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Author(s):

D. L. Tonks
R. Hixson
R. L. Gustavsen
J. E. Vorthman
A. Kelley
A. K. Zurek
W. R. Thissell

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SPALLATION STUDIES ON SHOCK LOADED URANIUM LOS ALAMOS REPORT LAUR-97-3169

D.L. Tonks, R. Hixson, R. L. Gustavsen, J. E. Vorthman, A. Kelly, A. K. Zurek, and W. R. Thissell

Los Alamos National Laboratory, Los Alamos, NM.

Several spallation experiments have been performed on uranium using gas gun driven normal plate impacts with VISAR instrumentation and soft recovery. The shock pressures achieved were 81, 53, and 37 kbar. This paper will focus on modeling the free surface particle velocity trace U with of 300 ppm carbon using the 1 d characteristics code CHARADE. The spallation model involves the growth and coalescence of brittle cracks. Metallographical examination of recovered samples and details of the experimental apparatus are discussed in separate papers.

INTRODUCTION

Several studies of spallation in uranium have been done in the past.(1, 2) They have included VISAR traces and computer modeling but no soft recovery with metallurgical examination. Metallurgical examination should be done where possible, however, as it helps greatly in modeling micromechanical processes.

In recent work, our group has measured VISAR traces and done metallographical examination of recovered samples of pure uranium (30 ppm carbon) and less pure uranium (300 ppm carbon). Shock strengths induced were nominally 81, 52.7, and 37 kbar for the less pure uranium and 53 and 35 kbar for the pure uranium. The details of the gas gun work and of the metallurgical examinations are presented in other papers in this volume. (3, 4)

In this paper, calculations of a simple brittle crack growth model of the less pure uranium VISAR traces are presented. The intent is to show that the brittle crack description has some validity. Preliminary spall strength results for the pure uranium data are also presented using a simple tensile threshold model. More detailed model calculations for the pure uranium will be done in the future.

SPALLATION MODELING

The 1D characteristics code CHARADE(5) was used to model VISAR free surface traces using both ductile and brittle crack damage models. The brittle crack model results were more like the data and these results will be reported on here, with brief comments about the ductile model results. The metallurgical sample examinations of the less pure uranium showed a mixed brittle/ductile mode of fracture with the brittle component predominating.

Before presenting the brittle crack damage model, the equation of state and plasticity modeling will be briefly described. The equation of state (eos) treatment is patterned after the “almost isotropic” approximation of Wallace(6). A “pressure dependent bulk modulus” for use in this treatment was obtained from the Hugoniot relations in the usual way. Strictly speaking, this modulus applies only on the Hugoniot. The elastic moduli were degraded because of damage using the framework for isotropically distributed and oriented brittle cracks of Addessio and Johnson (7). Their Eq. (10) was used to obtain the volumetric “inelastic crack opening strain” as a function of negative pressure. The inelastic strain was then added to elastic volumetric strain to obtain the total strain. The resulting formula leads to the following scaled bulk modulus:

$$B' = B/(1+D), \qquad (1)$$

where B’ and B are the scaled and unscaled bulk moduli, respectively, and D is the effective damage quantity:

$$D = 15B(2-\nu)\beta\,\overline{c}^{\,3}, \qquad (2)$$

where β is given by:

$$\beta = \frac{64\pi}{15}\frac{(1-\nu)}{(2-\nu)}\frac{N_o}{G}. \qquad (3)$$

ν is Poisson’s ratio; G is the “solid” shear modulus, N_0 is the volumetric crack center density; and $\overline{c}$ is the average crack radius. The elastic constants were scaled only under volumetric tension, not for volumetric pressure. A similar treatment was used to obtain the effect of crack growth on the pressure increment for use in the characteristic equations.

In Eq. (1) above, B is the bulk modulus in the “equivalent” solid material. In the expression for B mentioned earlier, B is a function of the compression, so using this equation for B requires an “equivalent solid compression”. Such a compression was obtained by dividing B into the “equivalent solid stress”, σ_s, given by:

$$\sigma_s = \sigma_{cell}(1+\phi), \qquad (4)$$

where ϕ is a “porosity” given by:

$$\phi = 1 - \exp(4\pi\overline{c}^{\,3} N_o/3), \qquad (5)$$

and σ_{cell} is the longitudinal stress in the computational cell.

The quantity ϕ should approximately account for the unstressed regions around a penny shaped crack: the quantity in the exponent is an effective crack volume and the exponential takes overlaps of such volumes into account.

