TITLE: AN IMPROVED TECHNIQUE FOR DETERMINING DYNAMIC MATERIAL PROPERTIES USING THE EXPANDING RING

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AN IMPROVED TECHNIQUE FOR DETERMINING DYNAMIC
MATERIAL PROPERTIES USING THE EXPANDING RING

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Since its introduction nearly two decades ago, the expanding ring test has shown considerable promise as a simple method of obtaining strain-rate-sensitive uniaxial material property data. The procedure is to monitor the kinematics of a uniformly expanding ring. The stress-strain-strain rate response of the ring material can then be calculated from the ring equation of motion and the recorded data.

Efforts in the past have been based upon recording the transient displacement of the ring. Determination of the stress in the ring then required double differentiation with respect to time of the ring displacement. The work reported herein is an attempt to overcome this difficulty by directly measuring ring velocity as a function of time by means of a laser velocity interferometer; this method requires one less differentiation of the data. The procedure is illustrated by experiments performed on annealed and hardened copper rings. Results are compared to quasi-static material properties determined for the same materials using conventional techniques.

I. INTRODUCTION

Material properties are an essential ingredient in any structural analysis, be it static or dynamic, elastic or plastic. Conversely, if one can accurately record the static or dynamic response of a structure, then it may be possible to infer the stress state from the equations of motion of the structure or from a general solution for the structural response using an appropriate material model with as-yet undetermined constants. Such testing of the structural response to characterize the material behavior has indeed been attempted (1). In fact, the standard uniaxial tension or compression test can be interpreted as a test on a truss member.

Ideally, a structure so tested should have as simple a stress state as possible and, for dynamic loading considerations, should have as nearly a spatially uniform stress state as possible to reduce distortion of the results by wave propagation effects. Such effects may become important in simple tensile tests performed at high strain rates, limiting the interpretation of this simplest of experiments.

Dynamically loaded simple structures particularly suited to material properties determinations by virtue of their inherently uniform stress state and minimal presence of wave propagation effects include the uniformly expanding complete spherical shell, long cylinder, and ring. If difficulties involved in obtaining the required symmetric expansion of these simple structures can be overcome, dynamic stress-strain data obtained on a given material utilizing these three structures would cover a large portion of stress space. In particular, consider the σ_1 - σ_2 plane of principal stress space shown in Figure 1. Balanced biaxial stress data can be obtained in the tension-tension quadrant by a complete, expanding spherical shell. Biaxial stress behavior along a line of slope equal to Poisson's ratio (and subsequently varying to a stress ratio of 0.5 upon reaching the yield surface) is obtained by expanding a long cylindrical shell in plane strain. Finally, a uniformly expanding thin ring provides uniaxial dynamic material behavior along the σ_1 -axis. Because of its inherent simplicity, the simple ring has received most of the attention of investigators to date.

In particular, fifteen years ago, Johnson, Stein, and Davis (2) presented a novel technique for determining dynamic material properties by using an explosively-driven expanding ring. Difficulties in data reduction were experienced, however, because the radial acceleration of the ring was determined by a double differentiation of the experimental displacement-time data. The ring acceleration is one of the crucial quantities required to determine the hoop stress.

6 1/2 X 9 7/8

FIGURE 1. von Mises yield surface showing regions in which dynamic material properties can be obtained by uniformly expanding simple structures.

FIGURE 2. Segment of circular ring.

6-1/2 x 9-7/8 in. trix
Elite typewriter
10% reduction
33-1/2 x 50 plus working size

The ring test was subsequently reappraised by Perrone (3) in an effort to overcome the experimental difficulties encountered. He suggested an alternate scheme of assuming general functional forms for the material behavior (with undetermined constants) as well as utilizing the corresponding peak displacement solution of the freely expanding ring. While the method presented in (3) overcomes the double differentiation difficulties, it does require a prior knowledge of the general stress-strain-strain rate relationship for the material, the very information that is being sought from the expanding ring test. Thus, while the method reported in (3) is useful if some information is available on the material, using the procedure on totally new materials is questionable.

