MTL TR 90-27

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AD-A223 278

THE MTL TORSIONAL SPLIT-HOPKINSON BAR

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MATERIALS DYNAMICS BRANCH

May 1990

JUN 1990

US ARMY
LABORATORY COMMAND
MATERIALS TECHNOLOGY LABORATORY

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MTL TR 90-27	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* THE MTL TORSIONAL SPLIT-HOPKINSON BAR		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR*(s)* Tusit Weerasooriya		8. CONTRACT OR GRANT NUMBER*(s)*
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Materials Technology Laboratory Watertown, Massachusetts 02172-0001 SLCMT-MRD		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 2102040064-8929 P61102 AMCMS Code: 611102.H420011
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Laboratory Command 2800 Powder Mill Road Adelphi, Maryland 20783-1145		12. REPORT DATE May 1990
		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT *(of this Report)* Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)* Torsion Strain rates Shear properties Copper (OFHC) Hopkinson bar Stress-strain High strain rates		
20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)* (SEE REVERSE SIDE)		

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ABSTRACT

A Stored Torque Split-Torsional Hopkinson bar (THBar) was developed (based on the principle of the one located at Brown University) and constructed at the U.S. Army Material Technology Laboratory (MTL). This report provides a detailed description of the THBar and its shear, axial and bending characteristics, and use of it to generate high strain rate shear stress-strain data of annealed OFHC copper (99.99% copper). With the present clamp of the THBar, shear stress-strain data can be generated for strain rates from 200 to 1300 s_L^{-1}. At the highest strain rate, a specimen can be deformed in shear to a maximum strain of 85% with the shear pulse of 655 μs. Three tests have been conducted for copper at strain rates of 400, 800, and 1200 s^{-1}. The shear stress-strain curves that have been generated at these three strain rates show a strain rate sensitivity for strains less than 35%; stress increases with strain rate for a constant strain. At higher strain rates and higher strains (greater than 35% strains), shear stress saturates to a constant value independent of the strain rate. High strain rate, shear stress-strain data correlate favorably with the trend found in the quasi-static rate data from a servohydraulic test machine.

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INTRODUCTION

When numerically simulating an event such as the penetration of an armor, where material deforms at a high strain rate and temperature, results will significantly depend upon the choice and the validity of the material constitutive model that is used in the simulation. To develop new models, evaluate existing models, and to obtain model parameter constants, it is necessary to obtain experimental stress-strain data as high deformation rates.

One method of obtaining experimental high strain rate (100 to 10^4 s^{-1}), stress-strain data is by using the split Hopkinson (also known as Kolsky bar) bar technique. Split-Hopkinson bar configuration consists of two elastic bars between which the specimen is held. In this test system, a stress pulse is applied to one bar (input bar) in the direction of the other bar (output bar) by an external mean; for example, by propelling a striker bar at the input bar or releasing a stored torque in the input bar. Part of the stress pulse will travel to the output bar (through the specimen) while the remainder will reflect back into the input bar. By measuring the elastic stress waves in the input (reflected) and output (transmitted) bars, Kolsky showed that it is possible to determine the stress-strain response of the sandwiched specimen.[1] It has been demonstrated that this technique can be used to obtain stress-strain response under compressive,[2,3,4] tensile,[5,6,7] or torsional[8,9] conditions.

Though the high strain rate behavior can be obtained by either compression or tension, there are many advantages to obtaining the stress-strain behavior by the torsional (shear mode) method. For example, when testing for large strains, the strains that can be achieved by tension is limited by necking, and compression is limited by barreling of the specimen. In addition, errors arising from dispersion of longitudinal stress wave on its travel along the elastic bars in a compression or tension test are not present in a torsion test; there is no wave dispersion in shear wave transmission. Although it is assumed that the stress conditions are uniaxial in a compression or tension test, at high rates, due to radial inertia (radial stress) that is opposing the Poisson's expansion associated with uniaxial stress, stress conditions may not be fully uniaxial. In a compression test, at high strains and/or strain rates, this inertia effect may get accentuated by the radial friction at the specimen and bar interface, even with the presence of lubrication. However, in spite of these disadvantages and limitations, the compression test has the advantage of requiring a simpler and cheaper specimen compared to the torsion or tension test.

Shear also is the main form of deformation that is present in high rate deformation events such as penetration of an armor. Therefore, to accurately predict material behavior in these types of situations, material constitutive models should be developed from shear data at

