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A METHOD FOR DETERMINING THE FRACTURE STRENGTHS OF
LOW-DUCTILITY MATERIALS SUBJECTED TO
SHOCK - WAVE LOADING

John G. Avery

James F. Norris

THE DOW CHEMICAL COMPANY
ROCKY FLATS DIVISION
P. O. BOX 888
GOLDEN, COLORADO 80401

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A METHOD FOR DETERMINING THE FRACTURE STRENGTHS OF LOW-DUCTILITY MATERIALS SUBJECTED TO SHOCK-WAVE LOADING

John G. Avery and James F. Norris

Abstract. This report introduces a novel method for testing the resistance of a brittle material to fracture when it is subjected to shock wave loading. An inexpensive and simple mechanical method is used to measure the peak stress of the shock wave; the wave may be generated by explosive detonation or electrical discharge.

The method of testing makes it possible to compare between different materials, or different processing variables on the same material, to determine the optimum processing and material for the particular application.

INTRODUCTION

This report describes preliminary work to develop a method for testing material behavior under shock-wave loading. The report also compares Rocky Flats ingot-sheet beryllium with some commercially produced grades. To provide an understanding of the methods used in this testing, a short discussion of shock wave characteristics is presented below.

A shock wave may be visualized as a wave whose amplitude is stress and whose length is time. Therefore, energy of a shock wave is the area under the curve, or specific impulse (Figure 1). This wave travels through a transfer medium at a shock velocity (V) characteristic of the transfer material and the amplitude of the wave. When the wave, traveling through air or water, impacts a metal, the impulse of the part of the shock wave transferred to the metal imparts a change in momentum to the atoms of the metal. This can be written as:

$$\int F dt = m \Delta V \quad (1)$$

Where:

F = force acting,
 dt = infinitesimal time interval,
 m = mass of metal being acted on,
 ΔV = change in velocity of the atom.

Figure 1. Typical Shock-Wave Profile.

At the same time, the stress in the shock wave, which is compressive, is transmitted to the metal according to the following relationship, (which is dependent on the stresses on the two sides of the boundary being equal and the atom velocities normal to the boundary being equal):¹

$$\sigma_t = \frac{2\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1} \sigma_1 \quad (2)$$

Where:

σ_1 = stress in transfer medium
 ρ_1 = density of transfer medium
 c_1 = velocity of sound in transfer medium
 ρ_2 = density of metal
 c_2 = velocity of sound in metal
 σ_t = transmitted stress

This transmitted stress wave is also compressive.

A portion of the shock wave is reflected by the interface and the magnitude of that portion is given by:²

$$\sigma_r = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \sigma_1 \quad (3)$$

In the case of air, where $\rho_1 \ll \rho_2$, equation 2 shows that a doubling of the stress occurs as the shock wave enters the metal. When the shock wave has propagated through the metal to the back side, equation 3 shows that the reflected wave, which propagates back through the metal, is tensile and is equal in magnitude to the incident wave.

There are two possible modes of failure in a brittle metal due to impulsive loading. One type, caused by reflection of a tensile type wave from an interface between a metal and a transfer medium is called spallation. This failure occurs when the reflected tensile-stress wave, minus the value of the incident stress wave at that position, exceeds the ultimate tensile strength of the metal. The second method of failure is due to energy absorbed from the wave in the form of momentum. The momentum tries to impart a velocity to the metal, and if the metal is restrained, stresses exceeding the ultimate tensile strength of the metal may occur and cause fracture. An awareness of these types of failures is essential in the proper designing of components which will be subjected to shock loading. This will be discussed later.

Another characteristic of shock waves, which is important in impulsive testing, is that both the shape and the total energy of a shock wave are dependent on the distance it has traveled from the source of initiation, be it chemical explosive or electrical discharge. This dependence is due to divergence³ and attenuation.⁴

When the shock wave radiates out in all directions from an initiation point, the volume of the sphere which defines the wave front increase as r^3 ; thus the total energy of the wave, being a constant, is spread out over an increasing area, and the energy per unit area of the wave decreases as $1/r^2$ where r is the distance from the point of initiation of the wave. As a shock wave travels thru a medium such as air or water, it performs work in moving the molecules and, as a result, loses energy. This energy loss is called attenuation.

