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THE MECHANICAL PROPERTIES OF COPPER AT HIGH STRAIN RATES

Volume I

THE EFFECT OF STRAIN RATE ON THE FLOW STRESS OF COPPER

J. D. Lubahn, R. C. Culver, and R. L. Straw

Colorado School of Mines Research Foundation
Golden, Colorado

Contract AF 29(601)-6042

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FOREWORD

This report was prepared by the Colorado School of Mines Research Foundation, Golden, Colorado, under Contract AF29(601)-6042. The research was performed under Program Element 7.60.06.01.D, Project 7811, Task 781105, and was funded by Defense Atomic Support Agency (DASA).

Inclusive dates of research are 1 May 1963 to 28 February 1965. The report was submitted 23 December 1965 by the AFWL Project Officer, Lieutenant Kenneth J. Davis (WLRP). Other Project Officers who have been associated with this work are Captain Winford E. Mauldin and Captain Robert G. Henning (WLRP).

The authors wish to acknowledge the assistance of Robert Anderson, Jack Kintner, and Howard Nicks, laboratory technicians.

This report has been reviewed and is approved.

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ABSTRACT

An experimental method of determining dynamic flow stress where the stress is homogeneous is developed using a pendulum bar suspension system. A small specimen is mounted on the end of one of the bars and the other bar is impacted on the free end of the specimen.

For copper, the dynamic stress is 29% larger than the static stress for a strain rate of about 100 sec^{-1} (or an increase in strain rate of about 5 orders of magnitude). For various tests, the increase in dynamic stress over the static value varied from 17% to 45%. This variation is comparable with the expected scatter for a typical test ($\pm 10\%$) predicted from the uncertainties in measurement.

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SECTION I

INTRODUCTION

A considerable amount of research has been performed to investigate the effects of strain rate on stress as a function of both strain and temperature. The rates studied in the work reported here varied from 10^{-3}/sec., which was obtained from an ordinary laboratory tension-compression testing machine, to 10^{2}/sec., which was obtained from the bar-bar pendulum impact tester.

The available dynamic tests from the literature are shown for copper in Tables 1 and 2. Copper was selected for this investigation because: (1) it has no energy-absorbing phase transformation, (2) it is relatively free from impurities which might affect correlation with the work of others, and (3) it is commonly used for test purposes.

The data of the various investigators were compared by a ratio of the dynamic stress to the static stress. The strain rate at which the dynamic stress was measured is given in the tables.

The tensile investigations of Manjoine & Nadai (1), Baron (2), and Culver (3) showed good agreement between the stress ratios ($\pm$4.4% from the average of 1.15). The specimen geometries were similar; but the strain rates varied by a factor of 20, the strains varied by a factor of 100, and the load-measuring and strain-measuring devices were different in each case.

The results obtained by Kolsky (4), Bell (5), and Davies & Hunter (6) on dynamic compression behavior, however, do not agree. The stress ratio obtained by Kolsky is more than 2, while Bell found that increasing the strain rate did not affect the stress at all. This difference in behavior exists even though the strains are the same in the three investigations and the strain rates are of the same order of magnitude.

Kolsky and Davies & Hunter obtained a strain rate effect in which the stress increased with increasing strain rate for a given strain. They both used the Hopkinson pressure bar with only slight modifications. Bell obtained no strain rate effect using the same strain (1.5% total strain) and a higher strain rate than either Kolsky or Davies & Hunter. Bell did obtain a strain rate effect at 10% strain, where he found a ratio of dynamic to static stress of about 0.8. This value would seem to indicate that stress actually <u>decreases</u> with increasing strain rate.

The test set-up used by Bell differed from those of the other two investigators in that he did not use a thin wafer for a specimen and his approach for measuring and interpreting the load-strain curves was quite different (see Tables 1 and 2). Because of these serious discrepancies in the dynamic compression behavior of copper for various investigators, it was considered desirable to devise an experiment that would use a more direct method for measuring the stress and strain.

TABLE 1

Previous Tension Impact Investigations

AUTHOR	Manjoine & Nadai (1940)	Baron (1956)	Culver (1963)
TEST MECHANISM	block-block	block-block	block-bar
ENERGY SOURCE	flywheel	Charpy pendulum	spring
LOAD MEASUREMENT	from elastic strain in rigid steel bar	weighbar with strain gages	from elastic strain in rigid steel bar
STRAIN MEASUREMENT	relative motion between two heads	calculated from force-time curve	drum camera and scribed lines on specimen
MATERIAL	annealed copper	annealed copper	annealed copper
SPECIMEN DIMENSIONS	solid 0.200" diam. by 1-1/8" long	solid 0.138" diam. by 0.75" long	solid 0.200" diam. by 1" long
DYNAMIC STRAIN RATE	900/sec.	90/sec.	45/sec.
DYNAMIC STRESS/ STATIC STRESS	1.15	1.2	1.1
METHOD OF DATA PRESENTATION	stress versus strain for different rates	stress versus strain for given rate	stress versus strain-time plotted on same axis
STRAIN	elastic plus plastic = 20%	0.2% plastic	elastic plus plastic = 10%

TABLE 2

Previous Compression Impact Investigations

AUTHOR	Kolsky (1949)	Bell (1960)	Davies and Hunter (1960)
TEST MECHANISM	bar-bar	bar-bar	bar-bar
ENERGY SOURCE	explosive charge	air gun	explosive charge
LOAD MEASUREMENT	cylindrical condenser microphone	calculated from strain-time curve	numerical analysis of displacement-time curve
STRAIN MEASUREMENT	parallel plate condenser microphone	diffraction grating with mercury arc	capacitance discharge with and without specimen
MATERIAL	annealed copper	annealed copper	annealed copper
SPECIMEN DIMENSIONS	solid 1" diam. by 0.05 cm thick	solid 0.990" diam. by 10" long	solid 0.3" thick by 1" diam.
DYNAMIC STRAIN RATE	2000/sec.	3660/sec.	1100/sec.
DYNAMIC STRESS/ STATIC STRESS	2.1	1.0	1.67
METHOD OF DATA PRESENTATION	stress versus strain for given rate	stress versus strain for given rate	stress versus strain for given rate
STRAIN	elastic plus plastic = 1.5%	elastic plus plastic = 1.5%	elastic plus plastic = 1.5%

SECTION II

CHOICE OF IMPACT MACHINE

Of the three types of testing machines commonly used (bar-bar, bar-block, and block-block), the bar-bar machine was selected because: (1) the mechanics of impact can be explained quite precisely by simple theory, (2) the bar-bar machine is more stable dynamically than either the bar-block or the block-block machines, (3) alignment adjustments are easy to make with the pendulum-type suspension system used, (4) this type of machine is very similar to the machines of the other investigators, and (5) an energy balance could easily be made on this system. The fact that an energy balance can be easily applied to the bar-bar pendulum suspension machine used for this experiment is most important and will be analyzed first.

SECTION III

ENERGY BALANCE

An energy balance for determining dynamic stress, when applied to the pendulum bar-bar impact machine (Fig. 1) used in this investigation, results in the following equation:

$$PE_{iB} = PE_{iA} + PE_{sA} + E_{wf} + E_{wire} + E_{vib} + E_{pw} \tag{1}$$

The zero energy level is the point where the two bars are at rest. For ease of nomenclature, the bar on which the specimen is mounted is termed the specimen bar and the other is termed the impacting bar. In Eq. (1) the system input energy, PE_{iB}, is the potential energy of the impacting bar before its release from a height above the specimen bar which is initially at rest. PE_{iA} is the potential energy of the impacting bar after the two bars have collided. PE_{sA} is the potential energy of the specimen bar when it has attained its maximum height after collision has taken place. E_{wf} is the energy lost due to windage and friction. E_{wire} is the energy lost to the support wires. E_{vib} is the energy lost by vibrations in the bars after separation. E_{pw} is the energy available for plastic work of the copper specimen tip (1/8 inch diameter portion of the specimen shown in Fig. 2). The potential energy of the specimen bar before impact is zero, and so this term is not included in Eq. (1). The thermal energy associated with plastic deformation is a direct result of the plastic deformation. This energy is not considered even though a small portion of it may have been dissipated while the other energy quantities were being measured. The work done in deforming the specimen plastically appears subsequently as internal energy and thermal energy; but it is the work that is wanted instead of the resulting energy, and so Eq. (1) contains this work term instead of the equivalent energy terms.