1. KOLSKY, H. *Stress Waves in Solids*. Oxford University Press, London, 1953.
2. LINDHOLM, U. S. *Some Experiments with the Split Hopkinson Pressure Bar*. J. Mech. Phys. Solids, v. 12, 1964, p. 317.
3. FRANTZ, C. E., FOLLANSBEE, P. S., and WRIGHT, C. E. *New Experimental Techniques With The Split-Hopkinson Pressure Bar*, in High Energy Rate Forming - 1984, Berman, I., and Schroeder. Ed., ASME, New York, 1984, p. 229.
4. FOLLANSBEE, P. S. *The Hopkinson Bar, High Strain Rate Compression Testing*, in High Strain Rate Testing, Mechanical Testing, Metal Hand Book, American Society for Metals, v. 8, p. 198.
5. LINDHOLM, U. S., and YEAKLEY, L. M. *High Strain Rate Testing: Tension and Compression*. Exp. Mech., v. 8, 1968, p. 1.
6. HARDING, J., WOOD, E. D., and CAMPBELL, J. D. *Tensile Testing of Material at Impact Rate of Strain*. J. Mech. Eng. Sci., v. 2, 1960, p. 88.
7. NICHOLAS T., and BLESS, S. J. *Split-Hopkinson Bar in Tension, High Strain Rate Tension Testing*, in High Strain Rate Testing, Mechanical Testing. Metal Hand Book, American Society for Metals, v. 8, p. 212.
8. BAKER, W. W., and YEW, C. H. *Strain Rate Effects in the Propagation of Torsional Plastic Waves*. J. Appl. Mech., v. 33, 1966, p. 917.
9. HARTLEY, K. A., DUFFY, J., and HAWLEY, R. H. *The Torsional Kolsky (Split-Hopkinson) Bar, High Strain Rate Testing, Mechanical Testing*. Metal Hand Book, American Society for Metals, v. 8, p. 218.

high strain rate and temperature. In addition, test results converted to shear from tension or compression data by using a criterion such as von Mises equivalent stress-strain is not valid at large strains above approximately 20%.[*,10] Shear tests can be conducted using a punch or double-notch type shear tests using a compression bar.[11] In this case, although high strain rates in the order of 10^4 s^{-1} could be achieved, disadvantages with compression bar such as geometric wave dispersion associated with longitudinal wave transmission, as well as non-uniform deformation in the specimen gage section will be present. However, a torsion test eliminates most of the above disadvantages. It is noted that rate change tests, also known as jump tests, (change of state keeping state variables representing the structure constant) that are required to develop and evaluate modern physically (dislocation dynamics) based high rate and temperature state variable constitutive models can be easily conducted using the torsional method. In a torsion test, shear stress pulse could be generated and released by explosives. This method of torsion testing could generate, in addition to the torsional pulse, a bending and axial pulse, as well as ringing in the torsional pulse, thus requiring elaborate mechanical filtering methods. In addition, an explosive capability has to be set up in the laboratory. In contrast, a torsional pulse that is generated and released by mechanical means (with mechanically releasing a clamp that would hold a stored torque that is generated by twisting the input bar) will not have the above complications, but will have higher rise-time and lower maximum achievable strain rate.

To facilitate the development and evaluation of constitutive models that would better predict shear behavior at high strain rate and temperature, and to make measurements such as strain and temperature in shear bands while they are being generated, a Stored Torque Torsional Hopkinson Bar (THBar) was developed at the U.S. Army Materials Technology Laboratory (MTL). This report presents the information and characteristics of the Torsional Hopkinson bar that was developed at MTL. Some preliminary torsional stress-strain data, at high strain rate and room temperature, for annealed OFHC copper (99.99% copper) from this test instrument is included in this report. High/low temperature and jump test capability are being added to the THBar.

DESCRIPTION OF THE APPARATUS

The design principal of our THBar is similar to that of the machine located at Brown University.[9] Here, the THBar consists of two elastic bars, a clamp with a sudden releasing mechanism, and a loading arrangement to twist one of the bars. Each end of the specimen is attached to one end of each bar so that the specimen is held between them. The clamp is used to hold the bar from rotating, while a twist is applied by the loading mechanism at the other end of the input bar. The release of the torque, that is stored between the loading end of the input bar and the clamp, by sudden release of the clamp will propagate a shear stress pulse along the bar toward the specimen, thus loading it in shear at high rate.

* WEERASOORIYA, T. Unpublished Research, 1989.
10. SHRIVASTAVA, S. C., JONAS, J. J., and CANOVA, G. J. Mech. Phys. Solids, v. 30, 1982, p. 75.
11. HARDING, J. Double-Notch Shear Testing and Punch Loading, High Strain Rate Testing. Mechanical Testing. Metal Handbook, American Society for Metals, v. 8. p. 228.