Hoggatt and Recht (4) subsequently refined the technique and reported experimental data on a number of engineering metals. They also experienced considerable difficulty in the double differentiation of experimental records during the development of their data reduction technique, but observed that over a wide range of strain, the recorded displacement-time profile of the ring was, within experimental accuracy, parabolic in shape. By fitting a parabola to the experimental record and then double differentiating the analytical function, the inherent noisiness of the process was circumvented. However, for materials exhibiting other than a parabolic displacement-time profile, the method is not generally valid unless one finds another differentiable function that precisely fits the displacement-time record.

In this paper, a modification to the expanding ring test that overcomes the double differentiation difficulties is presented.¹ The procedure used is to directly measure the radial velocity-time history of the expanding ring by means of a velocity interferometer. By both integrating and differentiating the velocity-time data only once, dynamic stress-strain curves for a material at various values of strain rate can be deduced. The method does not suffer from many of the drawbacks of the previous work cited, since neither double differentiation (2,4) nor assumptions on the functional form of the material behavior (3) are required.

II. GOVERNING EQUATIONS AND METHOD OF DATA PRESENTATION

Consider a small segment of a complete circular ring subtending an arc $d\theta$ as shown in Figure 2. The ring has current thickness, h , and radius, r . Application of Newton's Second Law results in the equation for circumferential stress, σ , in a thin

¹Numerical differentiation of experimental information and its difficulties are discussed in (5).

ring undergoing symmetric radial motion (4)

$$\sigma = -\rho r \ddot{r} \quad , \quad [1]$$

where ρ is mass density of the ring material and $\ddot{r}$ is radial acceleration. If one assumes that plastic strains conserve volume and the elastic volume change is negligible, then density does not change with ring expansion and Eq. [1] can be shown to be based on current cross-sectional area; i.e., σ represents true stress.

True strain is given by

$$\epsilon = \ln \frac{r}{r_0} \quad , \quad [2]$$

where r_0 = initial ring radius. True strain rate then becomes

$$\dot{\epsilon} = \frac{\dot{r}}{r} \quad . \quad [3]$$

Determination of dynamic stress-strain-strain rate contours is conceptually quite simple. The ring initially undergoes a rapid acceleration; then, as the ring expands outward, its radial velocity, $\dot{r}$, decreases because of the opposing hoop stress, σ . Based only upon radial ring velocity $\dot{r}(t)$, as measured directly by the velocity interferometer at some time t , it is possible to calculate radial displacement, $r(t)$, by numerical integration and radial acceleration, $\ddot{r}(t)$, by a single numerical differentiation. The stress-strain-strain rate point at that instant of time, t , can then be determined by appropriate application of Eqs. [1-3].

Because of the monotonically decreasing nature of the plastic strain rate with increasing time for a given expanding ring, only one data point at a given strain rate is obtained from each individual test. If the dynamic stress-strain behavior of a particular material (in a particular heat treatment and at a specified temperature) is desired, then several tests are run over a range of initial strain rates. In this way, stress-strain curves at a constant strain rate can be constructed using one data point from each test for each value of strain rate selected.

In this work we assume that the stress-strain-strain rate behavior can be represented by a surface in three-space, and, for purposes of illustration of the expanding ring technique, results are presented in stress-strain-strain rate space. Note that the trajectory of a given expanding ring is represented by a single curved line in stress-strain-strain rate space with strain rate monotonically decreasing and strain monotonically increasing when the material is deforming plastically. By running several experiments for a given material over a range of initial strain rates, a

series of lines is plotted in this three-space and a surface will emerge. Quasi-static data, which should also fall on this surface, are then plotted on the $\dot{\epsilon} = 0$ plane for comparison.

III. EXPERIMENTAL PROGRAM

A. Ring-Driver System

The experiment is constructed as shown in Figure 3. A ring of the material to be studied is press-fitted onto a steel cylindrical driver. The press-fit insures good contact between the ring and driver and pre-loads the ring to a hoop stress about equal to the yield strength. Subsequent radial displacement is essentially all plastic. A cylinder of high explosive is centered inside the driver and detonators are placed on both ends of the explosive. A field lens is placed approximately a focal length from the surface of the ring and the beam from a laser is focussed to a small spot on the ring which has been slightly roughened to diffusely reflect the beam. The lens also acts as a collector for this reflected beam, sending it back to the interferometer as a broad, parallel beam. The steel driver and ring are designed so that when the explosive detonates, the driver undergoes elastic and slightly plastic expansion. The thin ring, however, separates from the driver and undergoes large plastic deformations as its initial kinetic energy is dissipated into plastic work.