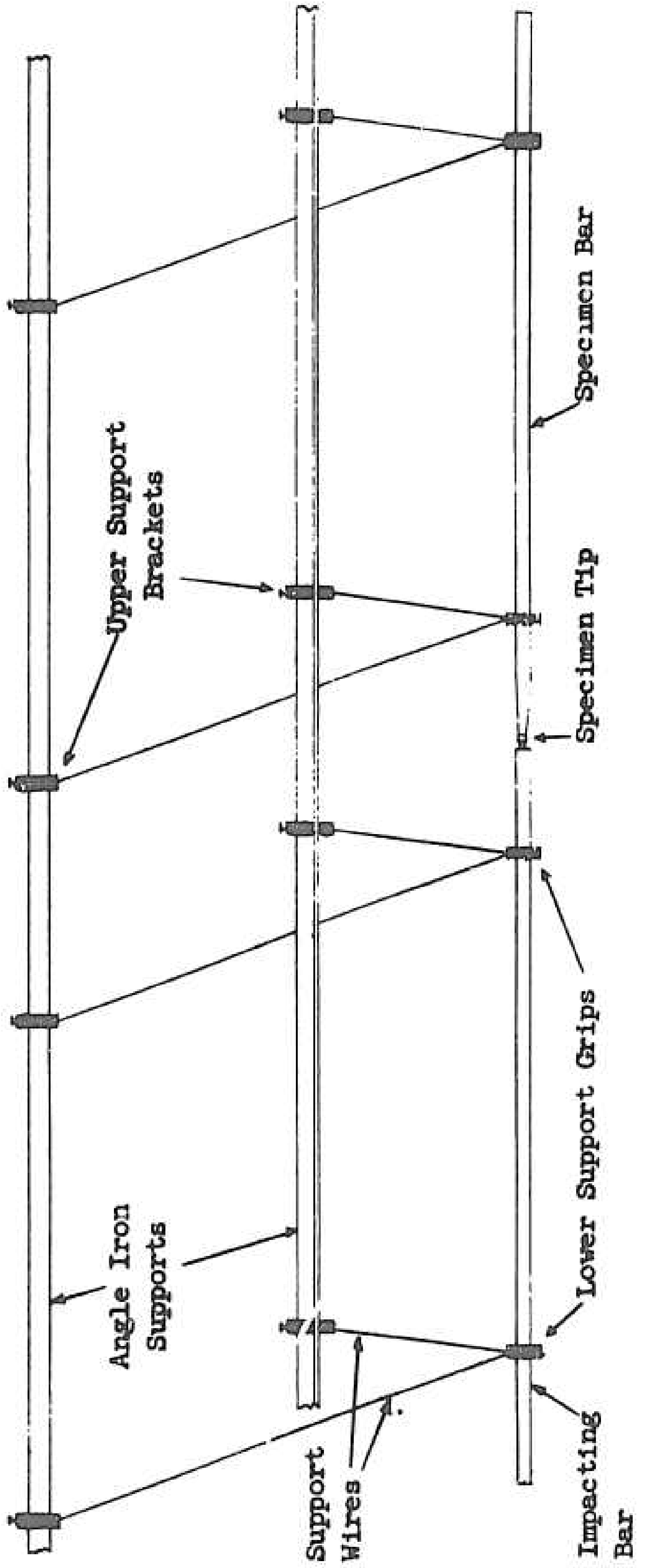


Figure 1. Pendulum Bar - Bar Impact Machine

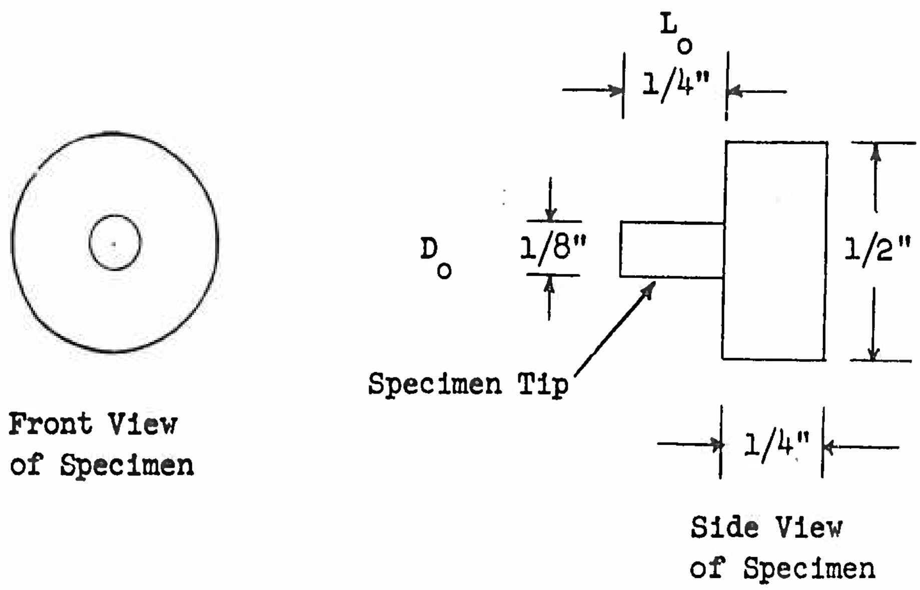


Figure 2. Test Specimen Dimensions

Plastic Work

Now let us consider the calculation of stress from the last term of Eq. (1), which represents the energy available for plastic work.

The work done in deforming the specimen elastically and plastically is given by

$$E_w = \int_0^{\delta} P d\delta$$

where P is the applied load and δ is the corresponding length change, or displacement of one end with respect to the other. Graphically, the integral represents the area under the load-displacement curve. This area may be divided by an elastic unloading line into an elastic and a plastic part. The elastic part corresponds to elastically stored energy, which appears later as potential energy or vibrational energy. The plastic part corresponds to the term E_{pw} in Eq. (1).

The plastic work can also be expressed as the area under a curve of load versus the plastic part of the displacement, or plastic length change, δ_p:

$$E_{pw} = \int_0^{\delta_p} P d\delta_p \tag{2}$$

Equation (2) can be rewritten in terms of stress and logarithmic plastic strain by using the facts that: (a) the load, P, is equal to the true stress, S, times the instantaneous cross-sectional area, A; and (b) the infinitesimal plastic deflection, $d\delta_p$, is equal to the instantaneous length, ℓ, times infinitesimal logarithmic plastic strain in the longitudinal direction, $d\epsilon$:

$$P = SA \tag{3}$$

$$d\delta_p = \ell d\epsilon \tag{4}$$

If the integration limits are changed and (3) and (4) are substituted into Eq. (2), the following relation is obtained:

$$E_{pw} = \int_0^{\epsilon} SA\ell d\epsilon \tag{5}$$

For plastic deformation the volume is a constant and the product may be removed from under the integral sign. The resulting equation divided by volume yields:

$$\frac{E_{pw}}{V} = \int_0^{\epsilon} S d\epsilon \tag{6}$$

For this investigation the integral of Eq. (6) can be evaluated easily since the essentially flat curve of true stress versus logarithmic plastic strain will be considered as horizontal (dashed line in Fig. 3) for both the static and dynamic cases. Thus, although the stress for a given strain may be higher for the dynamic case than for the static case, it is assumed that the stress is independent of ϵ, and thus the integral can be solved for true stress to obtain

$$S = \frac{E_{pw}}{V\epsilon} \tag{7}$$

The use of this equation requires that the dynamic stress be independent of logarithmic plastic strain. Equation (7) is also limited by the requirement that the stress be distributed essentially uniformly over the length, ℓ. The purpose of this investigation is to determine whether this stress will be greater than the static stress as represented by the dashed line of Fig. 3, and by how much.

The plastic work term E_{pw}, and therefore the stress S, may be obtained from Eq. (1) by difference after all the other terms have been measured. These terms will now be examined in detail.

Potential Energy

The energy input to the system is the potential energy of the impacting bar before impact, PE_{iB}, which is equal to the weight of the impacting bar, w_{ib}, times the height, h_{iB}, it is raised above the specimen bar:

$$PE_{iB} = w_{ib}h_{iB} \tag{8}$$

The height of the impacting bar before its release, h_{iB}, is determined by measuring the zero level height and the height of the bar in the tied-back position. The height, h_{iB}, is the difference in these two heights, measured by a vernier height gage.

The potential energies of the bars after impact were determined by measuring the arc lengths that the ends of the bars traveled. These arc lengths were then converted into bar heights by using Fig. 4. Fig. 4 represents the determination of arc length as a function of bar height both experimentally and analytically. The experimental determination of the relationship was conducted using a height gage to measure height and a steel tape to measure the arc length. The equation for Fig. 4 is:

$$h = \frac{(arc)^2}{134} \tag{9}$$

The arc length traveled by the impacting bar was measured with a ruler. Although this value is not actually the arc length, it is very close to the arc length since the radius of the path of travel (68 in.) is quite large in comparison to the arc length (10 in.). The arc length of the specimen bar was measured by attaching a spring-mounted ball point pen on the end of the bar. The trace of the ball pen was recorded on a trace board and the arc length was measured with a steel tape.