Figure 1 shows a photograph of the THBar apparatus, and a schematic diagram of the THBar is shown in Figure 2. The THBar consists of two 25.4 mm diameter 7075-T6 aluminum bars, input and output bars, 2438 mm in length. These two bars are mounted on top of a square box beam, using oilite bronze bearings. The bearing stands are designed in such a way that the bearings have the freedom to move in any direction; i.e., translate along and rotate about three mutually perpendicular axes of which one axis is lying along the axis of the bearing. Once the bearings are aligned, they are locked in that position. Alignment of the bearings is performed with the help of a helium-neon laser and a steel bar, 25.4 mm in diameter and 75 mm in length, which has the two end faces precisely machined perpendicular to the axis of the bar; a mirror is mounted on one end, and a cross (two lines that are perpendicular to each other and passing through the center), are scribed at the other end of the alignment bar.
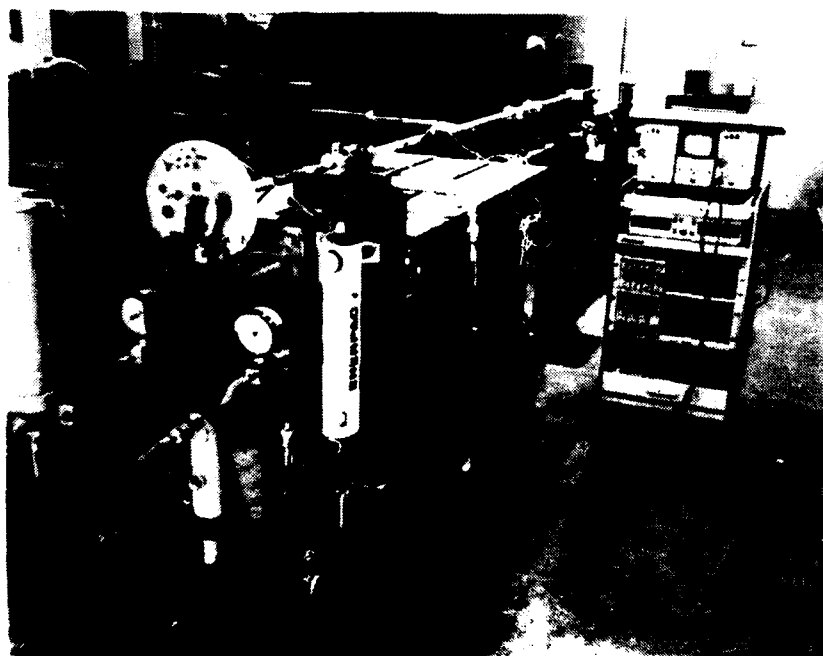
Figure 1. The Torsional Split-Hopkinson Bar Apparatus.

At one end of each aluminum bar, a hexagonal slot is machined to enable the attachment of a hexagonal-end specimen. Specimens are attached to the bar with 12 slotted screws, two on each face of the hexagon (Figure 3). Specimen geometry is discussed in a later section. When flat-end specimens are tested, these bars are replaced with two flat-end bars. In this case, using an epoxy, the specimen is glued to these flat ends of the bars.
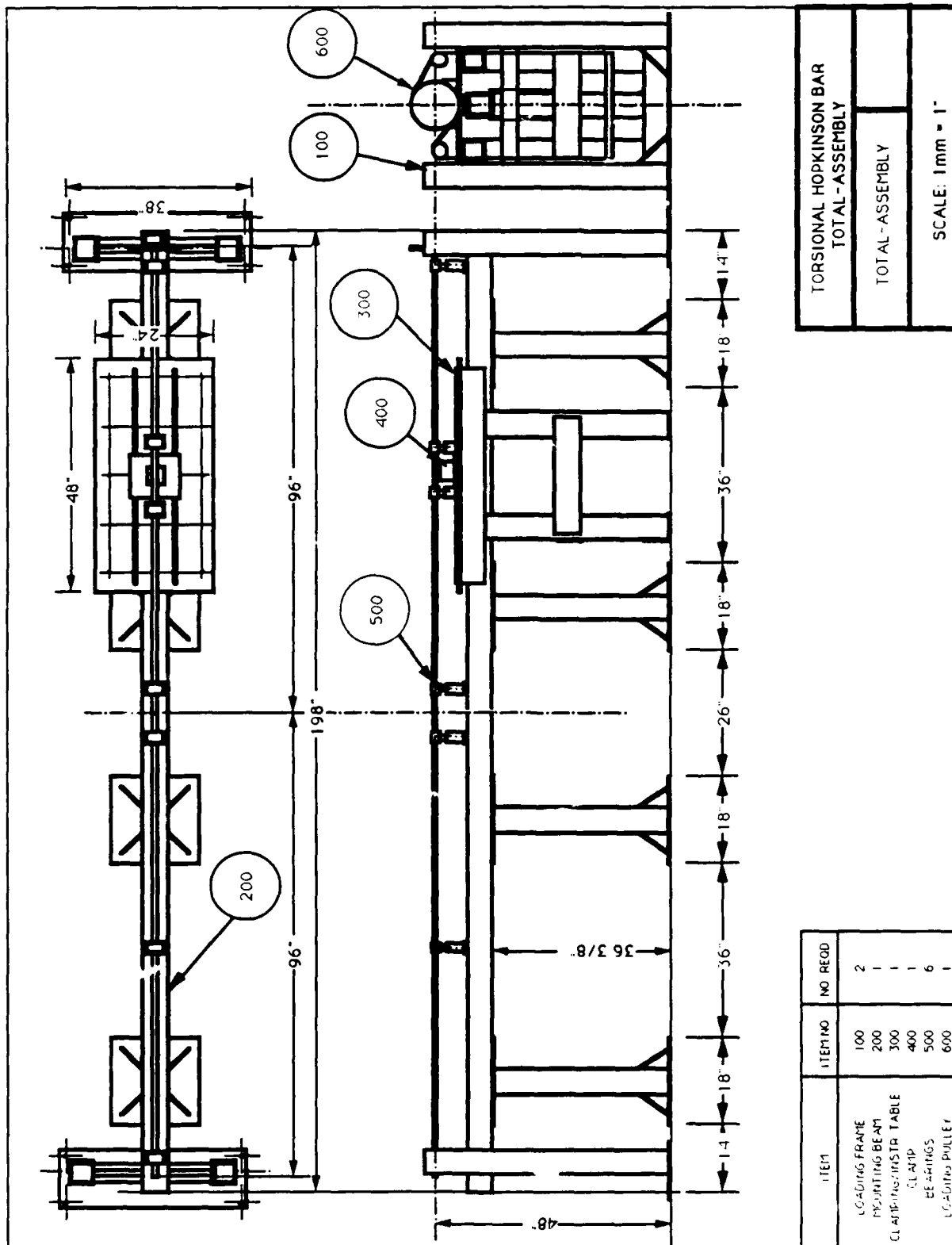
Figure 2. Schematic of the complete Torsional Hopkinson Bar Assembly.