B. Velocity Interferometer

Figure 4 shows a simplified schematic of the interferometer system. The return beam is reduced in size, split, and directed into two interferometers, the sensitivities of which can be adjusted independently. The interferometer layout is similar to the VISAR developed by Barker and Hollenbach (6). Because we needed greater velocity sensitivity than is normally possible with the VISAR using etalons as optical delays, a modified version of an air delay leg suggested by Amery (7) was incorporated into the high sensitivity interferometer on these experiments. Details of the interferometer and the data reduction are in (6) and (7). Briefly, the frequency of the return beam reflected from the moving target is Doppler-shifted by an amount proportional to the velocity of the target. In the individual interferometers, the beam is split and the light traversing one leg of the interferometer is delayed a small amount relative to the other leg (typically a few tenths of a nanosecond to as much as 20 nanoseconds). Thus, the two beams which are combined to give interference were reflected from the target at two different times. If the target is accelerating, these two beams will have slightly

FIGURE 3. Cross-sectional view of the experiment. Typical driver diameters are 50.8 mm and 25.4 mm; ring o.d. and thicknesses are either 54.0 mm and 1.6 mm or 27.0 mm and 0.8 mm.

FIGURE 4. Simplified schematic of the laser velocity interferometer system used in these experiments. Each of the two separate interferometers has a photomultiplier (PM) monitoring the return light and two PM's recording the interference information. Additional optics (not shown) permit quadrature recording of the interference information, enabling the sign of the target acceleration to be determined.

different frequencies and the resulting difference frequency is detected by photomultipliers and recorded on oscilloscopes. These traces provide a continuous record of the target velocity to within a few meters/second.

C. Experiments Conducted

To date, expanding ring experiments have been completed on both hardened and annealed copper as well as on 6061-T6 and 6061-O aluminum. Some details of these experiments are indicated in Table I. Note also that two basic ring-driver sizes were used--2-inch and a 1-inch diameter. For the same initial ring velocity, initial strain rates are a factor of 2 higher for the smaller ring-driver system.

As shown in Table I, for each basic material and ring-driver configuration, multiple experiments were performed at nominally-identical values of initial strain rate to evaluate reproducibility of the data. In addition, experiments were performed, for a given ring material, at significantly different initial strain rates by varying the quantity of explosive charge. These latter experiments serve to fill in the stress-strain-strain rate surface for that material.

IV. DATA REDUCTION CONSIDERATIONS

A. Reproducibility

As an indication of the reproducibility of nominally-identical experiments, the following direct comparisons of raw data (velocity-time traces) are presented.

1. Comparison 1

Comparison of the velocity-time traces for the two annealed copper rings with larger explosive charges (7.4 g) is shown in Figure 5(a). Shown in that plot is the early-time ringing of stress waves as the ring leaves the hardened steel driver. These data are difficult to interpret in terms of material stress. Later on in time, these through-thickness oscillations damp out and the velocity-time trace becomes considerably smoother.¹ This usable data window indicated in Figure 5(a) continues, as the ring

¹Damping is believed largely due to attenuation of the through-thickness signals propagating into material which is already in a plastic state due to tensile hoop stresses in the ring.

TABLE I

EXPANDING RING EXPERIMENTS

<i>Experiment No.</i>	<i>Ring Material</i>	<i>Nominal Ring Diameter (in.)</i>	<i>Explosive Mass (g)</i>	<i>Explosive Diameter/ Length (mm)</i>
2513	6061-T6 Al	2	2.5427	10/20
2515	6061-T6 Al	2	2.5427	10/20
2514	6061-T6 Al	2	7.5688	17.5/20
2520	6061-T6 Al	1	0.7359	7.64/10
2521	6061-T6 Al	1	1.18	9.65/10
2523	6061-T6 Al	1	0.9887	10/7.75
2527	6061-T6 Al	1	0.4230	5/10
2518	6061-O Al	2	2.5364	10/20
2517	6061-O Al	2	7.5731	17.5/20
2519	6061-O Al	1	0.7361	7.62/10
2522	6061-O Al	1	1.18	9.65/10
2526	6061-O Al	1	0.4245	5/10
2524	Hardened Cu	2	5.7175	15/20
2525	Hardened Cu	2	5.7242	15/20
2534	Hardened Cu	2	7.4378	17.3/20
2535	Hardened Cu	2	7.4435	17.3/20
2536	Annealed Cu	2	7.4430	17.3/20
2537	Annealed Cu	2	7.4342	17.3/20
2539	Annealed Cu	2	2.4803	10/20
2540	Annealed Cu	2	2.4913	10/20

(a)

(b)

(c)

(d)

FIGURE 5. Comparison of ring velocities for nominally-identical experiments: (a) strongly-loaded annealed copper; (b) moderately-loaded annealed copper; (c) strongly-loaded hardened copper; (d) moderately-loaded hardened copper.