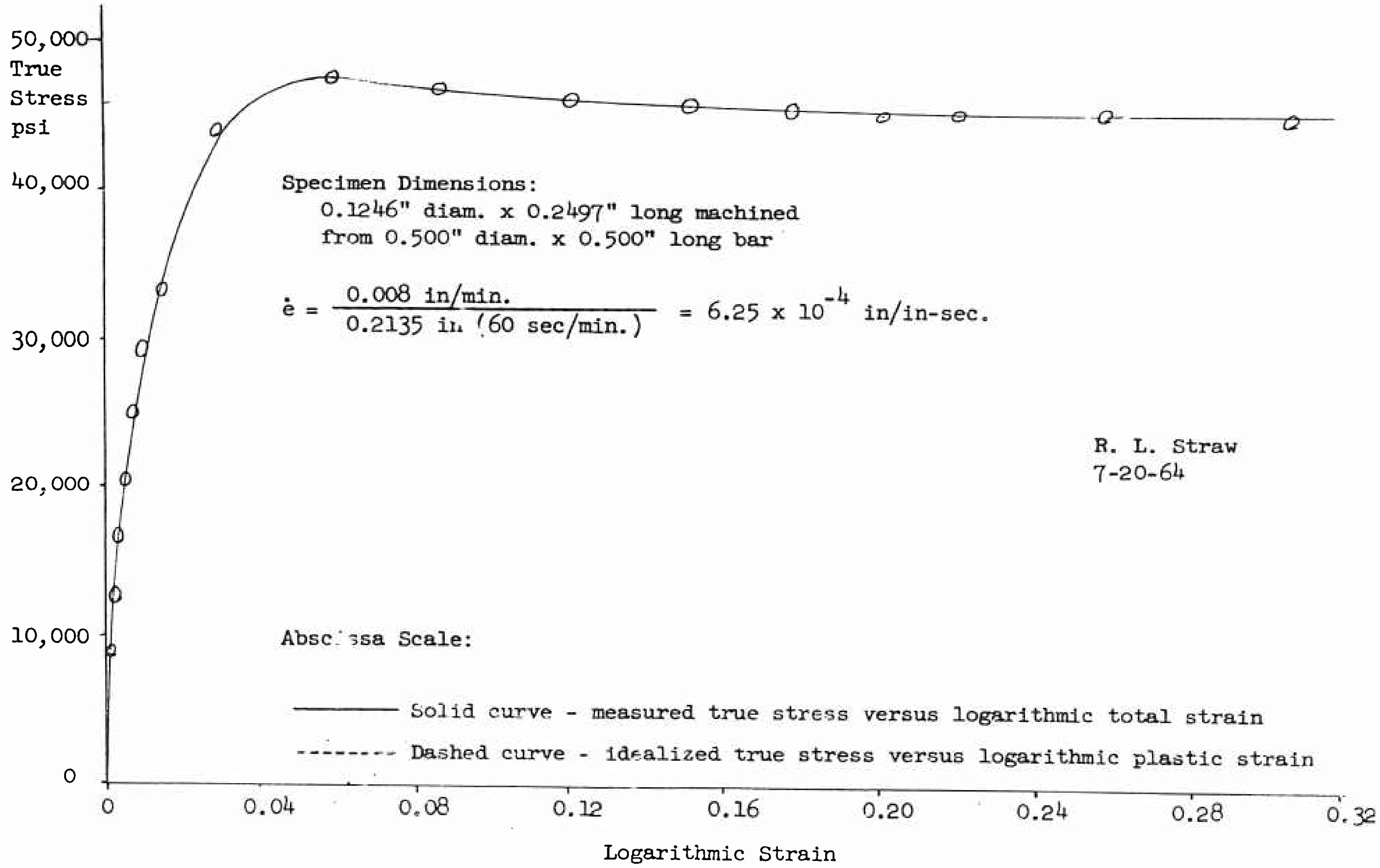


Figure 3. True Stress versus Logarithmic Strain for Tough Pitch Cold-Worked Copper

When the arc lengths and heights of both bars had been determined, the potential energies were evaluated from the following equations:

$$PE_{iA} = w_{ib}\, h_{iA} \tag{10}$$

$$PE_{sA} = w_{sb}\, h_{sA} \tag{11}$$

where w_{ib} and w_{sb} are the weights of the impacting bar and specimen bar respectively (including the weight of their support blocks), and h_{iA} and h_{sA} are the heights that the impacting and specimen bars reached after impact.

Windage and Friction Loss

The windage and friction loss was measured by allowing each bar to swing freely (without colliding with the other bar) and recording the heights of the initial point and the return point. These two points were recorded using the previously described ball pen and trace board. The two heights were obtained from Fig. 4 using the easily measured arc lengths. For a total arc length travel of 27.78 inches the energy loss due to windage and friction was 0.48 in-lb. For the relatively small variation of arc lengths involved in the tests, the energy loss due to windage and friction could be assumed to be proportional to the arc length traveled. If the experimentally measured values are used, the general expression for energy loss due to windage and friction, E_{wf}, is:

$$E_{wf} = 0.01728 \text{ (total arc length)} \tag{12}$$

where total arc length is the total travel for both bars.

Wire Loss

It is conceivable that the support wires might remove energy from the system while a test is in progress. In order to check whether energy is removed, and if so, how much, let us consider one wire separately from the bar and mounting block. The potential energy of the wire in the pulled-back position is:

$$PE_{wire} = w_{wire} \frac{h_b}{2} \tag{13}$$

where PE_{wire} is the potential energy of the wire, w_{wire} is the weight of the wire, and h_b is the height of fall of the lower end of the wire. The kinetic energy of the wire when the potential energy is zero is:

$$KE_{wire} = 1/2\, I_{us}\, \omega^2 \tag{14}$$

where I_{us} is the moment of inertia of the wire about the upper support and ω is the maximum angular velocity of the wire. If the potential and kinetic energies of the wire are equated and the following expression for I_{us} is used:

$$I_{us} = 1/3 mL^2$$

the following result is obtained:

$$mg\, h_b = 1/3 mL^2 \omega^2 \tag{15}$$

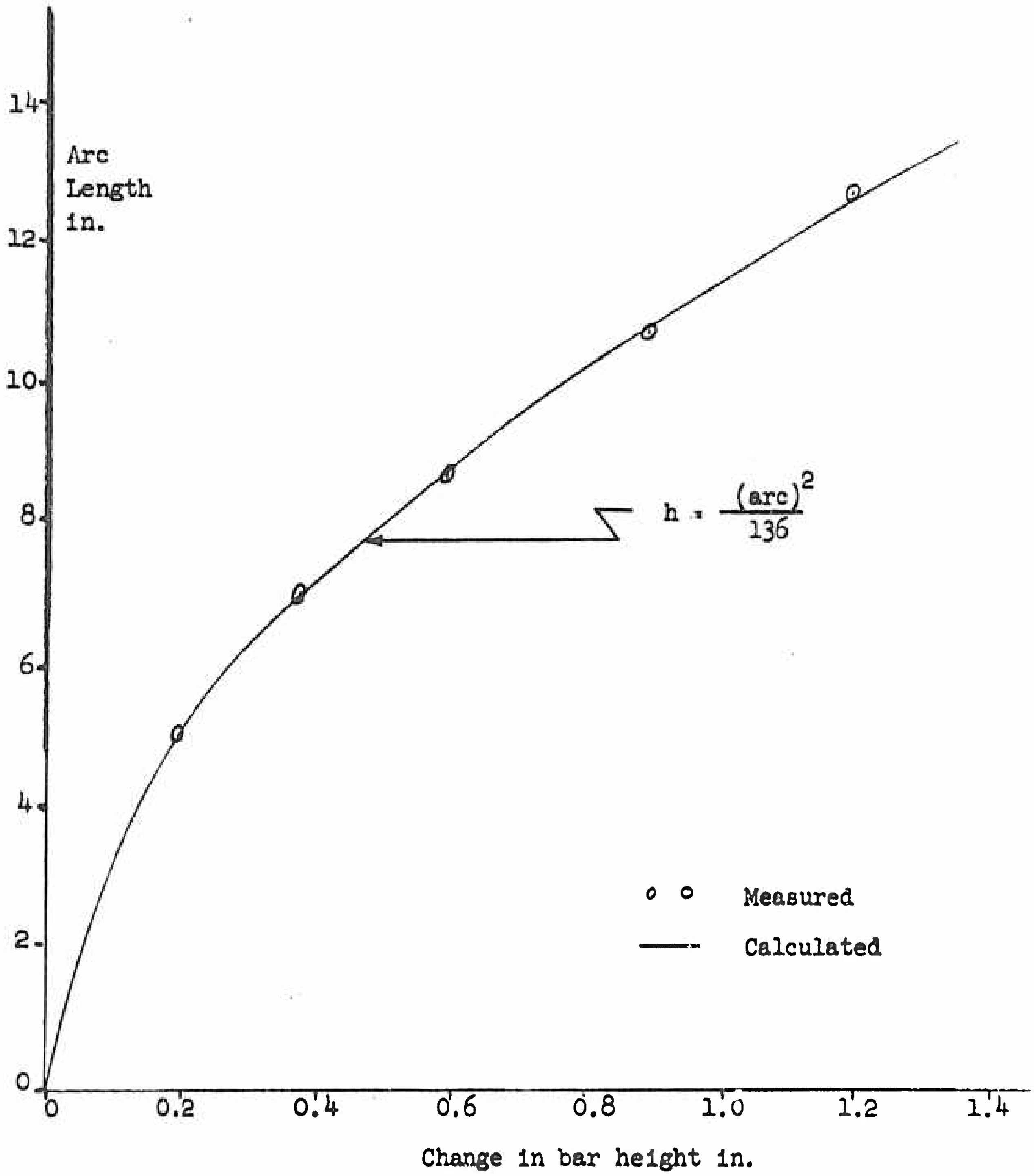


Figure 4. Arc Length Versus Change in Height for Both Bars

were Lω is V_b, the velocity of the lower end of the wire. Eq. (15) can then be rewritten as:

$$V_b = \sqrt{3g\ h_b} \tag{16}$$

Now, if the bar is attached to the lower end of the wire, and the velocity at this point again computed, the following expression results:

$$V_b = \sqrt{2g\ h_b} \tag{17}$$

If Equations (16) and (17) are compared, it can be seen that the wires do not remove energy from the system. The wires actually add a very small energy to the system. On the other hand, this small energy is included in the windage and friction term of Eq. (1) because of the way in which this term was determined experimentally, and so Eq. (1) reduces to:

$$PE_{iB} = PE_{iA} + PE_{sA} + E_{wf} + E_{vib} + E_{pw} \tag{18}$$

Vibration Loss

The lateral and longitudinal vibrations present in both bars after impact separation cause an energy loss, E_{vib}, which is difficult to measure when plastic work is done in the system. In order to find out how these vibration losses can be determined, a discussion of how the vibrations are caused and how they can be measured is needed.