ITEM	ITEM NO	NO REQD
LOADING FRAME	100	2
MOUNTING BEAM	200	1
CLAMPING/INSTR TABLE	300	1
CLAMP	400	1
BEARINGS	500	6
LOADING PULLEY	600	1

TORSIONAL HOPKINSON BAR
TOTAL-ASSEMBLY

TOTAL-ASSEMBLY

SCALE: 1mm = 1"

4

Figure 3. Specimen-ends of the bars. In this picture, hexagonal end
specimen is attached to the bars via the hexagonal slots in the bars.

Shear Pulse Generating System

Torque Generating Mechanism

A torque is applied to the opposite end from the slotted-end of the input bar, via a
pulley that is attached to the bar by a friction fit. Using a hydraulic hand pump and a
cylinder, the pulley is rotated to apply a twist to the input bar. The schematic and photo-
graph of this loading arrangement is shown in Figures 4 and 1, respectively. The pulley is
attached to a cross bar by cables. The cross bar is pushed down by the hydraulic cylinder,
thus rotating the pulley that is attached to the end of the input bar.

Clamp

A photograph of the clamping arrangement is shown in Figure 5, and a schematic dia-
gram of the clamp is shown in Figure 6. The clamp consists of two plates that are posi-
tioned on either side of the bar. The tops of the plates are connected by a 2024-T4
aluminum pin, 19.1 mm in diameter, with a 12.2 mm diameter notch at the center. Both
clamping plates are mounted in a carriage that is free to move on ball bearings perpendicular
to the bar, with pins, allowing the plates to freely rotate about these pins. While clamping,
application of lateral forces that would create bending and axial pulses are avoided by allow-
ing the free movement of the clamp relative to the bar. At both ends of the clamp, to
reduce any bending waves emanating from the release of the clamp, the input bar is mounted
on two additional 38 mm long oilite bronze bearings, which are located on either side of the
clamp. In addition to allowing the clamping plates to rotate about the attaching pins, the pin
of one plate is free to move toward the bar. Clamping is achieved by pushing this plate
toward the bar at this pin by a hydraulic cylinder attached to a hand pump. Further pump-
ing of the hydraulic oil to the cylinder will fracture the notched 2024-T4 aluminum pin at the
top of the bar, suddenly releasing the clamp and, therefore, the stored torque between the
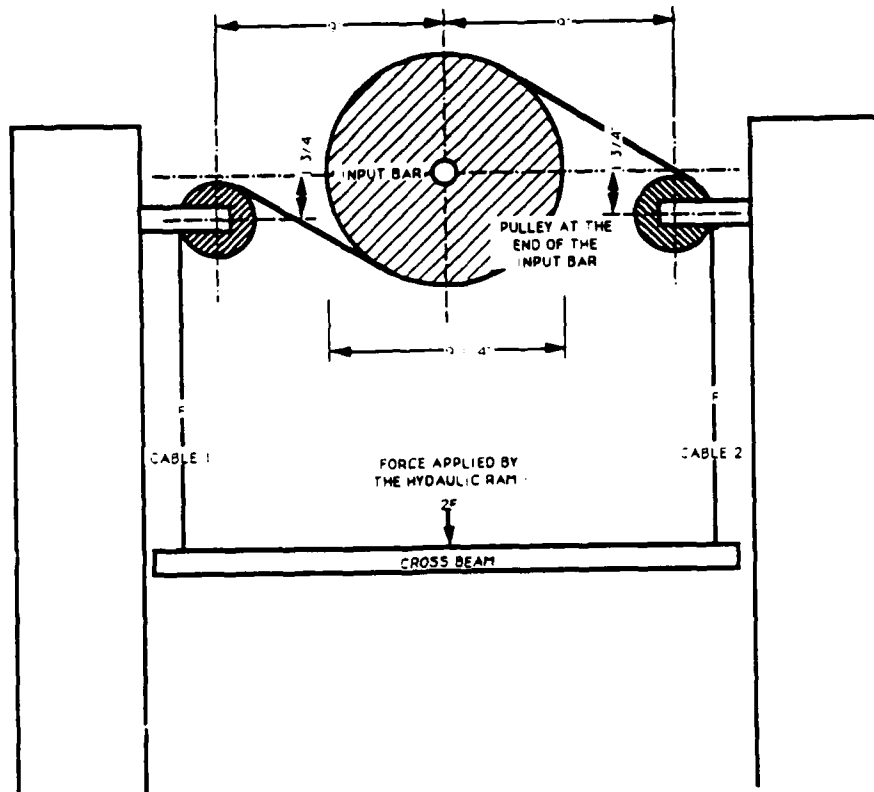clamp and the loading end.