6-1/2 x 9-7/8 in. trix
Elite typewriter
10% reduction
37-1/2 x 52 picas working size
30 x 47 picas final size

continues to strain, until a point is reached when the data become oscillatory and of questionable validity. Data are only considered during the smooth, midrange of travel. Note that early-time agreement of the two velocity-time traces is quite impressive. Further, agreement in the indicated usable range appears reasonable. It is important to note, however, that it is the slope of these curves that is the most important factor in determining the instantaneous stress in the given ring.

2. Comparison 2

A similar comparison for annealed copper is shown in Figure 5(b). Velocity-time traces within the indicated data window are seen to have similar slopes, although the magnitudes differ somewhat. Except for a slight amplitude difference, early-time agreement in ring velocities is rather striking.

3. Comparison 3

Velocity-time comparisons for strongly-loaded hardened copper are presented in Figure 5(c). Except for a slight amplitude difference, comparisons (particularly in slopes) are excellent. Note that the data window for experiment 2535 is quite small due to an apparent perturbation in the ring at 18 μ s.

4. Comparison 4

The final comparison, corresponding to moderately-loaded hardened copper is shown in Figure 5(d). Note in this case there is a significant difference in velocity at any given time, although within the data windows, there appears to be good agreement in slope, with the slope of experiment 2524 being somewhat less than the slope in experiment 2525. Since experiment 2525 is at a slightly higher strain rate, these apparent slight differences in slope may be due to rate dependence.

B. Data Reduction Difficulties and Selected Technique

Surprisingly, considerable difficulty was encountered even with the single differentiation of raw data required in the procedure reported herein. In order to reduce scatter, it was felt advantageous to fit the velocity-time data obtained from the interferometer within the usable data window to a quadratic function of the form

$$v(t) = a + bt + ct^2 \quad [4]$$

The constants a, b, and c, were determined by the selection of three points along the curve, one at each end of the data

1-1/2 x 9-7/8 in. tube
 E1100 typewriter
 10% reduction
 35-1/2 x 50 piece working size
 30 x 47 piece final size

window and one near the center of the window. The use of a higher-order polynomial has also been considered; however, even though the experimental curves can be approximated more closely, the slope can be quite misleading when inflection points occur in the range of interest. Other smoothing techniques are being considered, but have not yet been thoroughly tested.

V. STRESS-STRAIN-STRAIN RATE RESULTS

As an illustration of the technique, three-dimensional stress-strain-strain rate plots are presented in Figure 6(a) and (b) for both the annealed and hardened copper experiments, respectively. The quasi-static stress-strain data are also included. Recall that individual curved lines in both Figure 6(a) and (b) represent all usable data from a single ring test. Because of the limited number of experiments performed, the three-dimensional surface through these curves has not been completely defined. However, it is particularly significant to note that in both figures, the dynamic curves are initially at higher stresses than the static curves (this effect is more pronounced for the annealed copper, as one would expect), and as strain rate decreases, the surfaces tend toward the static curves.

VI. SUMMARY

In this paper, methods are presented for improving the expanding ring test for determining dynamic material properties. These improvements are centered around the incorporation of a direct velocity-measuring device (velocity interferometer) to alleviate the necessity of double differentiation of experimental data. While the data presented here are somewhat limited, the method has been demonstrated to be feasible and to offer a distinct advantage over earlier, direct displacement-measuring approaches.

VII. ACKNOWLEDGMENTS

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(a)

(b)

FIGURE 6. Stress-strain-strain rate plots for (a) annealed and (b) hardened copper.

1-1/2 x 1-1/2 x 1/2 in. flat
 1116 copper
 10% reduction
 15-1/2 x 1/2 plate working
 30 x 1/2 plate (trial only)

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