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Comparison Of Experimental Shock-Wave Profiles For Tungsten And Computer Simulations Using A Rate-Dependent Constitutive Model

Daniel J. Steinberg

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Comparison Of Experimental Shock-Wave Profiles For Tungsten And Computer Simulations Using A Rate-Dependent Constitutive Model*

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Daniel J. Steinberg
Lawrence Livermore National Laboratory
P. O. Box 808, Livermore, CA 94550 USA

Abstract

The Steinberg-Guinan-Lund, rate-dependent, constitutive model for Ta has been applied to W. Computer simulation successfully predicts the elastic precursor ahead of the second shock in a series of double-shock experiments. Based on the Cochran-Banner spall model, the spall strength of W is 0.9 ± 0.1 GPa, independent of loading stress from 10 to 200 GPa. The model provides an explanation of why some quasi-isentropes appear stiffer than the principal Hugoniot.

Introduction

In a previous paper,[1] Steinberg and Lund described a rate-dependent constitutive model applicable for strain rates from 10^{-4} to $10^{6} s^{-1}$. With this model, we demonstrated that a hydrodynamic computer code could successfully predict a number of experimental, shock-induced, rate-dependent phenomena in tantalum. In addition, the model predicts that there would be an elastic precursor ahead of the second shock in a double-shock experiment. Unfortunately, no double-shock experiments exist for Ta. One of the purposes of this paper is to show that this model can successfully simulate such experiments for another BCC metal, tungsten.

A second purpose is to determine the spall strength for W, using the Cochran-Banner spall model,[2] and show how the rate-dependent constitutive model affects the calculated spall simulations. Finally, I will describe how a constitutive model of this kind can explain why the yield strength in a quasi-isentropic loading experiment can be greater than the yield strength on the principal Hugoniot.

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The equations describing the rate-dependent constitutive model are given below; the details can be found in reference 1.

$$Y = \{Y_T(\dot{\varepsilon}_p, T) + Y_A f(\varepsilon_p)\} \frac{G(P,T)}{G_o}, \tag{1}$$

$$\dot{\varepsilon}_p = \frac{1}{\frac{1}{C_1} \exp\left[\frac{2U_K}{kT}\left(1 - \frac{Y_T}{Y_P}\right)^2\right] + \frac{C_2}{Y_T}} \tag{2}$$

The total yield strength Y is composed of two terms. The first is a thermally activated part Y_T, which is a function of the plastic strain-rate $\dot{\varepsilon}_p$ and the temperature T. The second, or athermal term, contains the initial athermal yield strength Y_A, multiplied by a work-hardening term $f(\varepsilon_p)$, which is a function of the plastic strain ε_p. The term $G(P,T)/G_o$ is the pressure P and temperature-dependent shear modulus divided by G_o, the modulus at STP conditions.

In eqn. 2, Y_P is the Peierls stress, $2U_K$ is the energy to form a pair of kinks in a dislocation segment of length L, and k is the Boltzmann constant. The constant C_2 is the drag coefficient D divided by the dislocation density ρ times the square of the Burger's vector b. The constant C_1 is

$$C_1 = \frac{\rho L a b^2 \nu}{2w^2}, \tag{3}$$

where a is the distance between Peierls valleys, w is the width of a kink loop, and ν is the Debye frequency. The functional forms and parameters for $f(\varepsilon_p)$ and G(P,T) are the same as in the rate-independent model of Steinberg, Cochran and Guinan.[3] Finally, we limit Y_T to be $\leq Y_P$.

For Ta, we have a suite of non-shock-wave data which was used to determine the parameters C_1, C_2, U_K, Y_P, and Y_A. No such data exist for W, so reasonable estimates had to be used. For C_1, C_2 and U_K, I assumed the same values as for Ta. This makes $C_1 = 0.71 \times 10^6 s^{-1}$, $C_2 = 0.012$ MPa-s, and $U_K = 0.31$ eV. There is some evidence that this is a valid approach to estimate U_K. Dorn and Rajnak[4] give a value of U_K for W only 10% larger than their value for Ta.