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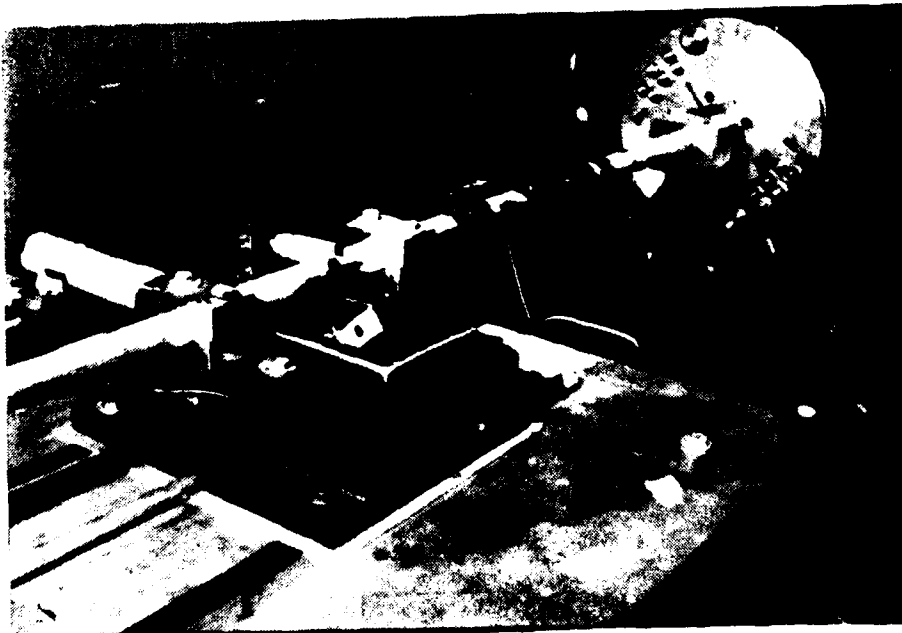Figure 4. Schematic of the loading arrangement.

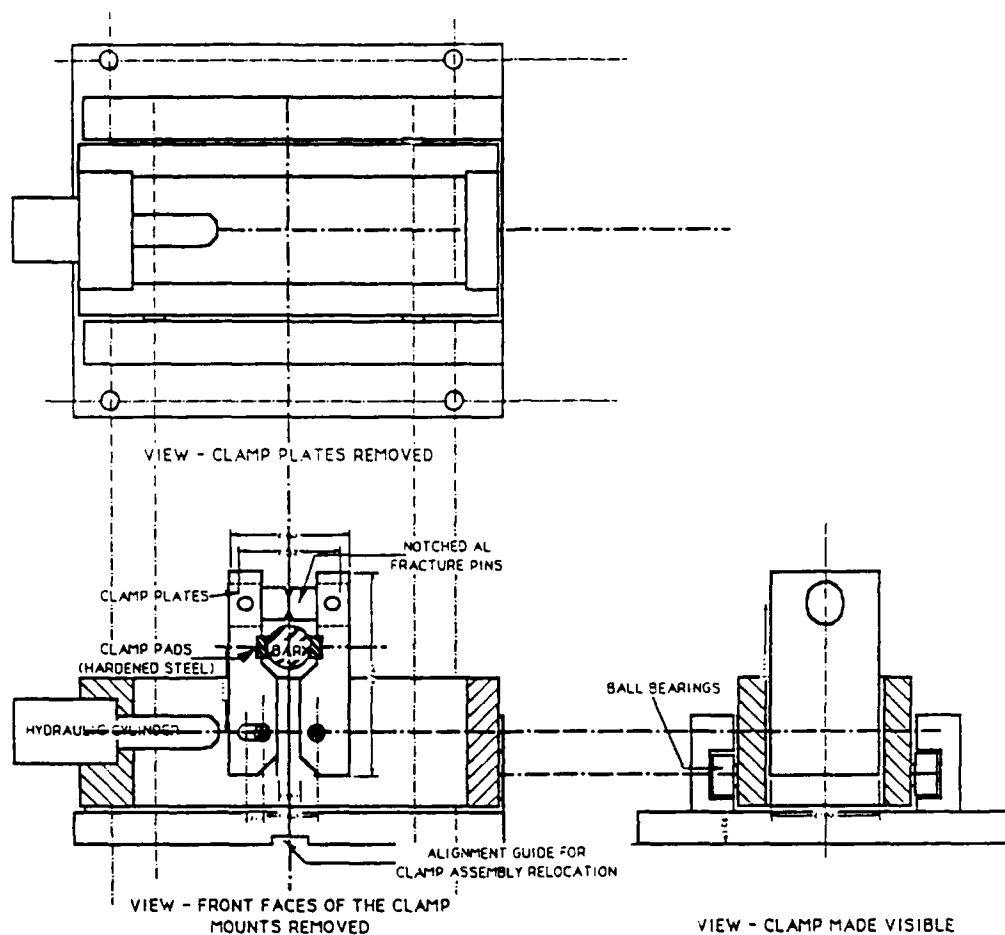Figure 5. The clamping assembly and the loading pulley.