The deviatoric plasticity, which was not degraded by damage, is the same as used earlier for Ta spall modeling.(8) The “normal” component of the deviatoric plasticity was approximated by writing the plastic strain rate as a power law to the second power in the deviatoric stress. Both a forward and backward yield stress were used. This deviatoric plastic strain rate was supplemented by a simple back stress model (8) in which a release immediately produces reverse plastic flow. These two plasticity models helped to produce a realistic release behavior preceding spall.

The brittle crack damage model is patterned somewhat after that of Grady and Kipp (9) and involves the breakout and growth of a single sized population of cracks of size $\overline{c}$. These cracks have all orientations and uniformly fill a computational cell. The cracks break out when the stress intensity reaches K_{IC} and arrest when it reaches K_{IA}. The applied stress intensity factor K_I is given by:

$$K_I = (2/\pi)\sigma\sqrt{c(t)}, \qquad (6)$$

where σ is the longitudinal stress and c(t) is the time dependent crack radius. During breakout and arrest, the crack radius grows at the constant rate $v_{crk} = f\,c_s$, where c_s is a shear sound velocity and f is a reducing factor. Thus, c(t) during the first such breakout is given by:

$$c(t) = c_a + v_{crk}(t - t_a), \qquad (7)$$

where c_a is the initial crack radius and t_a is the time of crack breakout. Before first breakout, the cracks are considered not yet formed and no elastic moduli reduction is performed.

Grady and Kipp’s modeling included a time delay in crack loading. In calculations using this delay, the results were almost identical to the ones given here.

The effect of the damage on the equation of state has already been discussed. Spallation is taken to occur when ϕ defined in Eq. (5) reaches 0.30. This rule uses a percolation argument to take approximately into account the regions unloaded by the cracks. When these regions overlap to form a path across the sample, it should be close to total fracture.

TABLE 1. Tensile threshold model spall strengths

Shot #	**Shock Strength**	**Spall Strength**
56-96-3	81 kbar	26 kbar
56-96-4	37 kbar	20 kbar
56-96-5	52.7 kbar	25 kbar
56-97-3 (pure)	35 kbar	25 kbar
56-97-5 (pure)	53 kbar	30 kbar

RESULTS

To obtain a rough idea of the spall behavior, a tensile threshold spallation model was used to calculate “spall strengths”. In this model, a computational cell is spalled when the normal stress, σ , falls below the “spall strength”. (σ is defined positive in compression.) There is no damage and no eos degradation before spall. This model was used to predict the point at which the damage release first occurred in the free surface trace. Table 1 shows these calculated spall strengths for both the impure and pure uranium. Note that these strengths are somewhat larger for the pure uranium (30 ppm carbon) than for comparable impure uranium (300 ppm carbon).

The approximation of one half the pullback velocity times the acoustical impedance gave the following spall strength approximations for the 81, 37, and 52.7 kbar shocks, respectively: 21.9, 17.2, and 22.0 kbar. Cochran and Banner (1) reported a model spall strength of 24 kbar for their experiments of shock strength 40 kbar and less. Grady (2) reported corrected spall strengths of 27.3 kbar and 29.2 kbar for shocks of strength 76.9 kbar and 97.3 kbar.

Figure 1 shows the calculated CHARADE free surface profiles with the experimental data. The experimental times were shifted arbitrarily to obtain correspondence with the calculations. 200 zones were used to model the sample plate in CHARADE. Calculated fits using 500 zones resulted in only slightly different parameter values but, often, significant changes in profile lineshape resulted.

TABLE 2. Brittle crack model parameter values, Series 56-96

Shock kbar	$V_{f/s}$ mm/μs	K_{IC} $Mbar\sqrt{cm}$	K_{IA} $Mbar\sqrt{cm}$	f
81	0.153	$0.9x10^{-3}$	$0.2x10^{-3}$	0.11
52.7	0.0704	$0.75x10^{-3}$	$0.4x10^{-3}$	0.13
37	0.1078	$0.8x10^{-3}$	$0.5x10^{-3}$	0.092

Table 2 gives the brittle crack model parameters and $V_{f/s}$ values used in the calculations. $V_{f/s}$ is the flyer/sample interface velocity. In many cases, it was adjusted slightly away from the values given by impedance matching and the experimental flyer velocity so that the calculated shock plateau velocity would match the data. This was done to better model the spallation. The value of 3.017 (mm/μ s) was used for c_s . The value 2x10^4 cm^{-3} was used for N_0 in all cases. The initial crack size, C_a , used was 1.5 10^{-3} cm.