Because Y_A for Ta is approximately one-half the value of Y_o, the yield strength at the Hugoniot elastic limit, I assumed Y_A was 1.1 GPa, as Y_o equals 2.2 GPa. The Peierls stress was also estimated from the simple relationship $Y_P \simeq 0.01\ G_o$.[5] This gives $Y_P = 1.6$ GPa. The final value of Y_P was determined from the best fit to an initial shock-loading profile which fortuitously also gave $Y_P = 1.6$ GPa.

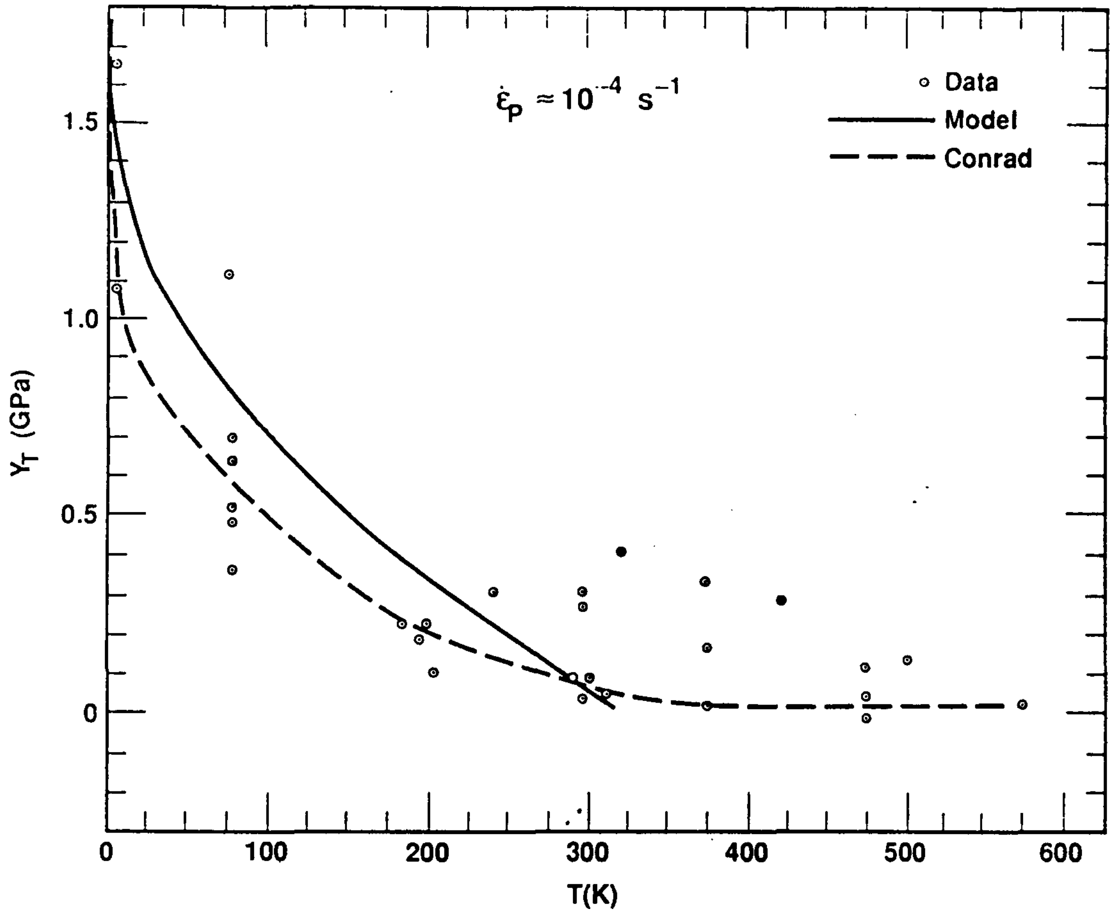

FIG. 1. Comparison of model and data for the thermally-activated yield strength vs temperature.

The choice of constants C_1, U_K and Y_P can be checked by comparing data for Y_T vs T at $\dot{\varepsilon}_p \simeq 10^{-4} s^{-1}$ and Y_T calculated from eqn. 2. Conrad[5] has reviewed the data for Y_T vs T and shows how sensitive Y_T is to interstitial impurities in W. In Fig. 1 are shown all the data quoted by Conrad for W with < 0.005 wt % interstitial impurities. The dash line is Conrad's estimate of what Y_T vs T should be for the purest W. Relatively impure W (> 0.02 wt %) exhibits substantially higher values of Y_T (e.g. ~ 0.65 GPa at T = 300 K) and Y_T does not go to zero until T ≃ 600 K.