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VIEW - CLAMP PLATES REMOVED

NOTCHED AL FRACTURE PINS

CLAMP PLATES

CLAMP PADS (HARDENED STEEL)

HYDRAULIC CYLINDER

BALL BEARINGS

ALIGNMENT GUIDE FOR CLAMP ASSEMBLY RELOCATION

VIEW - FRONT FACES OF THE CLAMP MOUNTS REMOVED

VIEW - CLAMP MADE VISIBLE

Figure 6. Schematic of the clamping assembly.

Lagrangian Diagram of the System

Langrangian of x-t diagram of the system is shown in Figure 7. The position of the shear wave front as a function of time can be inferred from this wave diagram. As seen from the diagram, at the release of the clamp, half of the torque stored between the clamp and the loading pulley will travel as a shear wave, at the shear wave speed (C_s) of aluminum, toward the specimen. Shear pulse of the same magnitude will travel at the same speed in the other direction unloading the torque that is stored at that end. This unloading pulse will reflect completely at the loading pulley (large pulley will act as a rigid boundary) and travel toward the specimen releasing the torque to zero; therefore, the total length of the shear pulse that will twist the specimen is equal to the time taken by the unloading pulse to travel toward the loading pulley and back to the clamp. By allowing the clamp to be relocated, the length of the pulse can be changed. To allow the clamp assembly to be moved and bolted easily, without drastically changing the alignment, the whole clamp assembly is mounted on a long table with guiding rails.

7
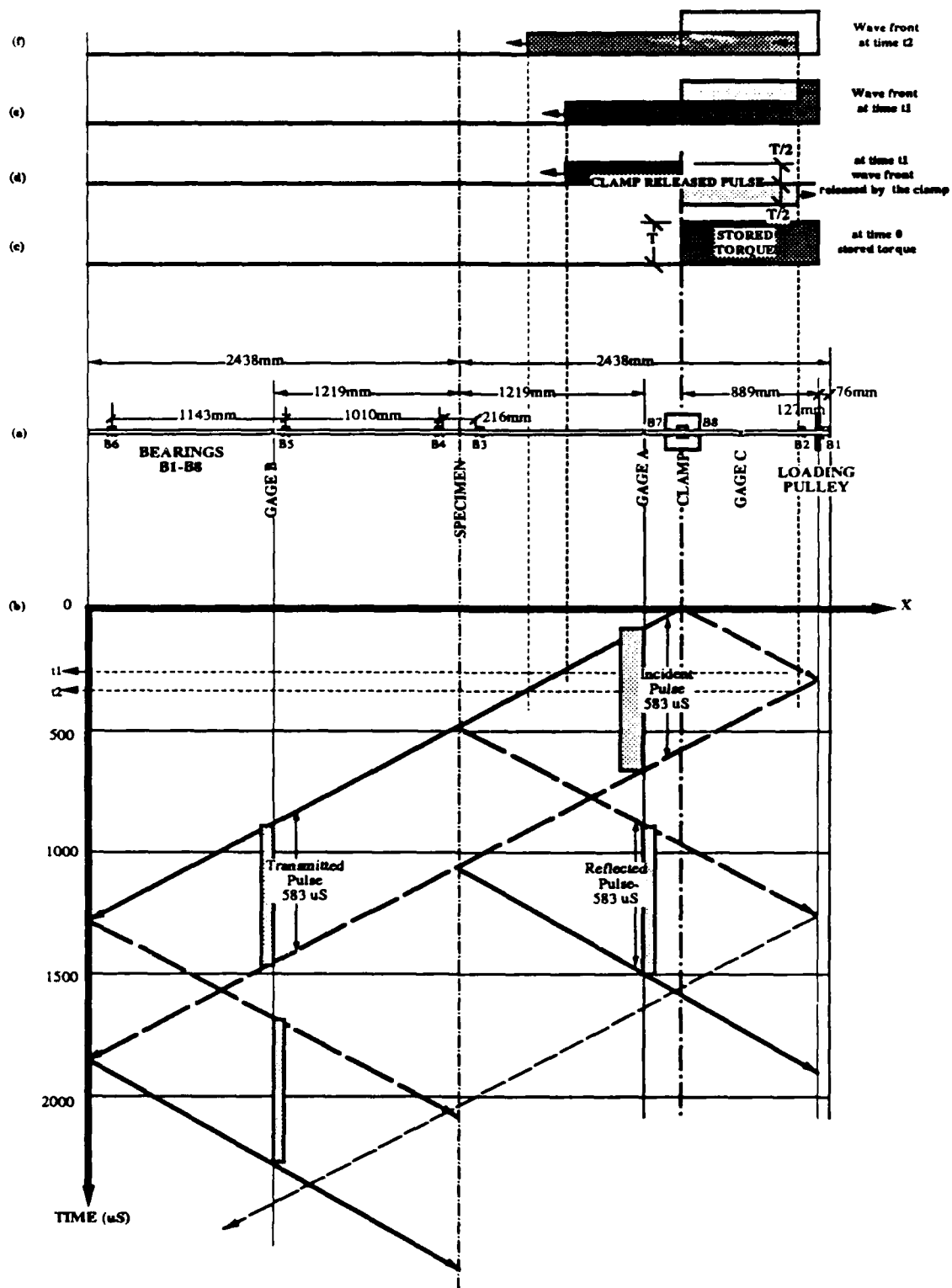
Figure 7. Lagrangian (x-t) diagram of the system.