In order to obtain a clear picture of the vibrations caused by impact, we shall consider the case of an ideal elastic collision (two bars of the same size and length, perfectly aligned and with ends flat and perfectly matched). When two such elastic bars collide, a compressive plane wave front is built up at the impacting surface of each bar. This wave front travels down the length of the bar and is reflected from the other end as a plane tensile wave front equal in magnitude to the initial compressive wave front, which unloads the bar. When the reflected wave reaches the impacting surface the bars are completely unloaded and free to separate. Thus no vibrational stress remains in the bars for ideal conditions. Any nonideality results in a residual vibration (vibrations which are present after the bars have separated) which may be longitudinal vibration, transverse vibration, or both.

Longitudinal vibrations arise from differences in the two bars or non-planar wave fronts. Lateral vibrations are caused by any of the following factors: (1) the bars are bent, (2) the bars are not concentric, (3) the bars are not aligned (axes parallel), (4) each bar does not swing parallel to its axis, or (5) the paths of the swinging bars do not describe a vertical plane. The lateral vibrations can be minimized by careful choice of equipment and proper care in alignment of the bars. These losses are difficult to eliminate completely and so must be determined by a suitable combination of measurement and analysis such that the term E_{vib} in Eq. (18) can be evaluated. However, we shall see that it is not necessary, for this purpose, to know the exact distribution of the lateral vibrations with respect to time or position.

The presence of a yielding link between the impacting surfaces of the previously described elastically colliding bars lowers the magnitude of the longitudinal and lateral vibrations but should not significantly alter the distribution of the strains caused by these vibrations. Hence, the measured vibration behavior in an elastic test can be used to determine the vibration in the plastic tests.

Since the lateral and longitudinal vibrations are independent, the losses, E_{lat} and E_{long}, which make up the total vibration loss can be added:

$$E_{vib} = E_{lat} + E_{long} \tag{19}$$

For uniform distribution of longitudinal vibration strains along the length of the bar, the longitudinal vibration loss may be determined in terms of the maximum strain in the longitudinal direction by means of the following relation:

$$E_{long} = \int_o^{\delta} P d\delta \tag{20}$$

where E_{long} is the energy lost due to longitudinal vibrations present after the bars have separated, P is the applied load that would cause stress equal to vibrational stress (equal in this case to the stress, S, times the original cross-sectional area, A_o), or

$$P = S A_o \tag{21}$$

and $d\delta$ is the infinitesimal change in length in the longitudinal direction (equal to the original length, ℓ_o, times the infinitesimal elastic longitudinal strain, de_{long}), or:

$$d\ell_{long} = \ell_o de_{long} \tag{22}$$

If Eqs. (21) and (22) are substituted into Eq. (20) and the limits of integration changed, the following expression results:

$$E_{long} = \int_o^{e_{long}} S A_o \ell_o de_{long} \tag{23}$$

The stress is equal to the longitudinal elastic strain, e_{long}, times Young's modulus, E, and $A_o\ell_o$ is a constant. Eq. (23) can then be solved to determine the longitudinal vibration loss for any test:

$$E_{long} = \frac{E \, e_{long}^{2} \, VOL}{2} \tag{24}$$

where VOL in this case is the volume of both bars.

Appendix 1 shows that the lateral vibration energy loss is a function of the maximum lateral strain trace amplitude, Am_{lat}:

$$E_{lat} = K \, (Am_{lat})^2 \tag{25}$$

where K is a constant of proportionality which depends on the distribution of the lateral strains, and Am_{lat} is the maximum amplitude as measured from a recording of the lateral strain trace.

Eqs. (24) and (25) provide a basis for the determination of the energy loss due to vibrations. A description of the equipment used for the determination of e_{long} and Am_{lat} is needed to see how these quantities are measured and how the constant K is determined.

Four, SR-4 brand, semiconductor, strain gages were mounted longitudinally at mid-length of the specimen bar on both sides, top, and bottom. The center of the bar was chosen because the first mode of lateral vibrations was expected to predominate over the other modes. The use of only four gages limits the number of strains that can be measured at any one time. The horizontal component of the lateral strain was always measured using two opposite gages, but the other two gages were sometimes used for measuring longitudinal strain and sometimes for measuring the vertical component of lateral strain. Semiconductor strain gages were used because their unusually high sensitivity (55 times normal sensitivity) was necessary for the proper amplification of the small strains encountered (20×10^{-6} in/in).

The side gages were wired into one Wheatstone bridge circuit and the top and bottom gages were wired into a second Wheatstone bridge circuit. Provision was made so that the top and bottom gages could either be placed both in one arm of the circuit in series, which would allow the longitudinal pulse and vibrations to be measured, or be placed in adjacent arms of the bridge circuit, which would allow the lateral vibrations to be measured. The gages on the sides of the specimen bar were left in opposite arms of their Wheatstone bridge circuit to measure the horizontal component of the lateral vibrations for every test.

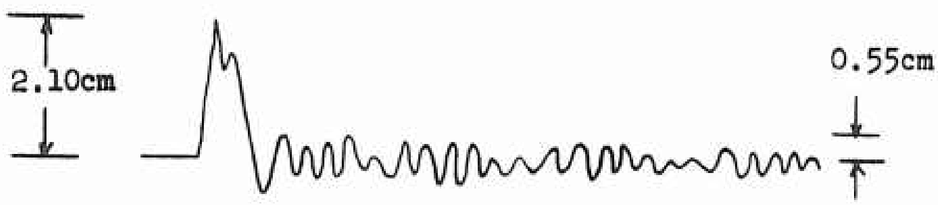
The outputs for each pair of gages were fed into separate amplifiers. The amplifier outputs were fed to separate oscilloscopes equipped with Polaroid oscilloscope cameras to record the vibration traces. A sketch of typical longitudinal and lateral traces is shown in Fig. 5.

The maximum longitudinal strain is obtained by measuring the largest amplitude of any of the peaks after the first two (which represent loading, that is, the time during which the two bars are still in contact - see Fig. 5). The strain causing this maximum longitudinal peak is given by the following expression:

$$e_{long} = \frac{2\ (VS)\,(Am_{long})}{(R)\,(I)\,(K_g)} \tag{26}$$

where e_{long} is the maximum longitudinal strain, VS is the vertical sensitivity on the oscilloscope (volts/cm), Am_{long} is the maximum longitudinal trace of strain amplitude after bar separation (cm), R is the resistance of one of the strain gages in ohms (the resistances of all the gages were assumed to be the same), I is the current in the circuit (amps), and K_g is 110, the gage factor (amplification factor) of the strain gages.

Lateral Oscilloscope Trace
(Test Number 15)



Longitudinal Oscilloscope Trace
(Test Number 11)

Figure 5. Traces of Oscilloscope Photographs of Strain Gage Output

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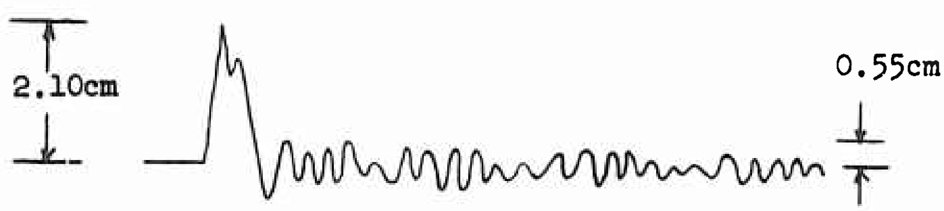
Lateral Oscilloscope Trace
(Test Number 15)



Longitudinal Oscilloscope Trace
(Test Number 11)

Figure 5. Traces of Oscilloscope Photographs of Strain Gage Output

For the tests of this investigation the vertical sensitivity was 0.005 volt per centimeter, the resistance was 120 ohms and the current was 0.040 ampere. If these values are substituted into Eq. (26) the longitudinal strain is:

$$e_{long} = 18.95 \times 10^{-6}\ Am_{long}$$

The maximum amplitude of the lateral strain traces is given by the following relationship:

$$Am_{lat} = \sqrt{Am_{vert}^{2} + Am_{horiz}^{2}} \qquad (27)$$

where Am_{vert} and Am_{horiz} are the maximum amplitudes determined from the vertical and horizontal lateral strain gage traces respectively.

Now the constant K can be evaluated. For this purpose, a special test is needed in which no plastic deformation takes place. This was accomplished without changing the geometry of the impacting surfaces by replacing the usual copper specimen with a hard steel specimen (yield strength > 100,000 psi). The steel specimen did not deform plastically in this test, and so Eq. (18) may be modified for this elastic test as follows:

$$PE_{iB} = PE_{iA} + PE_{sA} + E_{wf} + E_{vib} \qquad (28)$$

If the data for test A-1 with the hardened steel tip (see Tables 3 and 4) are used in the evaluation of the vibration loss in Eq. (28), the vibration loss is calculated to be 0.37 in-lb. The longitudinal vibration loss for this test was calculated using (24) and (26) as 0.11 in-lb. The lateral vibration loss was then evaluated using the following relation obtained from Eq. (19):

$$E_{lat} = E_{vib} - E_{long} \qquad (29)$$

The loss due to lateral vibrations was then 0.26 in-lb. for this test.

In order to determine K for Eq. (25) the maximum amplitude of the lateral strain trace must be obtained. Since both components of lateral strain were not recorded for this test, the value of the largest amplitude observed for the vertical component of 1.35 cm is used (see Table 3).* The maximum lateral amplitude, Am_{lat}, is then given by Eq. (27) as 1.84 cm. When this value is substituted into Eq. (25) along with the calculated value of the lateral vibration energy loss (E_{lat} = 0.26 in-lb.), constant K is found to be 0.0768 in-lb/cm^2. It must be noted that this value is based on the assumption that the lateral strain distribution differs only in magnitude and not in shape when elastic test results are compared with plastic results. Equation (25) then becomes:

$$E_{lat} = 0.0768\ (Am_{lat})^{2} \qquad (30)$$

*Taking the largest of all observed values for the vertical component of the lateral vibration amplitude, where the value for a particular test was not available, will result in a slightly smaller calculated rate effect than the true rate effect. In other words, the rate effect is slightly larger, if anything, than that stated in the conclusions.

