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TENSILE DAMAGE EFFECTS IN STEEL PLATE PERFORATION BY A TUNGSTEN ROD

Martin N. Raftenberg

U.S. Army Research Laboratory, Aberdeen Proving Ground, Maryland 21005-5066

The EPIC Lagrangian wavecode was used to study sensitivities of rolled homogeneous armor (RHA) target hole size and the length and speed of a tungsten heavy alloy (WHA) residual rod to RHA spall pressure. The target had a 50.8-mm thickness, and the rod had a 112.0-mm length, a 20.9-mm diameter, and a striking speed of 1.52 km/s. Corresponding to a spall pressure of ~ 0.5 GPa, good agreement with experiment was obtained in terms of target hole size and residual length for two different RHA fits to the Johnson-Cook strength model. Adiabatic shear banding in RHA is proposed to be the mechanism by which spall pressure is locally changed from its measured value of ~ 3.0 GPa.

INTRODUCTION

Raftenberg and Kennedy (1) presents results from an experiment in which a 50.8-mm-thick RHA plate was perforated by a WHA rod. The plate had a square face with a 457-mm edge length. Brinell hardness of the face was 302. The rod was a right circular cylinder of 112.0-mm length and 20.9-mm diameter. The WHA had a composition of 91W-6Ni-3Co and a Rockwell C hardness of 41.6. The impact speed was 1.52 km/s. A 7075-T651 aluminum drag flare was attached to the rear of the rod. In (2), Raftenberg used the EPIC wavecode (3) to model this experiment, with the focus on representations of the drag flare, the RHA yield function, the WHA shock Hugoniot, and the Grüneisen parameter for both RHA and WHA. All results were reasonably successful in predicting residual length, but they underpredicted the final perforation-hole diameter. The focus now is on damage modeling in RHA.

MODELING PROCEDURE

The plate was represented as a circular disc with a 500-mm radius to reduce the problem to axial symmetry. Slideline erosion (4) was based on an

equivalent plastic strain of 1.5. Meshes were composed of three-node triangular elements. RHA and WHA meshes were composed entirely of elements arranged in sets of four-element quadrilaterals (rectangles prior to deformation). The “original” meshes contained 5 such quadrilaterals across the rod’s radius and 25 across the plate’s thickness. The “refined” meshes had 10 and 50, respectively.

Undamaged dilatational behavior of RHA, WHA, and Al were governed by the Mie-Grüneisen equation of state. The shock Hugoniot curve served as the reference curve. Hugoniot pressure, p_H , was related to compression, μ , by the cubic

$$p_H(\mu) = K_1 \mu + K_2 \mu^2 + K_3 \mu^3. \quad (1)$$

Grüneisen parameter, Γ , was related to compression by

$$\Gamma(\mu) = \frac{\Gamma_o}{1 + \mu}. \quad (2)$$

Undamaged deviatoric behavior of RHA, WHA, and Al were governed by von Mises plasticity. Elastic shear modulus, G , was treated as a material constant. Flow stress, Y , was computed from the Johnson-Cook strength model (5),

$$Y = \left[C_1 + C_2 (\epsilon^p)^{C_4} \right] \left[1 + C_3 \ln \left(\frac{\dot{\epsilon}^p}{1.0 \text{ s}^{-1}} \right) \right] \times \left[1 - \left(\frac{\Theta - \Theta_r}{\Theta_m - \Theta_r} \right)^{C_5} \right] \quad (3)$$

ϵ^p is equivalent plastic strain, $\dot{\epsilon}^p$ is equivalent plastic strain rate, and Θ , Θ_r , Θ_m are current, room, and melting temperatures, respectively. Hardening was assumed to be isotropic. Damage behavior of WHA and Al was represented with the Johnson-Cook fracture model (6). All material constants were assigned values based on the literature. These values are listed in Table 4 of (2).

Two sets of values for C_1 , C_2 , ..., C_5 were assigned to RHA. One set, called "JC83," first appeared in (5) for 4340 steel. The second set, called "GCWL94," appeared in (7) for RHA. Both sets are listed in Table 1. The JC83 database included strains up to 1.0 and strain rates up to 650 s^{-1} . The GCWL94 database included strains up to 0.2 and strain rates as high as $7,000 \text{ s}^{-1}$.

TENSILE DAMAGE MODEL FOR RHA

Figure 14 in (8) shows an RHA specimen cut from a plate perforated by a shaped charge jet. The figure shows voids that have coalesced to form a fracture surface. The spheroidal nature of the voids suggests that their growth under tension had been in a ductile mode. A simple model to introduce into a finite element effects of such voids consists of two parts: a failure criterion and an algorithm for post-failure stress reduction.