The solid line in Fig. 1 is from eqn. 2. The W samples discussed in this paper have interstitial impurities of about 0.002 wt %. Considering the sensitivity of Y_T to impurity level, there is satisfactory agreement between the data, Conrad's estimate of Y_T and Y_T calculated from eqn. 2.

Brief Description Of The Experimental Data

The experimental shock-wave profiles are from two sources.[6,7] In the first of these,[6] three pairs of shock/release and shock/reshock experiments are reported. In all three cases the initial shock is ~ 9.7 GPa and the second shock ~ 14 GPa; the differences are in the thickness of the W sample. The data consist of velocimeter records of the interface between the sample and a sapphire window. These experiments are labeled WA4, 5 and 8 (release) and WA6, 9 and 10 (reshock). In the second report,[7] 13 shock-wave profiles are reported. Four of these were done with graded-density impactors whose equation-of-state I do not know, therefore they were not analyzed. Two of the tests (labeled MS2 and 5 in ref. 7) were quasi-isentropic loading experiments using a layered-impactor technique. Both the impactor and a buffer in front of the W samples contained PMMA. Preliminary analysis of these two experiments showed that they were too sensitive to the EOS of the PMMA to be good tests of the material properties of W. Estimated temperatures in the PMMA were a few eV; in this temperature range the EOS of PMMA is not well known. In addition, the PMMA reached a peak stress of 250 GPa, a stress in excess of even the known Hugoniot.

The 7 remaining experiments were completely analyzed and are reported here. Five of these were shock and release tests; two to ~ 70 GPa (WB3 and 4), two to ~ 100 GPa (WB1 and 2) and one to ~ 200 GPa (WB14). The difference within each pair of experiments is in the thickness of the sample. In the sixth experiment (WB5), a W impactor directly strikes a LiF window covered only by 34 μm of aluminum, shocking the W to ~ 34 GPa. Such an experiment is not subject to spall. For the last test (WB11) the W sample is buffered by a piece of LiF. In all cases the data consist of velocimeter records of the interface between the W sample and a LiF window.

Comparison Of The Data With Computer Simulations

The three pairs of experiments of Asay, Chhabildas and Dandekar[6] are compared with calculation in Figs. 2-4. The Peierls stress Y_p was adjusted to 1.6 GPa to give the best fit to the calculated shape of the initial loading curve in Fig. 2; no other parameter adjustments or fits to the data were made in any subsequent calculations.

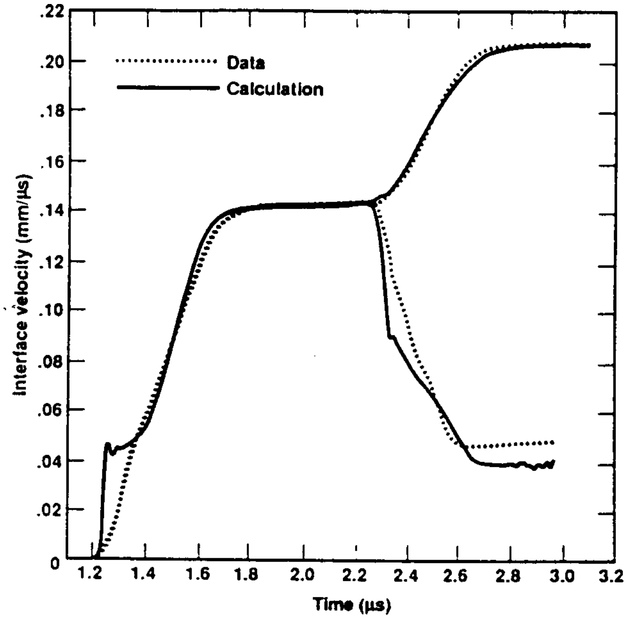

FIG. 2. Comparison of calculation and experiment for shots WA8 and 10. The data for shot WA8 have been reduced by 0.3%.