As energy is lost because of divergence and attenuation the area under the wave profile (Figure 1) must decrease. This means that the stress and momentum contained in the wave depends on the transfer medium

and the distance the wave has traveled. These two variables may be eliminated in impulsive testing by using the same transfer medium and standoff distance in all tests.

Under these conditions, and if more energy is supplied at the source, the various waves will have different stresses and impulses, but will very nearly exhibit geometric similitude as shown in Figure 2.

Figure 2. Geometric Similitude of Shock Waves.

CRITERIA FOR TESTING COMPONENTS SUBJECTED TO IMPULSIVE LOADING

The ability to successfully design a component to resist impulsive loads depends on the capability to test the component using the actual stress wave it will encounter in service. As an example, consider a component such as a piece of armour plate in which spallation would be the significant factor. In this case the wall thickness would eliminate fracture of the part by gross deformation, and failures would be due to a spallation-type fracture. The critical variable to measure in this case would be the peak stress of the shock wave because spallation occurs when the reflected tensile stress is greater than the ultimate tensile strength of the material.

However, if we consider a thin plate or shell, the failure would probably be due to gross deformation of the part. In this situation the total energy of the wave which is transferred as momentum to the part would be an important parameter. This is illustrated in Figure 3.

Figure 3. Variation of Impulse in Shock Waves of Equal Peak Stress.

Stress wave A and stress wave B are of equal stress magnitude and both are below the tensile strength of the particular metal under consideration. The greater time duration of B provides B with a greater specific impulse than A. Since this impulse is transmitted to the part it would be expected that wave B could fracture a thicker plate or shell than wave A. In this case, measurement of both the peak stress and energy of the wave would be important.

In a specific design, then, the stress wave to which the component will be subjected must be defined in terms of both peak stress and specific impulse. The component, or a configuration representative of the component, must therefore be tested under the impulsive loading conditions it will experience. The type of failure, if one occurs, will dictate the change that is necessary either in the design or material to prevent further failure.

EXPERIMENTAL PROCEDURE

Shock waves for this study were produced by an electrical discharge which vaporizes a bridge-wire. In this method, a controllable amount of stored electrical

energy, on being released, causes an aluminum bridge wire to vaporize. Rapid expansion of the metal vapors generates the shock wave (Figure 4). By controlling the standoff distance, the transfer medium (air or H_2O), the voltage at which the apparatus was fired, and the composition of the bridge-wire, the strength and energy of the shock wave can be controlled.

Figure 4. Experimental Setup Used for Testing Beryllium Blanks.

MEASUREMENT OF STRESS

The magnitude of the stress wave was measured by the use of a mechanical force measuring device.⁵ This device, illustrated in Figure 5, consists of a piston in a cylinder. (Figure 5 also shows the location of the beryllium blank to be fractured. This sample, to differentiate it from the hardness sample, will be referred to as the fracture-test sample.) A 10-mm-diameter hardened steel ball is mounted on the end of the piston. A circular blank of sample material having a known hardness is mounted in contact with the ball. As discussed in the introduction, when a shock wave impacts the piston the stress is transmitted through the piston. A force is developed in the piston by the propagating stress wave and the steel ball is forced into the sample material. The diameter of the indentation can be related to the force applied by the piston according to the following relationship:

Figure 5. Apparatus for Measurement of Stress of Shock Wave.

$$\text{BHN number} = \frac{P}{(\pi D/2) (D - \sqrt{D^2 - d^2})} \quad (4)$$

Where:

BHN = Brinell hardness number of the test material

P = Load on ball in pounds

D = 10 mm

d = Diameter of indentation in mm.