TABLE 3

Determination of Vibration Losses

Test No.	Am_{horiz} (cm)	Am_{vert} (cm)	Am_{lat} (cm)	Am_{long} (cm)	E_{lat} (in-lb)	E_{long} (in-lb)	E_{vib} (in-lb)
5	2.50	1.35*	2.84	0.50	0.62	0.13	0.75
7	2.50	0.65	2.58	-	0.51	0.13	0.64
8	1.30	1.10	1.70	-	0.22	0.13	0.35
11	1.40	1.35*	1.95	0.55	0.29	0.13	0.42
12	1.30	1.35	1.87	-	0.27	0.13	0.40
13	1.05	1.35*	1.71	-	0.22	0.13	0.35
14	1.15	1.35*	1.77	-	0.24	0.13	0.37
15	1.15	0.85	1.43	-	0.16	0.13	0.29
16	1.80	1.00	2.06	-	0.36	0.13	0.49
A-1	1.25	1.35*	1.84	0.50	0.26	0.11	0.37

* Assumed value needed for the purpose of calculation of Am_{lat}.

TABLE 4

Determination of Energy Available for Plastic Work

Test No.	in h_{iB}	arc iA	arc sA	PE_{iB} *1 in-lb	PE_{iA} *1 in-lb	PE_{sA} *2 in-lb	E_{wf} in-lb	E_{vib} in-lb	E_{pw} in-lb
5	5.00	9 1/4	16 13/16	61.10	7.81	24.87	0.90	0.75	26.77
7	5.00	9	15 1/4	61.10	7.38	20.45	0.87	0.64	31.76
8	5.00	9 1/4	14 1/2	61.10	7.81	18.48	0.86	0.35	33.60
11	5.00	10 1/4	16	61.10	9.57	22.55	0.90	0.42	27.66
12	3.00	7	12 7/8	36.66	4.47	14.58	0.69	0.40	16.52
13	3.00	7 3/4	13	36.66	5.47	14.88	0.70	0.35	15.26
14	3.00	7 5/8	12 1/8	36.66	5.31	12.92	0.69	0.37	17.37
15	3.00	7 1/2	12 1/4	36.66	5.13	13.18	0.69	0.29	17.37
16	5.00	9 3/8	15 5/8	61.10	8.02	21.45	0.88	0.49	30.26
A-1	0.50	0	7 7/8	6.11	0	5.46	0.28	0.37	0

*1 Weight of impacting bar is 12.22 lbs.

*2 Weight of specimen bar is 11.78 lbs.

Now that K has been determined, let us return to the determination of the vibration loss in a plastic test. Since only two plastic tests using the copper specimen tips have records of the longitudinal strain trace, the maximum amplitudes for these two tests will be averaged (0.525 cm from tests 5 and 11) to obtain the energy lost to longitudinal vibrations from Eqs. (24) and (26):

$$E_{long} = 0.13 \text{ in-lb.} \tag{31}$$

which will be the same for all the plastic tests.*

The energy available for plastic work can now be obtained by modifying Eq. (18) to yield:

$$E_{pw} = PE_{iB} - PE_{iA} - PE_{sA} - E_{wf} - E_{vib} \tag{32}$$

The formulas required for evaluating the quantities on the right-hand side of Eq. (32) may now be summarized:

$$PE_{iB} = w_{ib}\ h_{ib} \tag{8}$$

$$PE_{iA} = w_{ib}\ h_{iA} \tag{10}$$

$$PE_{sA} = w_{sb}\ h_{sA} \tag{11}$$

$$E_{wf} = 0.01728 \text{ (total arc length)} \tag{12}$$

$$E_{vib} = 0.13 \text{ in-lb.} + E_{lat} \qquad (19)\ \&\ (31)$$

$$E_{lat} = 0.0768\ (Am_{lat})^2 \tag{30}$$

*The lateral vibrations will be different in different tests, depending on how the bars hit (concentricity, alignment, etc.); but the longitudinal vibrations will depend only on the dimensions of the two bars and the fact that they do hit, and so the longitudinal vibrations will be the same in different tests. Table 3 shows this to be the case.

SECTION IV

DETERMINATION OF STRESS AND STRAIN

The stress can be evaluated from Eq. (7) after the strain and volume have been determined. The volume of the specimen tip was calculated from the original dimensions of the copper specimen tip (1/8" diam. x 1/4" long nominally). The logarithmic plastic strain in the axial direction is most reliably* determined by first calculating the logarithmic plastic strain in the radial direction, ϵ_r, given by the following formula:

$$\epsilon_r = \ell n \frac{D_{ave}}{D_o} \qquad (33)$$

where D_{ave} is the average diameter** after impact (determined by measuring the diameter at 0.01" intervals along the axis of the deformed tip and dividing the sum of these diameter readings by the number of readings), and D_o is the initial diameter of the specimen tip. The readings of diameter after impact were obtained by using two opposing 0.0001" dial strain gages fitted with small rounded points.

The longitudinal logarithmic strain, ϵ, can then be evaluated using the constant volume condition for the plastic case as follows:

$$\epsilon = -2\epsilon_r \qquad (34)$$

*Diameter measurements were used instead of length measurements because of the larger number of measurements (various positions along the length), because of the uncertainty associated with penetration of the 1/8" - dia. tip into the 1/2" - dia. base, and because the end of the tip was machined slightly conical to minimize vibration.

**The degree of nonuniformity of diameter is given in Table 5 on page 28.

SECTION V

DETERMINATION OF STRAIN RATE

The average strain rate, $\dot{\epsilon}$, can be determined by dividing the strain, ϵ, by the time of straining, Δt:

$$\dot{\epsilon} = \frac{\epsilon}{\Delta t} \tag{35}$$

The strain is given by Eq. (34) and the time for straining is determined by equating impulse and momentum:

$$F\ (\Delta t) = m\ \Delta V \tag{36}$$

where F is the force on the specimen tip, equal to the area of the tip, A, times the stress in the tip, S,

$$F = SA$$

m is the mass of the impacting bar, and ΔV is the change in velocity of the impacting bar.

The change in velocity of the impacting bar is the initial velocity before impact, V_{iB}:

$$V_{iB} = \sqrt{2gh_{iB}} \tag{37}$$

minus the velocity after impact, V_{iA}:

$$V_{iA} = \sqrt{2gh_{iA}} \tag{38}$$

The strain rate from (35) to (38) is then:

$$\dot{\epsilon} = \frac{\epsilon\ SA}{m\ (\sqrt{2gh_{iB}} - \sqrt{2gh_{iA}})} \tag{39}$$

SECTION VI

DESCRIPTION OF EQUIPMENT

Specimens

All test specimens consisted of copper tips from one piece of tough pitch (99.2+% pure), cold-rolled, round copper rod machined according to the nominal dimensions specified in Fig. 2. The end face was tapered slightly, so that first contact would be at the centerline, thereby minimizing lateral vibrations. The specimens were glued on the end of the specimen bar with Eastman 910 glue and a glue accelerator. A length to diameter ratio of 2 was used to prevent undue transverse restraint of the specimens (which appears when L/D is less than 2) and to prevent buckling (which is caused by using L/D of greater than 2).

Bars

The impacting bars were made from 6-foot lengths of 3/4-inch diameter, SAE 1018, cold-rolled steel. The impacting end of the specimen bar was tapered down to 1/2-inch diameter over a 6-inch length for ease of centering the specimens. The end of the impacting bar was fitted with a hard steel disk (yield strength 100,000 psi) which protected the end of the bar from being plastically deformed.

Support Grips and Wires

Accurate alignment was assured by constructing identical, precision-made grips, as shown in Fig. 6. In order to have the portions of the bars in the vicinity of the ends as nearly in a horizontal plane as possible, in spite of slight bending, the grips supported the bars at a distance of 14.5" from each end. This spacing was calculated using the model of a uniformly loaded beam with equal overhang on both ends (Timoshenko, 1955). The wire supports were threaded on the ends (0-80 threads) to provide for ease in adjustment of the length, and constant length was assured by use of lock nuts on both sides of the yoke at each end of each wire.

Ball bearings were mounted in the extended upper arms of the Y-shaped specimen grips and in the vertical adjustment pin of each upper support, as shown in Figs. 6 and 7. These bearings provided a ball-bearing pivot for the yokes at the ends of the support wires, thus allowing the wires to swing freely with minimum friction losses and no wire bending.

Upper Supports and Adjustments

To provide fine adjustment for the bars, the wires were suspended from special three-directional adjustment devices. The upper supports consisted of microscope stages, which possessed two degrees of horizontal freedom, mounted to the angle iron supports. On the ends of the microscope stages were mounted specially constructed vertical adjustments, as shown in Fig. 7. When final adjustments were completed on the upper supports, the microscope stages were fastened to the angle iron supports by means of C-clamps to prevent any motion during testing.

a recording of the lateral strain trace.