Figure 1 shows that the brittle crack model reproduces the general spallation behavior of the data. In particular the extent of rebound after spall is modeled fairly well. The calculated profiles tend to have too many calculated “wiggles”. This probably means that the late stage damage modeling needs improvement. The modeling contains no detailed crack coalescence mechanisms beyond the inclusion of overlapping in the “regions of influence” of the cracks. In the modeling it was noticed that spallation occurred over a fairly wide area and that the smallest calculated ring periods were due to spalled cells lying closer than reasonable to the free surface.

Another problem is that Equation 1 for the degradation of elastic moduli gave calculated degradations that were quite extreme. This is because the theory behind Eq. (1) is an approximate linearized theory. A more accurate treatment including crack crack interactions would yield smaller degradations. This behavior also contributed to the smallest ring periods in the calculated profiles.

A ductile void growth model, similar to that of Johnson (10) was also tried. Although the general

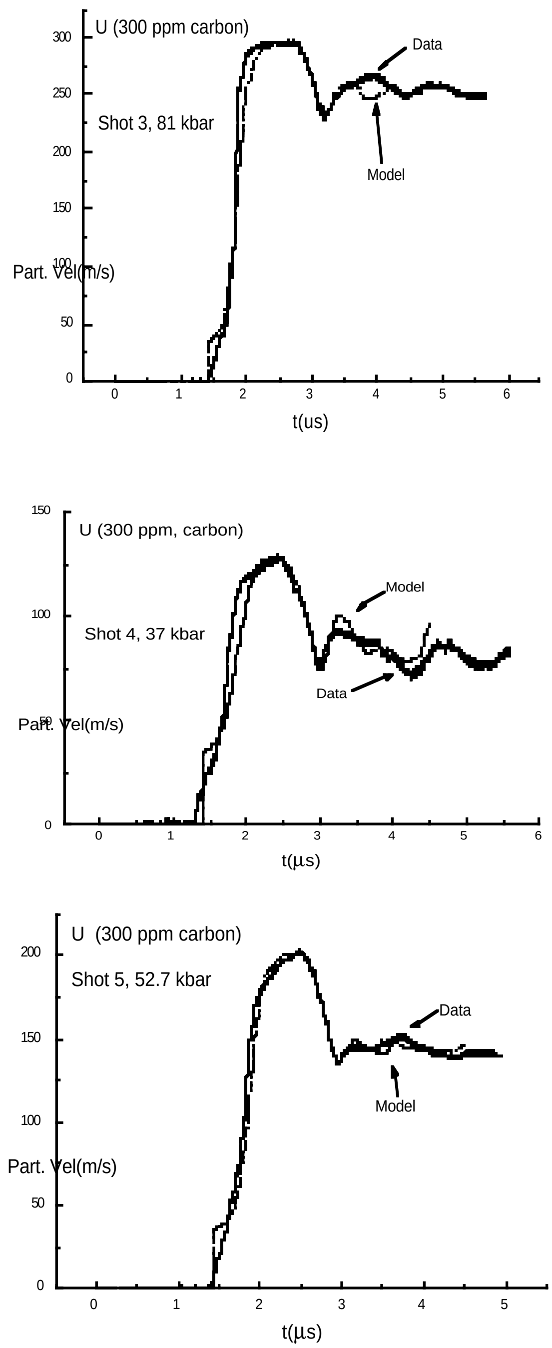

FIGURE 1. Calculated and measured free surface particle velocity profiles.

spallation features could be reproduced, the reproduction of the details was significantly worse. The ductile model did the best job for the 81 kbar shot, suggesting that the 81 kbar experiment was more "ductile".

The brittle crack fitting parameters are reasonable. The initial crack size of 15 microns and crack growth velocity of about 1/10 the shear sound velocity are plausible. Incidentally, the results are very sensitive to the crack growth velocity. The values of K_{IC} used here are smaller than those typical of low alloy steels(11), e. g. $5\text{x}10^{-3}$ Mbar $\sqrt{cm}$ but larger than the K_{IC} value $0.126\text{x}10^{-3}$ Mbar $\sqrt{cm}$ found by Grady(9) for novaculite, a rock. When quantitative analysis of micrographs is available, the micromechanical realism of the model can be better assessed and improved. In conclusion, it seems that the brittle crack description of spallation in not so pure uranium has some validity. It will be generalized in the future to obtain a mixed brittle/ductile spallation model.

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