Since BHN, D, and d, can be measured, P can be calculated. Then,

$$\frac{P}{\text{Area of piston}} = \frac{\text{Stress of portion of shock wave transmitted to test sample.}}{\text{sample.}} \quad (5)$$

In these particular tests it was found that lead, with a BHN of 4, provided hardness indentations large enough to be measured accurately. Lead was used because the size of the beryllium blank tested required a relatively weak shock wave to cause fracture, and the weak wave would produce only a very small indentation in a harder metal such as stainless steel.

As a check on the validity of this method for measuring stress, some stainless steel hardness samples were tested using a voltage setting (of the discharge unit) high enough to produce a measurable hardness indentation in the steel. The stress calculated was within

5% of the stress calculated using a lead hardness sample at the same voltage.

Figure 6 shows the hardness indentation diameter as a function of the voltage using air as a transfer medium. The diameter varies nonlinearly with the voltage because the amount of electrical energy is proportional to the squares of the voltage. To be able to provide a wider range of stress levels, water was also used as a transfer medium. Figure 7 shows the hardness indentation diameter as a function of voltage using water as a transfer medium.

Figure 6. Hardness Indentation Diameter Versus Voltage. Air Transfer Medium.

Figure 7. Hardness Indentation Diameter Versus Voltage. Water Transfer Medium.

Figure 8 is a plot of the Brinell indentation diameter in lead as a function of the stress. For low stress levels air was used as a transfer medium, whereas water was used if a higher stress was required for testing a particular material condition. The curve of Figure 8 is non-linear and it is seen that greater accuracy in converting to stress is possible if the hardness indentation diameters are kept below about 5 mm. On the other hand, difficulty in measuring the diameter may be expected if the indentation is less than 1 mm. It is desirable, therefore, to have a fracture-sample blank-thickness which will allow fracture when the corresponding hardness indentations are between 1 and 5 mm.

Figure 8. Brinell Indentation Diameter in Lead Samples versus Stress of Shock Wave.

TEST METHOD

In the actual testing of fracture samples, the cylinder and piston assembly was removed and replaced by the sample blank. The voltage was set and the blank was shocked. If no fracture occurred, the voltage was increased and the test was repeated. Once the level of fracture of a particular material condition had been established, additional samples were tested at that level. The additional samples fractured in one or two shots, and this eliminated the variable that caused work-hardening of the blank as the result of multiple shots.

MATERIAL

Blanks of beryllium 0.050-in. thick by 4-in. in diameter were used. The conditions of the various grades of beryllium tested are shown in Table I. The chemical compositions of grades are shown in Table II, and the mechanical properties are shown in Table III.

Table I. Conditions for Testing the Grades of Beryllium.

Condition	Number of Blanks Tested
1. Wrought ingot*, annealed 760°C, unetched	6
2. Wrought ingot, annealed 760°C, etched 0.005 per side	6
3. Wrought ingot, annealed 640°C, unetched	6
4. Wrought ingot, annealed 640°C, etched 0.005 per side	6
5. S-200**, unetched	6
6. S-200, etched 0.005 per side	6
7. S-200 cross rolled, unetched	6
8. S-200 cross rolled, etched 0.005 per side	6

*Source Rocky Flats.

**Source Brush Beryllium Company.

Table II. Chemical Composition of Beryllium Grades (%)

	Grade		
	Wrought Ingot	S-200	S-200 CR
Be	99.6	98.8	99.1
BeO		1.05	0.77
Fe	0.154	0.08	0.13
Si	0.06	0.03	0.04
Al	0.061	0.05	0.07
Mg	0.001	0.03	0.02
C	0.07	0.11	0.12

Table III. Mechanical Properties of Samples Tested.

Material	Yield Strength (10 ³ psi)	Ultimate Strength (10 ³ psi)	Elongation (%)
Wrought ingot, annealed 760°C	25	42	5.0
Wrought ingot, annealed 640°C	40	50	2.7
S-200	53	36	2.0
S-200 cross-rolled	50	75	1.9

RESULTS

The data are listed in Table IV and shown graphically in Figure 9. The shock stresses ranged from 8 to 78 psi.