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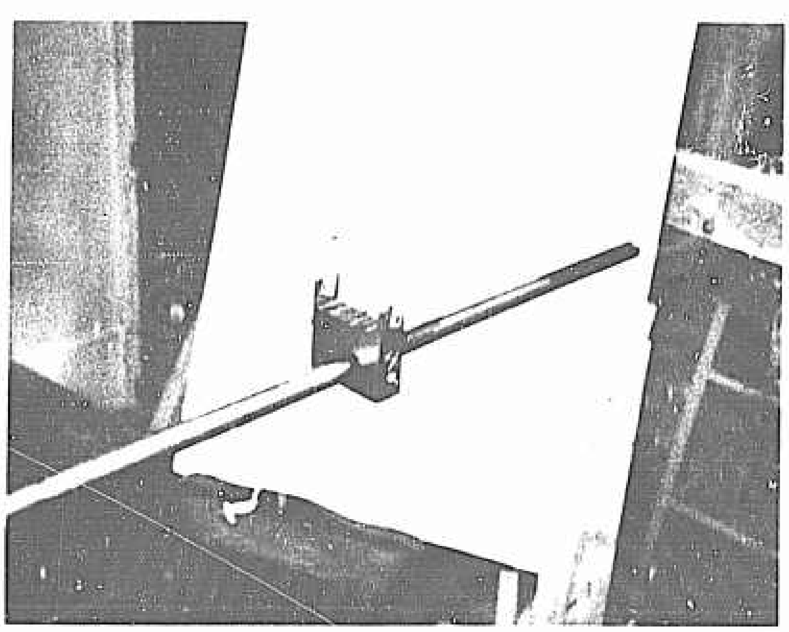

FIG. 6 SPECIMEN BAR, GRIPS, AND LOWER WIRE MOUNTINGS

FIG. 7 UPPER SUPPORT AND MICROSCOPE STAGE MOUNTING

Support Frame

The angle iron bars were rigidly mounted to a wooden 2x4 frame which supported each 12-foot span of the angle irons at both ends and the middle. The wooden frame was cross-braced at both ends and one side and was bolted rigidly to a support wall. This was done to prevent any motion of the frame during testing.

SECTION VII

EXPERIMENTAL PROCEDURE

Preliminary Alignment

Proper alignment of the bars is required to minimize the vibration losses and to prevent any transverse bending of the specimen tip. The axes of the bars must be coincident when they are at rest. As the bars swing, they must remain horizontal and must travel in the same vertical plane. To this end, the support wires must be perpendicular to the axes of the bars when they are at rest.

The four upper pivot points for each bar were squared and leveled. The longitudinal distances (parallel to the bar axes) of the upper supports were set equal to the distance between the grips on the bars. The diagonals were then measured and set equal. After clamping the horizontal adjustments fixed, the points were made horizontal by adjusting the vertical position of the four points for each bar. These points were checked by a transit and adjusted until they all lay in the same horizontal plane. When the upper supports had been adjusted according to this procedure, they were not adjusted again, since it was found in practice that they did not move after many tests.

For purposes of bringing the axes of the two bars into coincidence, horizontal lines were scribed at both ends of both bars. These lines were 90 degrees apart, lying in horizontal and vertical planes through the axis of the bar. When all eight lines on the sides of the bar lay in a single horizontal plane, the axes of the two bars also lay in that same horizontal plane. When all four lines on top of the two bars lay in a single vertical plane, the axes of the two bars also lay in that same vertical plane. Transits were used to determine when any given set of lines were all contained in one plane. The adjustments required for leveling the bars and placing them in the same straight line when at rest were made by changing the lengths of the support wires. This was accomplished by adjusting the lock nuts on each wire.

Mounting the Specimen Tip

The specimen tips were mounted by using a cylindrical sleeve that fitted over the impacting bar on one end and was machined on the other end to hold the barrel of the specimen. The tip was placed in the sleeve and Eastman 910 glue applied to the back. Accelerator was then spread on the impacting end of the specimen bar, and the specimen and specimen bar were pressed together. As soon as the tip was securely mounted, the alignment sleeve was removed. This procedure assured concentricity of the specimen tip and impacting bar.

Alignment of Ball Pen and Trace

The alignment of the ball pen, mounted on the end of the specimen bar, and the trace board were checked; and the board was positioned so that the force on the ball pen required to obtain a trace was a minimum.

Release of Impacting Bar

Before releasing the impacting bar, all the steps on the alignment procedure sheet were checked to be sure all necessary pre-test information was recorded. The impacting bar was then released from its initial position by burning the tie-back string with a match.

SECTION VIII

TEST DATA AND CALCULATIONS

A sample calculation for the stress and strain rate for a typical test (test #12) is shown in Appendix 2. A sample experimental data sheet is shown in Fig. 8 with the test information for test 12 inserted as a sample of the recorded information. The determination of the vibration loss for each test is summarized in Table 3. The determination of the energy available for plastic work is summarized in Table 4. The determination of plastic strain for each test can be found in Table 5. The values of stress, strain, and strain rate for each test are in Table 6.

IMPACT TEST PROCEDURE

Test no. 12 Specimen Material Copper Date August 21, 1964

No.	Step	Check when completed		Initial reading	Final reading
1.	Measure specimen dimensions	X	L_{total}	0.6687	0.6450
2.	Align bars with three transits	X	$-L_{thick}$	0.4125	0.4125
3.	Glue specimen on tip using sleeve	X	L_{spec}	0.2562	0.2325
			Diam	0.1249	0.1322
4.	Adjust pen and trace paper	X	h_{high}	———	
5.	Measure differential height, Δh, of impacting bar	X	$-h_{low}$	———	
			Δh	3.00	
			Current =	4 ma.	
6.	Set strain gage current	X	Lateral trace	2	
7.	Check position of oscilloscope trace	X	Longitudinal trace	No	
			oscill. sweep speed	2 ms/cm	
8.	Check type of trace picture(s) taken	X	Oscill. vertical sensitivity	0.005 v/cm	
9.	Record oscilloscope settings	X	Specimen bar arc	12-7/8"	
			Impacting bar arc	7"	
10.	Check and set trigger	X	TEST COMMENTS:		
11.	Release bar with match	X			
12.	Record arc lengths traveled by both bars after impact	X		None	
13.	Record final specimen dimensions	X			

FIG. 8 SAMPLE TEST DATA INFORMATION SHEET

TABLE 5

Determination of Logarithmic Axial Plastic Strain

Test No.	L_o in.	L_f in.	D_o in.	D_{max} in.	D_{ave} in.	$\frac{D_{ave}}{D_o}$	ϵ_r	$-\epsilon$
5	0.2454	0.2050	0.1263	0.1395	0.1366	1.0815	0.0783	0.1566
7	0.2503	0.2118	0.1242	0.1370	0.1346	1.0836	0.0804	0.1608
8	0.2531	0.2096	0.1250	0.1376	0.1356	1.0848	0.0814	0.1628
11	0.2722	0.2344	0.1249	0.1371	0.1349	1.0801	0.0771	0.1542
12	0.2562	0.2325	0.1249	0.1322	0.1303	1.0432	0.0423	0.0846
13	0.2515	0.2282	0.1260	0.1335	0.1313	1.0421	0.0413	0.0826
14	0.2514	0.2234	0.1252	0.1322	0.1316	1.0512	0.0500	0.1000
15	0.2509	0.2287	0.1253	0.1330	0.1315	1.0495	0.0483	0.0966
16	0.2510	0.2120	0.1240	0.1373	0.1351	1.0894	0.0856	0.1712
A-1	--	--	--	--	--	--	--	--

TABLE 6

Determination of Stress, Strain, and Strain Rate

Test No.	E_{pw} (in-lb)	$10^{-3}in^3$ vol	$-\epsilon$	Dynamic Stress (S)	Static Stress (S_s)	Stress Ratio $\frac{S}{S_s}$	Dynamic Strain Rate ($\dot{\epsilon}$) (sec^{-1})	Static Strain Rate ($\dot{\epsilon}$) (sec^{-1})
5	26.77	3.07	0.1566	55,600	46,000	1.21	101	$6.25x10^{-4}$
7	31.76	3.03	0.1608	65,200	46,000	1.42	116	$6.25x10^{-4}$
8	33.60	3.10	0.1628	66,600	46,000	1.45	124	$6.25x10^{-4}$
11	27.66	3.33	0.1542	53,900	46,000	1.17	100	$6.25x10^{-4}$
12	16.52	3.14	0.0846	62,200	46,000	1.35	71	$6.25x10^{-4}$
13	15.26	3.14	0.0826	58,900	46,000	1.28	71	$6.25x10^{-4}$
14	17.37	3.10	0.1000	56,000	46,000	1.22	81	$6.25x10^{-4}$
15	17.37	3.09	0.0966	58,200	46,000	1.27	80	$6.25x10^{-4}$
16	30.26	3.02	0.1712	58,600	46,000	1.27	114	$6.25x10^{-4}$
A-1	-	-	-	-	-	-	-	-

Averages:

h_{1B} (in)	S (psi)	S/S_s	$\dot{\epsilon}$ (sec^{-1})
5.00	60,000	1.30	111
3.00	58,800	1.28	76

TABLE 7

Determination of Error in Calculating Dynamic Stress
(results for a typical test #12 analyzed)

