strength. Nevertheless, it should be emphasized that work hardening may be

important for simulating other types of experiments that have different geometries. Simulations of spherical (converging) geometries are being done currently.

Hugoniot Sensitivity

Figure 13 shows the reshock experimental data and simulations using two different Hugoniot equations. The basic model has $U_s = 0.80 + 1.124 U_p$, and the other simulation has $U_s = 0.776 + 1.4 U_p$ (see Beryllium Hugoniot section and Fig. 4). The figure shows that the simulation with $U_s = 0.776 + 1.4 U_p$ has slightly earlier wave arrival times than those predicted by the basic model.

Zone Size Sensitivity

The beryllium zone size in the preceding 1-D simulations is 56 μm . However, typical 2-D simulations are constrained by cost, time, and storage to use a 2000 μm beryllium zone size. To determine the effects of zone size on the simulations, we simulated the release experiment with fine zoning (143 zones of beryllium at 56 μm) and coarse zoning (4 zones of beryllium at 2000 μm). In order to keep the impedance matched in the latter simulation, all the materials were coarse zoned (number of zones decreased by 37, and thickness of zones increased by 37). Figure 14 shows the experimental data for the release experiment, the fine zoned, and the coarse zoned simulations. As expected, coarse zoning causes a severe loss of resolution. The particle velocity of the shocked state ($t = 1 \mu\text{s}$), obtained from the coarse zoned simulation, is significantly different from the experimental data. At $t = 1.2$ and $2.2 \mu\text{s}$, the experimental particle velocity is decreasing, while in the coarse zoned simulation it is increasing. These simulations demonstrate that even if a "perfect" constitutive model were available, the coarse zoning that is typical of 2-D simulations would obscure much of the detail.

Uniqueness of Constitutive Models

It is easy to show that constitutive models derived as above are not unique. We have "synthesized" a constitutive model that is different from the

basic model and based on different assumptions. This alternate model simulates the Compression, Reshock, and Release experiments as well as the basic model, and is described below.

The zone size for beryllium in the simulations is $56\text{ }\mu\text{m}$, which is approximately the average grain size of beryllium ($35\text{ }\mu\text{m}$). For dimensions that are on the order of the grain size, beryllium is anisotropic, consisting of randomly oriented grains. The yield strength of these individual grains can be as high as 25 kb [Pope and Johnson, 1975], depending on grain orientation with respect to the shock wave direction. To account for the variation of yield strengths, due to the anisotropic microstructure, we assign a different yield strength in each computational zone. We determine the distribution of yield strengths by using a Weibull distribution with a mean of 3.3 kb and a standard deviation of 1.19 kb. We use a Weibull distribution, because it has been used successfully to describe observed distributions of yield strengths of various materials [Weibull, 1951]. The 3.3 kb mean was chosen to be consistent with Y_0 in the basic KOVEC model, which is based on the macroscopic behavior of beryllium. The 1.19 kb standard deviation was chosen arbitrarily. We note that the following simulations do not depend strongly on the specific Weibull parameters. A uniform distribution of yield strengths gives similar results.

The alternate model differs from the basic model (see Introduction), as follows:

<u>Basic Model</u>	<u>Alternate Model</u>
$G(P, T)$	G_0 (constant)
$Y(e^P, P, T)$	Y (Weibull, elastic perfectly plastic)

Figures 15-17 show the experimental data, and simulations using the basic and alternate models.[†] Figure 15 shows that the simulation of the

[†]Simulations using the alternate model were done using AFTON [Glenn, 1978], because a distribution of yield strengths cannot be generated by KOVEC. Simulations using AFTON and the basic model are identical to those obtained using KOVEC and the basic model.

Compression experiment, using the alternate model, is qualitatively similar to the experimental data. The elastic wave makes a smooth transition into the plastic wave for both loading and unloading. The ramped elastic precursor is present also in the Reshock (Fig. 16) and the Release (Fig. 17) simulations. The most significant effects occur for the Compression experiment (Fig. 15), in which $Y \sim P$. The alternate model fits these experimental data as well as the basic KOVEC model.

Summary and Future Work

We have checked the consistency of the KOVEC constitutive model for beryllium with experimental data, by examining work hardening, the temperature dependence of the yield strength, strain-rate effects, and the Hugoniot ($U_s - U_p$) relations. We have found the following discrepancies between the KOVEC model and the experimental data:

- the cap on the work hardening model for beryllium is not supported by the experimental data;
- the experimental data suggest that the temperature dependence of the yield strength is larger than is in the model currently;
- the experimental data do not support the use of a viscoplastic constitutive model for shock loaded beryllium.