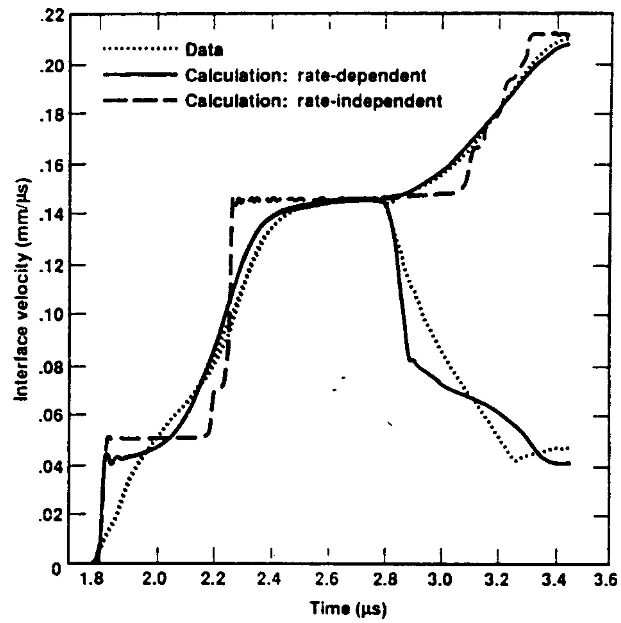

FIG. 3. Comparison of calculation and experiment for shots WA4 and 6.

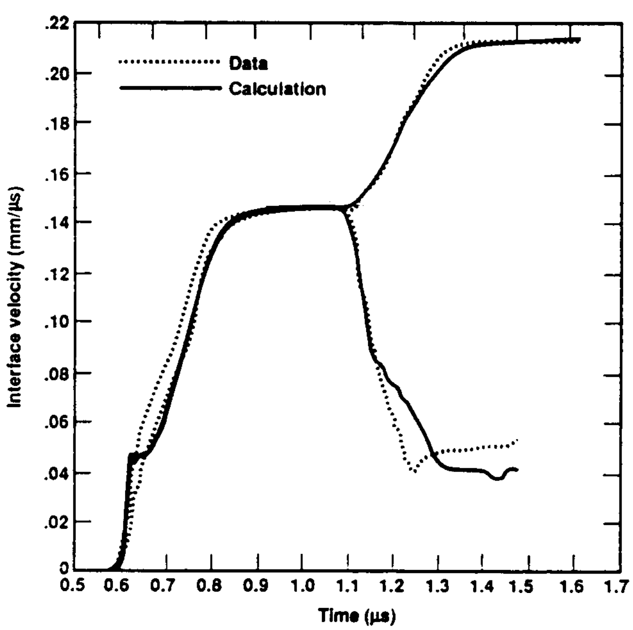

FIG. 4. Comparison of calculation and experiment for shots WA5 and 9. The data for shot WA9 have been reduced by 0.5%.

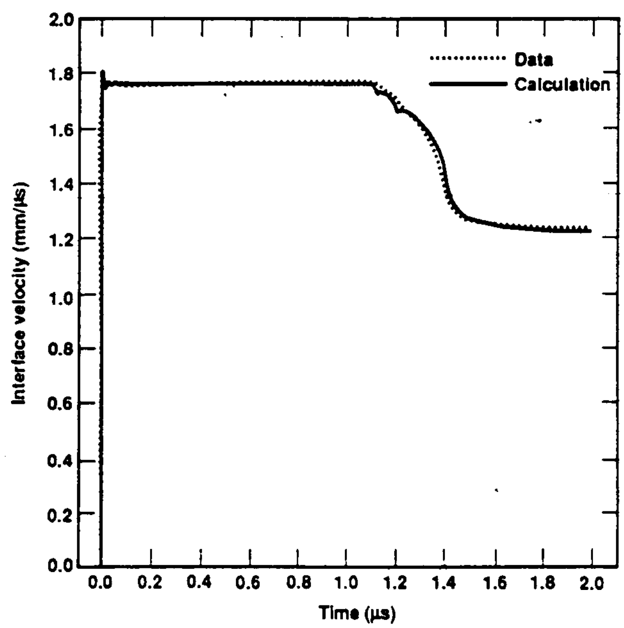

FIG. 5. Comparison of calculation and experiment for shot WB5. The data have been reduced by 0.3%.

The data all show dispersive initial elastic waves. Because the model is not visco-elastic, it is unable to simulate this feature. However, the calculations do an excellent job of reproducing the entire shock-reloading profile, including the elastic precursor. Fig. 3 includes a rate-independent calculation, and it is clear that the entire double-shock loading profile is not calculated correctly, in particular, the elastic precursor ahead of the second shock.