Quantity	Value	Possible Error
h_{iB}	3.00"	$\pm$ 0.005"
Arc_{iA}	7"	$\pm$ 0.125"
Arc_{sA}	12 7/8"	$\pm$ 0.0625"
Arc_{wf}	39.93"	$\pm$ 0.06"
Longitudinal Vibration amplitude	0.525 cm	$\pm$ 0.05 cm
Lateral Vibration amplitude	1.87 cm	$\pm$ 0.1 cm
PE_{iB}	36.66 in-lb.	$\pm$ 0.06 in-lb.
PE_{iA}	4.47 in-lb.	$\pm$ 0.16 in-lb.
PE_{sA}	14.58 in-lb.	$\pm$ 0.15 in-lb.
E_{wf}	0.69 in-lb.	None
E_{long}	0.13 in-lb.	$\pm$ 0.03 in-lb.
E_{lat}	0.27 in-lb.	$\pm$ 0.03 in-lb.
E_{pw}	16.52 in-lb.	$\pm$ 0.43 in-lb.
D_{ave}	0.1303"	$\pm$ 0.0002"
D_o	0.1249"	$\pm$ 0.0002"
ℓ_o	0.2562"	$\pm$ 0.0002 "
$-\epsilon$	0.0846	$\pm$ 0.0062
V	$3.14 \times 10^{-3} in^3$	$\pm$ $0.015 \times 10^{-3} in^3$
S	62,200 psi	$\pm$ 6400 psi ($\pm$10%)

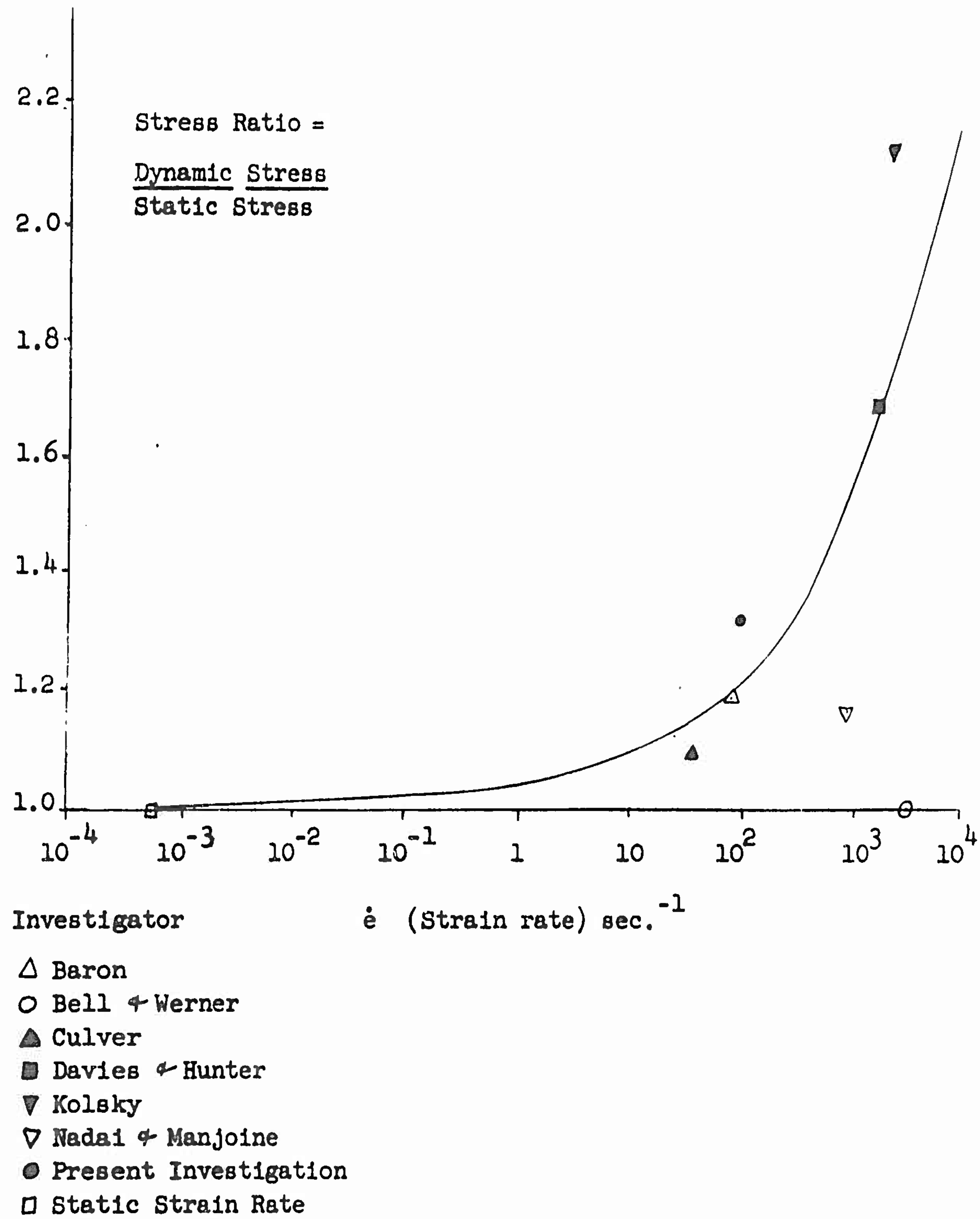

Figure 9. Stress Ratio Versus Strain Rate for Pure Copper from Various Investigators

APPENDIX 1

Determination of Energy Associated With Lateral Vibrations

In order to make an energy balance, the vibrational energy in the bars after they have separated from the condition of impact must be determined. The total vibrational loss is given by the following equation:

$$E_{vib} = E_{lat} + E_{long} \tag{11}$$

The energy loss due to longitudinal vibrations, E_{long}, has already been determined, Eq. (23). The energy loss due to lateral vibrations, E_{lat}, will now be determined. The general expression for elastic energy caused by force, F, causing a deflection, δ, is as follows:

$$\text{Energy} = \frac{F\delta}{2} \tag{A-1}$$

Fig. 10 will be helpful in the determination of energy resulting from lateral vibrations.

The stress, S, is constant over any element of the cross section, $dA = 2\sqrt{R^2 - x^2}\,dx$, which allows the differential of force to be evaluated as:

$$dF = 2S\sqrt{R^2 - x^2}\,dx = 2\,Ee\sqrt{R^2 - x^2}\,dx \tag{A-2}$$

The change in length, δ, is related to the initial length, ℓ_o, and the strain acting on this length, e,

$$\delta = \ell_o e \tag{A-3}$$

If the relations A-2 and A-3 are substituted into the energy Eq. (A-1) the following relation is obtained:

$$E_{lat} = 2\int_o^R E\ell_o e^2 \sqrt{R^2 - x^2}\,dx \tag{A-4}$$

Because of the compatibility condition the strain is proportional to x.

$$e = e_s \frac{x}{R} \tag{A-5}$$

If relation A-5 is substituted into A-4 the energy can be evaluated as:

$$E_{lat} = 2\,\frac{E\ell_o e_s^2}{R^2}\int_o^R x^2\sqrt{R^2 - x^2}\,dx \tag{A-6}$$

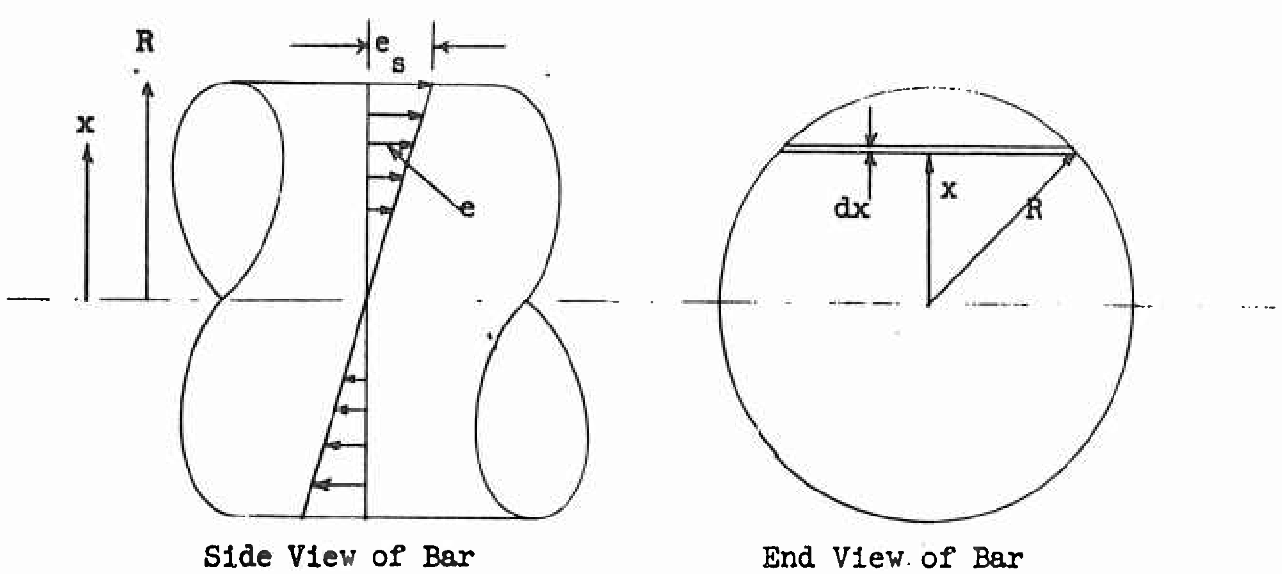

Figure 10. Lateral Strain Distribution in a Round Bar

The surface strain, e_s, is measured by means of two gages mounted on opposite sides of the bar. These gages are connected into adjacent arms of the bridge circuit, so that their outputs are subtracted electrically. This means that the longitudinal component of the vibration is subtracted out, and the lateral component, which has opposite signs on opposite sides of the bar, results in an output that corresponds to twice the lateral strain component. This output is amplified and shows up on the oscilloscope as a wave trace whose maximum amplitude is proportional to the output of the bridge circuit. If we call the constant of proportionality C, the maximum amplitude of the oscilloscope trace for the lateral vibration component, Am_{lat}, is related to the lateral surface strain, e_s, by

$$Am_{lat} = C(2e_s) \tag{A-7}$$

Solving for e_s and substituting in Eq. (A-6) gives:

$$E_{lat} = \frac{E\ell_o \ (Am_{lat})^2}{2R^2C^2} \int_o^R x^2 \sqrt{R^2-x^2} \ dx \tag{A-8}$$

Note that the lateral vibration energy is proportional to the square of the maximum amplitude of the lateral strain gage trace. Lumping everything but $(Am_{lat})^2$ on the right side of Eq. (A-8) into a single constant K, we obtain:

$$E_{lat} = K \ (Am_{lat})^2 \tag{25}$$

Eq. (A-8) implies that the lateral strain is uniformly distributed along the length of the bar. This is not true, but the energy lost in lateral vibrations can be determined from the observed trace amplitude anyway if the distribution of lateral strain along the length of the bar is similar for similar conditions of loading, that is, if the constant K in Eq. (25) can be determined. The method of determining this constant is discussed in the main body of the text.