We have examined at the sensitivity of simulations of uniaxial strain plate impact experiments, in which beryllium was used, to changes in work hardening, Hugoniot, and zone size. Our simulations show that the zone size sensitivity is very large. There is a significant loss of resolution when coarse zoning (zoning typical of a 2-D calculation) is used, as compared to fine zoned (400 fine zones = 1 coarse zone) simulations. There is only a small sensitivity to changes in work hardening and the Hugoniot for beryllium.

We have also illustrated the non-uniqueness of the KOVEC model by simulating the experiments discussed above, using a material model for beryllium that is different from the basic model, and based on different assumptions. We used a constitutive model for beryllium that included the effects of the microstructure on the yield strength of beryllium. The basic KOVEC model treats the yield strength as a macroscopic property. The alternate model

simulates the data as well as the basic KOVEC model. Thus, fitting experimental data is a necessary, but not sufficient condition for validating constitutive models.

Future work will consist of:

- A sensitivity study of simulations of converging flows;
- High temperature Hopkinson bar compression experiments on 1319 beryllium, to quantify the temperature dependence of the yield strength;
- Biaxial tests (compression and torsion) on 1319 beryllium, to examine work hardening and Bauschinger effects.
- Construction of a properly invariant Bauschinger model that can be used in both 1- and multi-dimensional code simulations.

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TABLE 1. BERYLLIUM SPECIFICATIONS

Type	Data	%Be	%BeO	Tensile strength (kb)	Tensile yield (kb)	Average grain size (μm)
S200	Froula, 1968 Isbell, 1968	98.32	1.95	3.39	2.28	Large variation
S200D	Green and Schierloh, 1968	>98.00	<2.00	2.76	2.07	35
S200E	Christman and Feistmann, 1972	>98.00	<2.00	2.76	2.07	≤ 25
S200E	(Received)	98.55	1.39	3.9	2.63	10.3
1162A	Wise, Asay, and Chhabildas, 1981 Breithaupt, 1981	>98.00	<1.50	2.41	2.62-1.72	≤ 35 max. ≤ 125
1319B	Mayville, 1980 Breithaupt, 1981	>98.5	<1.20	3.45	3.45-2.41	≤ 15
●	Weaponized					

TABLE 2. TEMPERATURE DEPENDENCE
OF THE YIELD STRENGTH OF BERYLLIUM

Type	T(°K)	$Y_0(T, \dot{\epsilon})/Y_0(300^\circ\text{K}, \dot{\epsilon})$	$\dot{\epsilon}$	Test (Uniaxial stress)
S200D	644	0.65	~1000	Compression
		0.70	~0.001	
		0.93	~80	Tension
		0.78	~0.002	
1319B	643	0.66	~0.0001	Tension
	923	0.32	~0.0001	Tension
Basic model	644	0.91)	All strain-rates	Tension and Compression
	923	0.84)

Fig. 1 Uniaxial Stress Work Hardening Data

Fig. 2 Numerical Fit to Split Hopkinson Bar Data

Fig. 3a Optical Micrographs of an Undeformed Split Hopkinson Bar Specimen

Fig. 3c Optical Micrographs of a Split Hopkinson Bar Specimen ($e^p \sim 0.16$)

Fig. 3d Optical Micrographs of a Split Hopkinson Bar Specimen ($e^p > 0.24$)

Fig. 4 Beryllium Hugoniot Data

Fig. 5 Effective Viscosity of Beryllium

Fig. 6 Uniaxial Strain Plate Impact Experiments

Fig. 7 Compression Experiment Simulation Using the Basic Model

Fig. 8 Reshock Experiment Simulation Using the Basic Model

Fig. 9 Release Experiment Simulation Using the Basic Model

Fig. 10 Compression Experiment Simulation: Work Hardening Sensitivity

Fig. 11 Reshock Experiment Simulation: Work Hardening Sensitivity

Fig. 12 Release Experiment Simulation: Work Hardening Sensitivity

Fig. 13 Reshock Experiment Simulation: Hugoniot Sensitivity

Fig. 14 Release Experiment Simulation: Zone Size Sensitivity

Fig. 15 Compression Experiment Simulations Using the Basic and Alternate Models

Fig. 16 Reshock Experiment Simulations Using the Basic and Alternate Models

Fig. 17 Release Experiment Simulations Using the Basic and Alternate Models

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