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Stress, Strain, and Strain Rate Computation

Magnitude of stress, strain, and strain rate of the specimen can be computed form the measured shear strain records of the input and output bars (Kolsky analysis method[1]). Shear strain of the specimen (γ_s) is equal to the relative rotation of the ends of the gage section of the specimen divided by its length:

$$\gamma_s = \frac{D_s \phi_1 - D_s \phi_2}{2L_s} \tag{1}$$

where ϕ_1 and ϕ_2 are angles of twist at the interface between specimen (Figure 8) and input and output bars, respectively, L_s is the gage length of the specimen, and D_s is the mean diameter of the thin wall of the specimen. The magnitude of ϕ_2 can be determined from γ_T: the transmitted shear strain at the surface of the output elastic bar:

$$\gamma_T = \frac{D}{2} \frac{\partial \phi_2}{\partial x} = \frac{D}{2C_s} \frac{\partial \phi_2}{\partial t} \tag{2}$$

where $C_s = \sqrt{G/\rho}$ is the shear velocity in the output bar, D is the diameter of the output bar, and G and ρ are shear modulus and the density of the output bar, respectively. Rearrangement yields:

$$\phi_2 = \frac{2C_s}{D} \int_0^t \gamma_T(t)dt \tag{3}$$
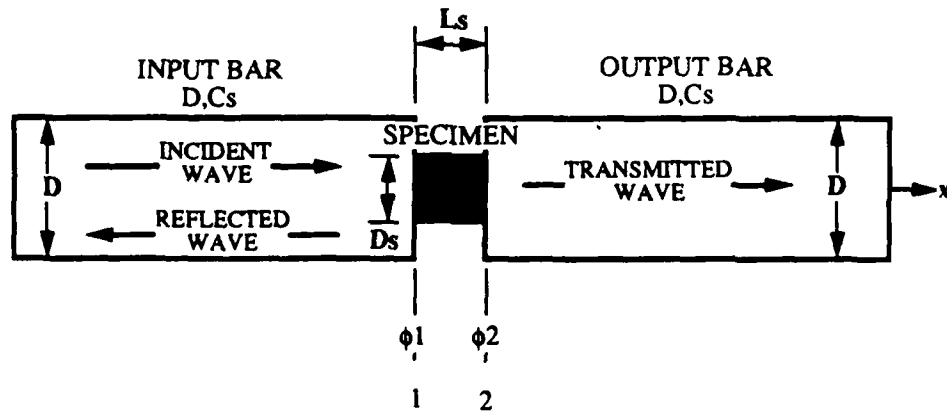
Figure 8. Schematic of the specimen bar interfaces.

The magnitude of ϕ_1 can be determined from the values of shear strains, the incident (γ_I) and reflected (γ_R) waves at the specimen/input bar interface, on the surface elastic input bar:

$$\gamma_I - \gamma_R = \frac{D}{2} \frac{\partial \phi_1}{\partial x} = \frac{D}{2C_s} \frac{\partial \phi_1}{\partial t} \tag{4}$$

and integrating

9

$$\phi_1 = \frac{2C_s}{D} \int_0^t [\gamma_I(t) - \gamma_R(t)] dt \; . \tag{5}$$

By substituting the derivatives of ϕ_1 and ϕ_2 from Equations 3 and 5 in Equation 1,

$$\overset{\circ}{\gamma}_s(t) = \frac{C_s D_s}{L_s D} [\gamma_T(t) - \{\gamma_I(t) - \gamma_R(t)\}] \tag{6}$$