The calculated release profiles are not in very good agreement with the data. One explanation is that the dispersive quality of the elastic wave may be reflected in a more dispersive release. A second is that a Bauschinger effect must be included in the calculations.

Spall has been calculated using the Cochran-Banner model with a spall strength Σ of 0.9 GPa and a damage length of 10 μm. This value of Σ works well for experiments WA4 and 5, but 0.5 GPa seems more appropriate for experiment WA8. In addition, Asay, Chhabildas and Dandekar quote 0.66 GPa for WA5 and 0.42 for WA4. It is not clear why these discrepancies exist.

The loading profile for release experiment WA5 is different from that of WA9 as shown in Fig. 4. Asay, Chhabildas and Dandekar say the reason for this deviation is not understood. A similar, but more severe problem, has also been noted by Isbell, Christman, and Babcock[8] in their work on Ta.

The data of Chhabildas, Asay and Barker[7] are at such high stress levels that the effects of rate-dependence on yield strength are not easy to discern. Figs. 5-10 compare calculation with experiment for the 6 shock and release experiments, WB1-5 and 14. As with the earlier experiments, some of these data also show a dispersive elastic wave. Also, the calculated release profiles all exhibit the same problems as for the other, lower stress, data. Again, it would appear that a Bauschinger model should be included in the calculations.

These experiments were also calculated with a spall strength of 0.9 GPa. At these high stresses, a few tenths of a GPa change in Σ is hard to discern in the amount of velocity pullback. However, the slope of the calculated wave-profile during spall is best matched with $\Sigma=0.9\pm0.1$ GPa. The ringing seen in Fig. 10 demonstrates that the Cochran-Banner spall model is not as robust as it should be.

Fig. 11 compares the data of experiment WB3 with a rate-independent calculation. This figure, in turn, should be compared with Fig. 6. It is clear that the rate-independent constitutive model does not produce satisfactory results; there is much more structure in the calculation than in

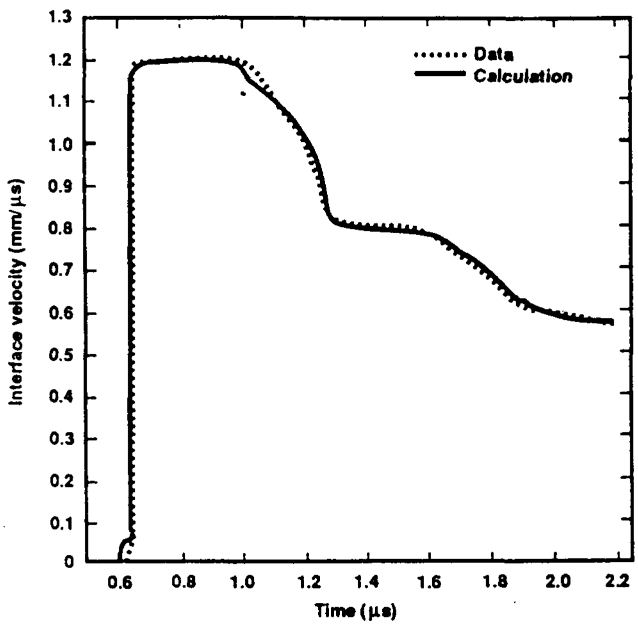

FIG. 6. Comparison of calculation and experiment for shot WB3. The data have been increased by 0.1%.

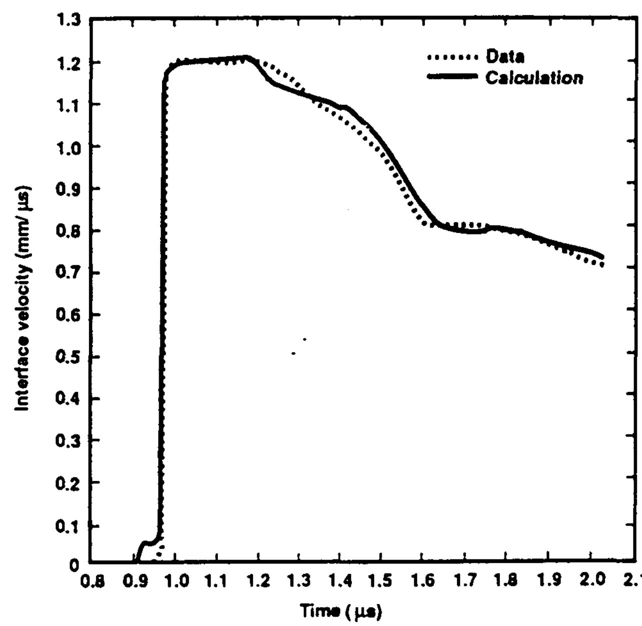

FIG. 7. Comparison of calculation and experiment for shot WB4.