Table IV. Strengths of Shock Waves Needed to Fracture Various Grades of Beryllium.

Material	Average Stress (psi)	Deviation (psi)
Wrought ingot, annealed 760°C, no etch	11.0	+4 -5
Wrought ingot, annealed 640°C, no etch	7.9	+2.6 -2.4
S-200, no etch	10.0	+4.5 -4.5
S-200 cross-rolled, no etch	14.0	+3 -3
S-200 cross-rolled, etched 0.005 per side	25.5	+1.5 -1.5
S-200, etched 0.005 per side	77.5	+5.5 -15.5
Wrought ingot, annealed 640°C, etched 0.005 per side	13.0	+5 -4
Wrought ingot, annealed 760°C, etched 0.005 per side	42.0	+0.0 -0.0

NOTE

(The absolute values of the stress given are open to question due to the presence of two possible sources of error in the measuring method. Neither of these would affect the relative values, however.

The first possible source of error is attenuation of the shock wave by the piston. As the shock wave travels through the thickness of the piston, work in the form of heat is done by the shock wave. Thus, the stress wave may be significantly weaker when it reaches the back, or free surface of the piston. This would lead to a lower value of stress than is present in the beryllium test blank.

The second possible source of error is due to strain rate effects when the ball in the Brinell test indents the lead sample. In this test the force is applied through the ball to the lead sample for a fraction of a second as opposed to the standard Brinell test where the load is applied for 10 seconds. If there is a strain rate effect in lead, this could result in a smaller indentation than normal. Thus, a lower stress than actually existed would be calculated. Further work is planned to evaluate the amount of any error due to these two factors.)

Figure 9. Strengths of Shock Waves Needed to Fracture Various Grades of Beryllium.

By making the reasonable assumption that the shock wave was uniform over the area of the 0.050-inch thick beryllium blank, it was possible to calculate the fracture stresses in the blank.*

For blanks which broke in a brittle manner it was assumed that the maximum deflection prior to fracture was less than one-half the blank thickness (0.025 in.). For this case,

$$S_{\max} = \frac{3w}{8\pi t^2} \left(\frac{3}{\nu} + 1 \right) \quad (6)$$

Where:

$$W = w \pi a^2 \quad (7)$$

Where:

- $S_{\max}$ = maximum radial tensile stress
- W = load
- w = applied source/unit area
- ν = Poisson's ratio (0.03)
- t = thickness (0.050)
- a = plate radius (1.75 in.)
- E = Young's modules (42×10^2 psi)

*Credit for calculations to C.W. Heiple, Rocky Flats Division, The Dow Chemical Company.

For blanks which showed some ductility before fracture where the maximum deflection was more than $t/2$, the following diaphragm equations were used.

$$\frac{wa^4}{Et^4} = \frac{64}{63(1-\nu)} \left(\frac{y}{t}\right) + .376 \left(\frac{y}{t}\right)^3 \quad (8)$$

$$S = \frac{Et^2}{a^2} \left[\frac{1.238}{1-\nu} \left(\frac{y}{t}\right) + .294 \left(\frac{y}{t}\right)^2 \right] \quad (9)$$

The y value is determined by numerical solution of equation 8. The y value is then used in equation 9. The results are listed in Table V and shown graphically in Figure 10.

Table V. Fracture Strengths of Various Grades of Beryllium.