TABLE 1. RHA Strength Constants

Material Parameter	JC83	GCWL94
C_1 (GPa)	0.7922	0.900
C_2 (GPa)	0.5095	1.305
C_3	0.014	0.0575
C_4	0.26	0.90
C_5	1.03	1.075

The tensile failure criterion is based on a negative-valued material constant, the "spall pressure," p_{fail} . Material in a given finite element is deemed to fail instantaneously at the first time step in which the condition

$$p \leq p_{fail} < 0 \quad (4)$$

is met. Here, p is current pressure within the element. Considering only current pressure neglects the influence of load duration on damage.

In the literature, axial spall stress, σ_{fail} , has been determined for various materials by means of plate impact experiments. Bless reported an axial spall stress of -6.0 GPa for RHA specimens (9). Since in plate impact tests the condition of uniaxial strain is closely satisfied, spall pressure, p_{fail} , and σ_{fail} are related by

$$\sigma_{fail} + p_{fail} = \frac{4Y}{3}, \quad (5)$$

as shown in (2).

Table 2 evaluates p_{fail} of RHA for several reasonable values of Y .

The post-failure algorithm, applied in the element at the time step of failure detection and at every time step thereafter, is that the element is not allowed to support any hydrostatic tension or deviatoric stress. The element's ability to support hydrostatic compression is undiminished. This algorithm treats the effects of tensile damage as occurring instantaneously. This is a good approximation if the time scales associated with these effects are much smaller than other time scales in the problem.

TABLE 2. p_{fail} vs. Y for RHA

Y (GPa)	p_{fail} (GPa)
1.0	-4.7
1.5	-4.0
2.0	-3.3
2.5	-2.7

RESULTS AND DISCUSSION

The problem was run with the original and the refined meshes until 1 ms after initial impact.

Figures 1, 2, and 3 plot as functions of p_{fail} results at 1 ms for the perforation-hole diameter averaged through the thickness, $\bar{D}$, the residual length, L_r , and the residual speed, v_r , respectively. For each value of p_{fail} , four solutions were obtained: JC83 strength constants and the original mesh, JC83 and refined mesh, GCWL94 and original mesh, and GCWL94 and refined mesh. Also included are experimental results reported in (1) for $\bar{D}$ and L_r .

Throughout the range $-4.0 \leq p_{fail} \leq -1.5$ GPa, the solutions show little dependence on p_{fail} . With either the original or the refined mesh, JC83 constants led to larger values of $\bar{D}$, L_r , and v_r than did the GCWL94 constants. This was to be expected, since the GCWL94 constants consistently lead to a larger flow stress for given levels of ϵ^p , ϵ^p , θ . It is also true that throughout this range of p_{fail} , with either the JC83 or the GCWL94 constants, the refined mesh consistently led to larger values of $\bar{D}$, and smaller values of L_r , than did the original mesh; no consistent trend was observed in v_r .

All computational results for $\bar{D}$ in this p_{fail} range are smaller than the experimental measurement. With

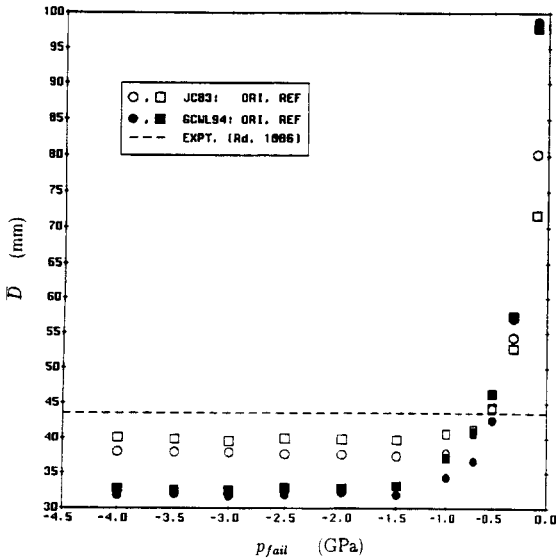


FIGURE 1. Through-thickness-averaged perforation hole diameter vs. spall pressure.