APPENDIX 2

Sample Calculation of Stress and Strain Rate

In order to show how the equations summarized on pages 18 and 19 are used, a sample calculation of stress and strain rate will be made using the data of test number 12 which is a typical test. The experimentally recorded data for test 12 is recorded in the sample test data sheet, Fig. 8. The first quantity that must be calculated is the energy available for plastic work:

$$E_{pw} = PE_{iB} - PE_{iA} - PE_{sA} - E_{wf} - E_{vib} \tag{32}$$

In order to calculate the energy avai ɔle for plastic work, the terms on the right hand side of Eq. (21) must be evaluated. They will be evaluated in their order of appearance.

The potential energy of the impacting bar, PE_{iB}, before its release (equal to the total system initial energy) is given by Eq. (8):

$$PE_{iB} = W_{ib}(h_{iB}) \tag{8}$$

$$= 12.22\ (3.00) = 36.66\ \text{in-lb.}$$

The potential energy of the impacting bar after the collision, PE_{iA}, is given by Eq. (10):

$$PE_{iA} = W_{iB}\ (h_{iA}) \tag{10}$$

The height h_{iA} is determined from Fig. 4 from the known arc length of 7" and found to be 0.365 in. The potential energy, PE_{iA}, is then found to be:

$$PE_{iA} = 12.22\ (0.365) = 4.47\ \text{in-lb.} \tag{10}$$

The potential energy of the specimen bar after impact, PE_{sA}, is given by Eq. (11):

$$PE_{sA} = W_{sb}\ (h_{sA}) \tag{11}$$

where the height, h_{sA}, can be determined by using Fig. 4 and the known arc length of 12 7/8" to be 1.24 in. The potential energy, PE_{sA}, is then:

$$PE_{sA} = 11.78\ (1.24) = 14.58\ \text{in-lb.} \tag{11}$$

The energy loss due to windage and friction, E_{wf}, is given by Eq. (12):

$$E_{wf} = 0.01728\ (\text{total arc length}) \tag{12}$$

The total arc length is the sum of the arc lengths traveled by both bars before and after impact. The arc length traveled by the impacting bar before impact can be determined from Eq. (9):

$$h = \frac{arc^2}{134} \tag{9}$$

For h = 3.00" the arc length is determined to be 20.05 in. The total arc length is then:

$$\text{total arc length} = Arc_{1B} + Arc_{1A} + Arc_{sA}$$
$$= 20.05 + 7.00 + 12.87$$
$$= 39.92 \text{ in.}$$

The energy loss due to windage and friction is then:

$$E_{wf} = 0.01728\ (39.92) = 0.69 \text{ in-lb.} \tag{12}$$

The energy loss due to vibrations is given by Eq. (19):

$$E_{vib} = 0.13 + E_{lat} \tag{19}$$

where E_{lat} is given by:

$$E_{lat} = 0.0768\ (Am_{lat})^2 \tag{30}$$

The maximum lateral amplitude, Am_{lat}, is given by Eq. (27):

$$Am_{lat} = \sqrt{Am_{vert}^{\ 2} + Am_{horiz}^{\ 2}} \tag{27}$$

If $Am_{vert} = 1.30$ and $Am_{horiz} = 1.35$ from Table 3 for test #12 are substituted into (27), the maximum lateral trace amplitude, Am_{lat} is:

$$Am_{lat} = \sqrt{1.30^2 + 1.35^2} = 1.87 \tag{27}$$

The vibrational loss due to lateral vibrations is then:

$$E_{lat} = 0.0768\ (1.87)^2 = 0.27 \text{ in-lb.} \tag{30}$$

The total vibrational loss is:

$$E_{vib} = 0.13 + 0.27 = 0.40 \text{ in-lb.} \tag{19}$$

The energy available for plastic work can now be evaluated from Eq. (32):

$$E_{pw} = 36.66 - 4.47 - 14.58 - 0.69 - 0.40 \tag{32}$$
$$= 16.52 \text{ in-lb.}$$

The average flow stress is determined from Eq. (7):

$$S = \frac{E_{pw}}{V\epsilon} \tag{7}$$

In order to determine the stress, S, the volume and logarithmic plastic strain must be calculated. The volume is obtained from the initial dimensions of the specimen tip.

$$vol = \frac{\pi}{4}\ (0.1249)^2\ (0.2562) = 3.14\text{x}10^{-3}\text{in}^3$$

The logarithmic plastic strain in the axial direction, ϵ_p, is determined from the constant volume condition:

$$\epsilon = -2\epsilon_r \tag{34}$$

The logarithmic plastic strain in the radial direction, ϵ_r, is obtained from:

$$\epsilon_r = \ell n \frac{D_{ave}}{D_o} = \ell n \frac{0.1303}{0.1249} = 0.0423 \qquad (33)$$

The strain ϵ is then:

$$\epsilon = 2\epsilon_r = -2(0.0423) = -0.0846 \text{ in/in} \qquad (34)$$

If the proper substitutions are made, the average flow stress can be determined from Eq. (7):

$$S = \frac{16.52}{3.14\text{x}10^{-3}(-0.0846)} = 62{,}200 \text{ psi} \qquad (7)$$

The dynamic strain rate $\dot{\epsilon}$, is given by Eq. (39):

$$\dot{\epsilon} = \frac{\epsilon SA}{m\sqrt{2g}\,(\sqrt{h_{iB}} - \sqrt{h_{iA}})} \qquad (39)$$

where m, the mass of the impacting bar, is:

$$\frac{12.22}{12\text{x}32.2} = 0.0316,$$

$$\sqrt{2g} = \sqrt{(2)\ (12)\ (32.2)} = 27.8,$$

and A, the cross-sectional area of the specimen, is:

$$\frac{\pi}{4}\,(0.1303^2) = 0.01332$$

Substituting:

$$\dot{\epsilon} = \frac{(0.0846)\,(62{,}200)\,(0.01332)}{(0.0316)\,(27.8)\,(\sqrt{3} - \sqrt{0.365})} = 70.8/\text{sec.} \qquad (39)$$

Note that conservation of momentum requires $W\Delta\sqrt{h}$ be the same for both bars. For test no. 12, these values are:

Impacting bar: $(12.22)(\sqrt{3.00} - \sqrt{0.365}) = 13.8$

Specimen bar: $(11.78)(\sqrt{1.24} - \sqrt{0} = 13.1$

Comparison of the two numbers gives an indication of the reliability of the measurements.

BIBLIOGRAPHY

1. Manjoine, M. and A. Nadai, "High-Speed Tension Tests at Elevated Temperatures": Proc. of the American Society for Testing Materials, vol. 40, (1940), p. 822-837.

2. Baron, H. G., "Stress-Strain Curves of Some Metals and Alloys at Room Temperatures and High Rates of Strain": Journal of the Iron and Steel Institute, vol. 182, pt. 4 (1956), p. 354-65.

3. Culver, R. S., A Study of Dynamic Deformation Phenomenon, Unpublished Doctoral Thesis, Cambridge University (1963).

4. Kolsky, H., "An Investigation of the Mechanical Properties of Materials at Very High Rates of Loading": Proc. Physical Society, B vol. 67, p. 676, 1949.

5. Bell, J. F. and W. M. Werner, "Applicability of Taylor Theory of Polycrystalline Aggregate to Finite Amplitude Wave Propagation in Annealed Copper": J. Applied Physics, vol. 33, no. 8, (1962), p. 2416-25.

6. Davies, R. M. and S. C. Hunter, <u>The Dynamic Compression Testing of Solids by the Methods of the Split Hopkinson Pressure Bar</u>: Part II, A.R.D.E. Report (MX) 7/60, July 1960.

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13. ABSTRACT

An experimental method of determining dynamic flow stress where the stress is homogeneous is developed using a pendulum bar suspension system. A small specimen is mounted on the end of one of the bars and the other bar is impacted on the free end of the specimen.

For copper, the dynamic stress is 29% larger than the static stress for a strain rate of about 100 sec^{-1} (or an increase in strain rate of about 5 orders of magnitude). For various tests, the increase in dynamic stress over the static value varied from 17% to 45%. This variation is comparable with the expected scatter for a typical test ($\pm$10%) predicted from the uncertainties in measurement.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Bar-bar impact, shock loading High velocity deformation, strain rate Sensitivity, impact loading of copper Residual strain in impacted copper Elastoplastic wave propagation Shock wave propagation						

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