Material	Average Fracture Stress (psi)	Deviation (psi)
Wrought ingot, annealed 760° C, no etch	15,300	+5600 -7000
Wrought ingot, annealed 640° C, no etch	11,000	+3600 -3400
S-200, no etch	25,000	+6300 -6300
S-200 cross-rolled, no etch	19,500	+4200 -4200
S-200 cross-rolled etched 0.005 per side	37,300	2200 -2200
S-200 etched 0.005 per side	86,900	6200 -17400
Wrought ingot annealed 640° C etched 0.005 per side	18,100	17000 -5600
Wrought ingot, annealed 760° C etched 0.005 per side	56,600	+0 -0

Referring to Figure 11, it is apparent that etching has a beneficial effect on resistance to impulsive loading for both wrought and powder pressed beryllium. Not only did etching generally raise the fracture strength by a factor of 4, it greatly reduced the scatter seen in the unetched sampled. These results are similar to those of bend tests upon glass rods, where chemical etching removed Griffith cracks. This results in reduced data scatter and higher fracture strengths compared to unetched glass rods.

Figure 10. Fracture Stresses of Various Grades of Beryllium.

Figure 11. Typical Fracture-Test Sample. (Unetched wrought-ingot blank.)

It is also apparent but somewhat unexpected that the resistance of the to impulsive loading is dependent on the ductility rather than the yield strength.

Referring to the data in Table V, etched wrought ingot annealed at 640 °C had a fracture stress of 18.1 ksi, whereas etched wrought ingot annealed at 760 °C had a fracture stress of 56.6 ksi. When we look at the static mechanical properties of the two conditions, we find that the 640 °C anneal produces 40,000 psi yield strength and 2.5 to 3.0 % elongation while the 760 °C anneal results in only 25,000 psi yield strength but 4.9 to 5.4 % elongation. The results from the powder product are similar. The S-200 CR had a fracture stress of 37.3 ksi and S-200 had a fracture stress of 86.9 ksi. The yield strengths, ultimate tensile strengths, and elongations of S-200 CR and S-200 are as follows: 51,000 psi, 75,000 psi, and 1.8% and 39,000 psi, 57,000 psi, and 3.2%, respectively. The S-200 has a higher fracture strength than wrought ingot, even though S-200 has lower ductility. This suggests that strength under impulsive loading is also dependent on the ultimate tensile strength. The dependence of fracture strength on the two factors of ductility and ultimate tensile strength suggests that, as a rough approximation, the tensile stress-strain curve may be used to compare the resistance of materials to impulsive loads.

Any comparison between the impulsive load strengths of powder and wrought-ingot beryllium is valid only for the type of shock wave generated in this test. An electrical discharge produces a spike type of wave which tends to decay exponentially as it progresses outward. For example, this shock wave is significantly different in shape and duration from that resulting from detonation of explosives.

Figure 11 shows an unetched wrought-ingot blank. Figures 12 and 13 show an etched S-200 blank tested at Rocky Flats. It can be seen that the S-200 actually started to form before fracturing, something which was not noted in the wrought material. Electron fractography of wrought and powder blanks was performed to try to explain the difference in the ability of the materials to resist shock loads. Although no clear conclusions could be drawn from this analysis, the wrought ingot failed in a classic cleavage (brittle) manner, whereas the S-200 showed less evidence of cleavage.

Figure 12. Plastic Deformation in S-200.

Figure 13. Plastic Deformation in S-200.

CONCLUSIONS

1. Etched S-200 grade beryllium is 85% stronger than etched wrought-ingot beryllium under the type of shock wave generated in this experiment.
2. Etching produces a four-fold increase in the fracture strength under impulsive loading conditions of both powder and wrought-ingot beryllium compared to unetched samples.
3. The resistance of beryllium to shock-wave loading is related to the material's ductility and ultimate tensile strength rather than to its yield strength.
4. The experimental method used for this testing is accurate and reproducible and can be applied to other materials.

ADDITIONAL WORK

The following items should be investigated to improve the accuracy of measurement of the shock wave and to expand the capabilities of the test.

1. Determine and correct possible errors caused by attenuation and strain rate.

2. Develop a method for measuring the energy of a shock wave by using the experimental set-up of Figure 4 for producing the wave.
3. Use other methods of generating shock waves (such as a square wave) which will allow use of waves with profiles other than spikes for testing materials.
4. Test a shape other than a flat blank and calculate the local-failure stresses in areas of interest.

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