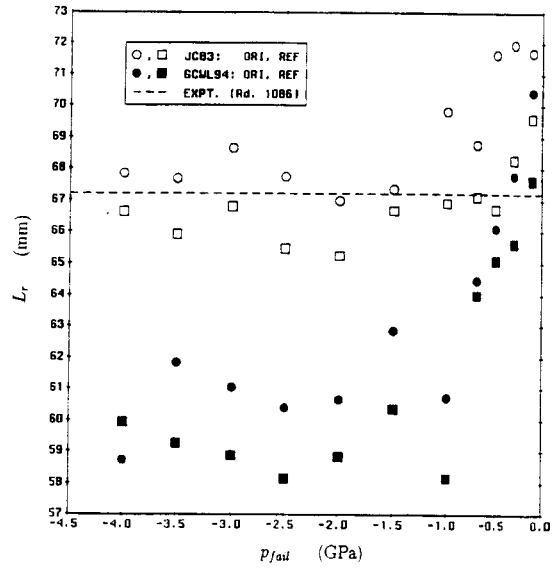


FIGURE 2. Residual length vs. spall pressure.

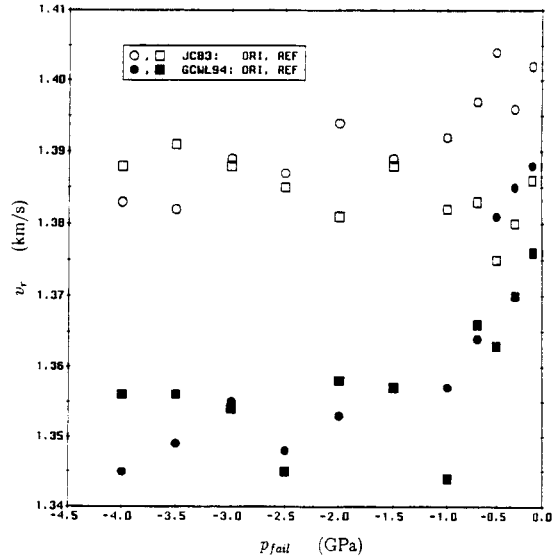


FIGURE 3. Residual speed vs. spall pressure.

JC83, the original mesh results of about 38 mm are smaller by about 6 mm, and the original mesh results of about 40 mm are smaller by roughly 4 mm. It is not clear how much of the remaining discrepancy can be made up by further mesh refinement. Each refined-mesh problem required at least 48 CPU hours

on a Silicon Graphics R8000 processor, and no further mesh refinement has been attempted to date. With JC83, original and refined mesh results for L_r , mainly bounded the experimental measurement in this p_{fail} range. GCWL94 results for $\bar{D}$ and L_r , with both sets of meshes were substantially smaller than experiment.

At a p_{fail} of about -1.0 GPa, the tensile failure model began to exert a strong influence on the solutions. $\bar{D}$ began its dramatic increase for both sets of strength constants. With both sets of meshes and both sets of RHA strength constants, $\bar{D}$ crossed the experimental result at a p_{fail} of about -0.5 GPa. Moreover, with GCWL94 constants, L_r and v_r also increased beginning at a p_{fail} of about -1.0 GPa. L_r achieved close agreement with experiment at a p_{fail} of -0.5 GPa.

These results raise the question of whether a physical mechanism exists to locally change spall pressure by an order of magnitude from -3.0 to -0.5 GPa. Ref. (8) contains evidence to implicate adiabatic shear banding. Figures 7 and 16 show that cracks emanating from the perforation hole boundary run along shear bands. Material surrounding the shear bands is not fractured. Figures 17 and 20 show that recovered RHA fragments are bounded by shear bands, suggesting that shear banding is key to the fragmentation process.

The following scenario is proposed: In both the target and the rod, a shock wave travels from the site of initial impact, leaving compressed material in its wake. Shear banding occurs in the compressed RHA in the vicinity of the hole boundary, where deviatoric stresses are largest. When the shocks reach the rear surface of the target and rod, they reflect to create tensile waves. The tensile wave in RHA travels back toward the entrance face. That in WHA travels toward the target interface and enters the RHA. As regions of the hole boundary become unloaded, release waves form. Interactions between the reflected tensile waves and these release waves lead to regions of large hydrostatic tension. This tensile stress, while insufficient to fail the original RHA material (i.e., less negative than -3.0 GPa), encounters weaker material within shear bands. That material within transformed shear bands is weaker in tension than the original material is a reasonable hypothesis. If the shear band is still hot, the material

within is presumably more ductile and more susceptible to void growth. If the material within has had time to quench, it is harder than the original RHA (8) and is more susceptible to brittle fracture.

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