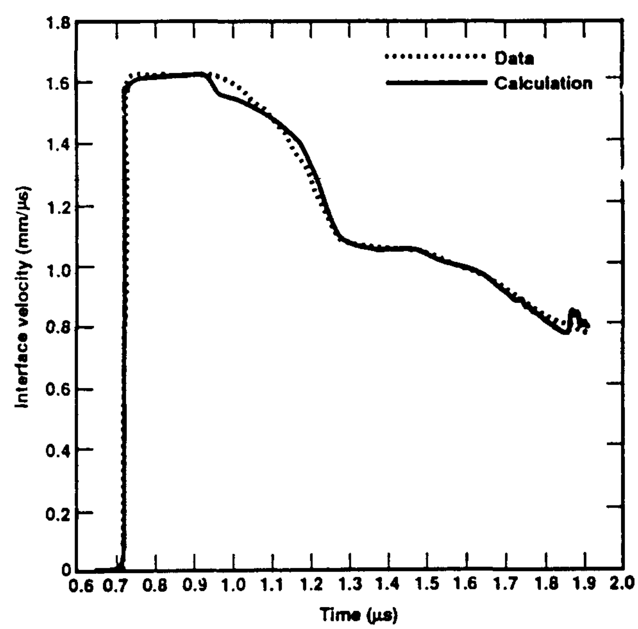

FIG. 8. Comparison of calculation and experiment for shot WB1.

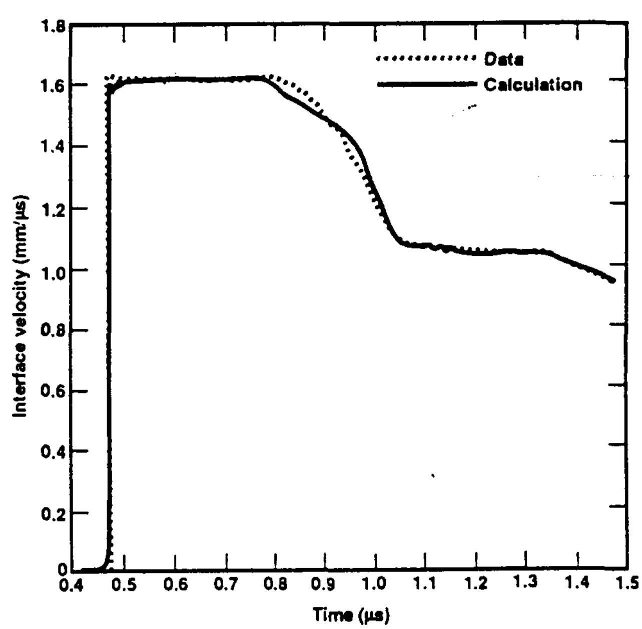

FIG. 9. Comparison of calculation and experiment for shot WB2.

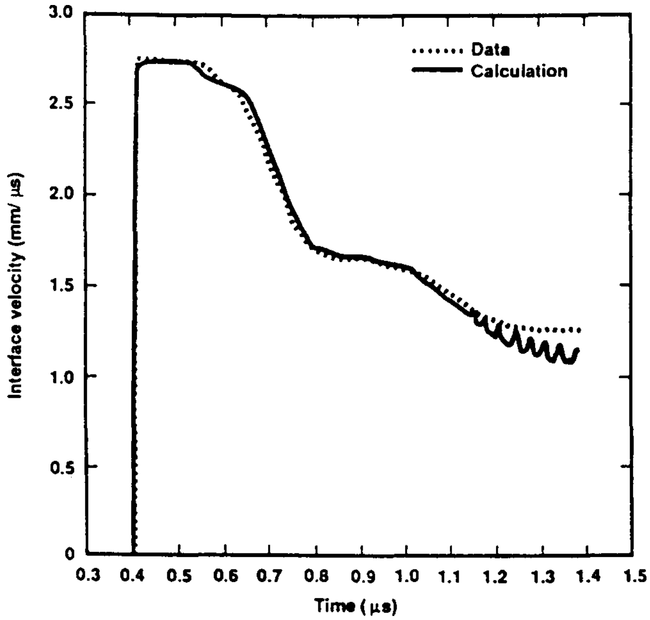

FIG. 10. Comparison of calculation and experiment for shot WB14.

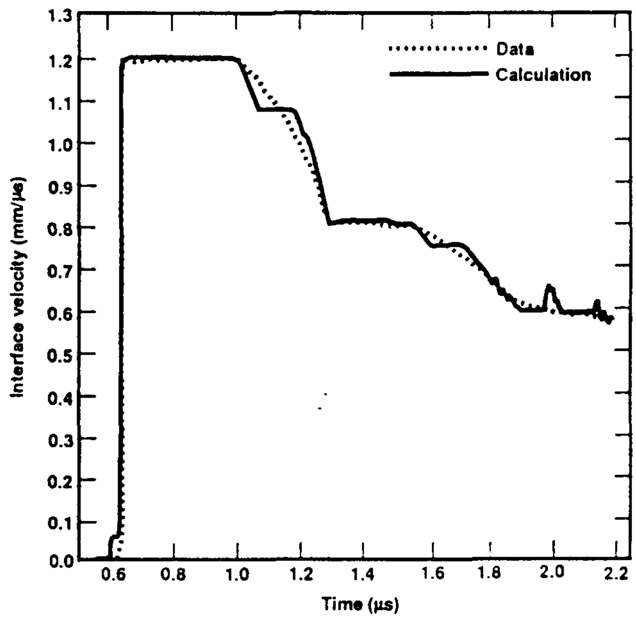

FIG. 11. Comparison of a rate-independent calculation and experiment for shot WB3. The data have been increased by 0.1%.

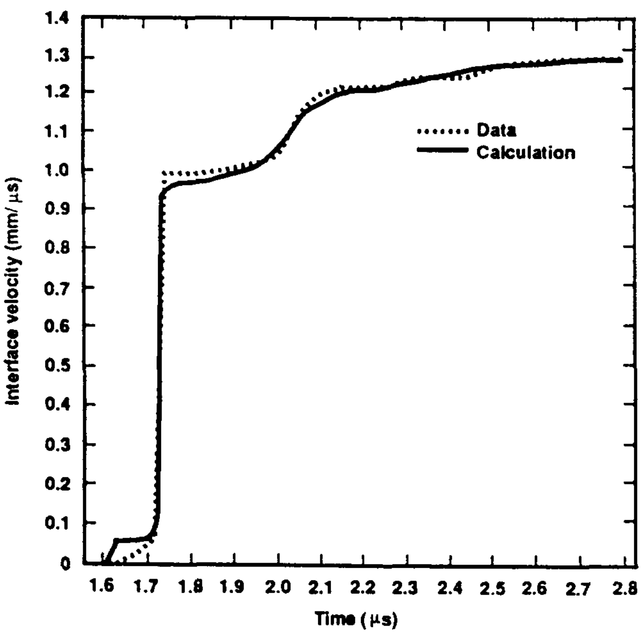

FIG. 12. Comparison of calculation and experiment for shot WB11. The data have been reduced by 1%.

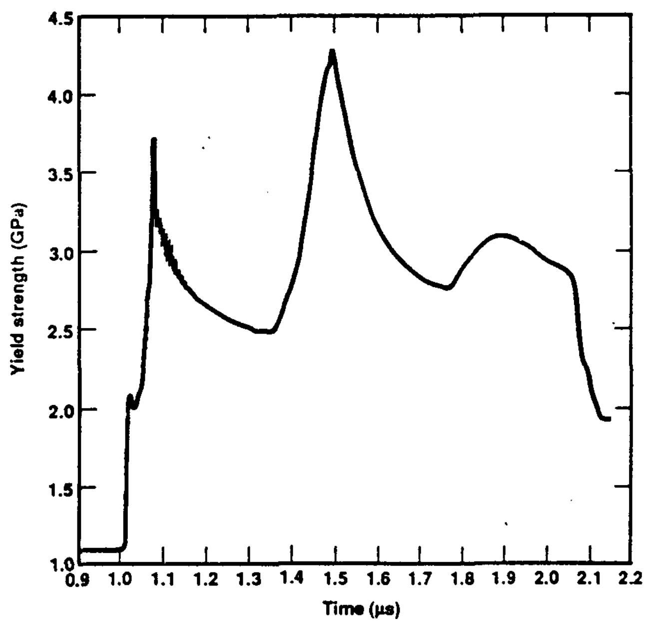

FIG. 13. Yield strength vs time in the center of the W sample in shot WB11.

the data. (However, the structures at the end of the calculation are due to problems with the spall model.) Qualitatively similar smoothing on the release profiles can be obtained by adding a Bauschinger effect to the rate-independent model. This points out again how important the addition of a Bauschinger effect is to any constitutive model. We are in the process of improving our Bauschinger model so that we may obtain the maximum benefit from both rate-dependence and Bauschinger effect.

Fig. 12 compares the calculation and the experiment for the multiple-shock experiment WB11 that uses the LiF buffer. The overall agreement is good. However, even though the experiment has been reduced by 1% to match the maximum calculated velocity, the calculated first shock is still about 1% too low. The calculation does show the signature of an elastic precursor ahead of the second shock, i.e. the gentle rise in the velocity, which shape is in very good agreement with the data. However, the rise time of the second shock is not as abrupt in the calculation as it is in the data.

One plausible explanation for these differences was alluded to when the problem of the PMMA buffers was described above. In this experiment, the off-Hugoniot EOS in the LiF buffer plays an important role in the calculations. The problem should not be as large as it is in PMMA. However, in the calculation of this experiment, the W reaches a temperature of approximately 630K, and the total energy in the LiF is ~ 13 times the total energy in the W. Therefore, the temperature in the LiF is probably high enough that the uncertainty in the temperature effect in the LiF Gruneisen gamma could easily account for velocity differences at the 1% level.

Fig. 13 shows the calculated yield strength vs time at the center of the W sample for the previous experiment, WB11. The many multiple shocks and releases produce a complicated time history. Consequently, it is impossible to say that the yield strength is any particular value in this experiment; one can only define a specific yield strength at a specific time. It is possible to do an experiment similar to WB11, with only a simple change of material thicknesses, and produce a different time history, one where the yield strength in the first experiment is at one time greater than, at another time less than Y in the second experiment. Indeed, as there are an infinite number of stress-loading profiles, any Y vs time history can be produced. Consequently, on the basis of this model, which is dependent on $\dot{\epsilon}_p$, ϵ_p, T, P, and compression, it is easy to see why Y depends in a complex way on how a material is loaded, not just on the maximum stress reached.

It might seem obvious that the temperature on the principal Hugoniot will be greater than on a quasi-isentrope. However, for a thick flyer which produces a long-lasting shock in the sample, the strain rate, just before release, can be less than $\dot{\varepsilon}_p$ on some quasi-isentropes. Both the higher temperature and lower strain rate will make Y on the Hugoniot low compared to Y on a quasi-isentrope.

The temperature effect probably dominates the sort of experiments described in refs. 6 and 7. Nevertheless, this model would imply that for other loading conditions, $\dot{\varepsilon}_p$ could be more significant. The importance of strength in any measurement will be pronounced in W which has such an unusually high overall strength. This model predicts similiar behavior for other BCC metals and even for some HCP metals[4], but the behavior may not be experimentally observable.

Conclusions

The rate-dependent model of Steinberg, Guinan and Lund has been applied to shock-wave profile data for W. The computer simulations successfully predict the elastic precursor ahead of the second shock in double-shock experiments.

Using the Cochran-Banner spall model, the spall strength of the W material used in these experiments is 0.9±0.1 GPa, independent of initial loading from 10 to 200 GPa. With the rate-dependent constitutive model, the computer simulations are smoother and match the data better than similar calculations done with a rate-independent model. However, it appears that a Bauschinger effect should be included to provide an even better match.

The rate-dependent constitutive model provides an explanation as to why some quasi-isentropes appear stiffer than the principal Hugoniot.

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