By integrating the above relationship for specimen strain rate, the strain of the specimen can be determined as a function of time. At a uniform state of strain in the specimen, the transmitted torque at the output bar/specimen interface (T_2) is approximately equal to the torque at the input bar/specimen interface (T_1); i.e., the transmitted shear strain pulse is equal to the sum of the incident and reflected shear strain pulses at the specimen. Therefore, $\gamma_T \approx \gamma_I + \gamma_R$ and Equation 6 reduces to:

$$\overset{\circ}{\gamma}_s(t) = \frac{2C_s D_s}{L_s D} \gamma_R(t) \tag{7}$$

Integration of Equation 7, strain of the specimen can be obtained:

$$\gamma_s(t) = \frac{2C_s D_s}{L_s D} \int_0^t \gamma_R(t) \, dt \tag{8}$$

Shear stress (t_s) is given by:

$$\tau_s(t) = \frac{2T_s}{\pi D_s^2 t_s} \tag{9}$$

where t_s is wall thickness and T_s is average torque in the specimen: T_s is the average of T_1 and T_2, torques at the input bar interface and output bar interface of the specimen, respectively. These torques, T_1 and T_2, can be computed from the shear strains in the elastic input and output bars as follows:

$$T_1 = \frac{G\pi D^3}{16} (\gamma_I + \gamma_R) \tag{10}$$

and

$$T_2 = \frac{G\pi D^3}{16} \gamma_T \tag{11}$$

As discussed earlier, when the specimen is deforming uniformly; i.e., $\gamma_T \approx \gamma_I + \gamma_R$, from Equation 9 using Equations 10 and 11:

$$\tau_s(t) = \frac{GD^3}{8D_s^2 t_s} \cdot \dot{T}(t)$$ (12)

Measurement of Shear Pulses in the Bars

Shear stress pulses in the input and output bars are measured using a strain gage bridge. The strain gage bridges are attached to each bar at the mid-points (at the locations A and B in Figure 7). By locating A and B gages at the mid-points, both transmitted and reflected waves will reach the gage locations at the same instant; also, reflected and incident pulse will be separated in time in the trace captured at the A gage. In addition, another strain gage bridge (C in Figure 7) is attached between the clamp and the loading pulley; this bridge is provided to measure the magnitude of the applied (stored) torque to the bar. All the bridges consist of four strain gages. Each bridge consisting of two pairs, one pair attached diametrically opposite the other on the surface of the bar. The gages are oriented at a 45° angle to the axis of the bars; gages arranged this way will measure only shear strains by excluding both axial and bending strains.

Each bridge is powered by a separate DC power supply, an HP6218C constant voltage (50V), or current (0.2A) power supply, in which the voltage can be set with a potentiometer. Output of the bridges are directly fed into an 800 kHz Nicolet (Model 4562) digital oscilloscope. Power supply voltage output to strain gage bridges are adjusted to achieve a chosen calibration factor and is discussed in the Calibration and Data Reduction Method Section.

To measure axial and bending pulses that will be generated by the clamp, four additional strain gages are attached to the bar, 90° apart, at each A and B location. Two diametrically opposite gages are connected in series to act as the active part of a single gage bridge-amplifier setup (2 MHz bandwidth). Axial stresses are measured by this bridge configuration. The other two gages that are 180° apart are a part of a two active gage bridge-amplifier unit (2 MHz) that is set up to measure the bending stress pulses of the bar; in this case, the two active gages are located at opposite locations of the bridge.

Calibration and Data Reduction Method

Figure 9 shows typical waveforms captured by the digital oscilloscope at A and B gages. The trace from A gage contains both the incident ($v_I(t)$) and reflected ($v_R(t)$) traces separated from each other in time space. The trace from B gage represents the transmitted pulse ($v_T(t)$) through the specimen. In these traces, vertical axes represent a voltage output from the strain gage bridge that is proportional to the shear strain at the surface of the bars. For a four gage bridge, the shear strain (γ) at the surface of the bar is given by the expression:

$$\gamma = \frac{2v}{FE} ,$$ (13)

where v is the output voltage of the bridge, F gage factor of the strain gages, and E is the input DC voltage of the bridge. By using Equations 13 and 7, shear strain rate of the specimen:

$$\dot{\gamma}_s(t) = \frac{2C_s D_s}{L_s D} \frac{2v_R(t)}{FE_A}$$ (14)

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where subscript R represents the reflected pulse and A represents the gages at A. Similarly, Equation 12 representing shear stress will become:

$$\tau_s(t) = \frac{GD^3}{8D_s^2 t_s} \frac{2v_T(t)}{FE_B}$$ (15)

where subscript T represents the transmitted pulse through the specimen and B represents the gages at location B. By selecting a value for $E_{A/B}$, (A or B) calibration factors (i.e., for a unit output bridge voltage) for strain rate and stress can be chosen. For chosen calibration factors, E_A and E_B can be calculated from Equations 14 and 15. With these input bridge voltages, when a known precision calibration resistor (R_c) is shunted across one gage of the bridge, the output bridge voltages ($v_{R/T}$) can be computed by the expression:

$$v_{R/T} = \frac{RE_{A/B}}{4F_{A/B}(R + R_c)}$$ (16)

where R is the resistance of a single gage.

Shear Stress Pulses at A and B Locations
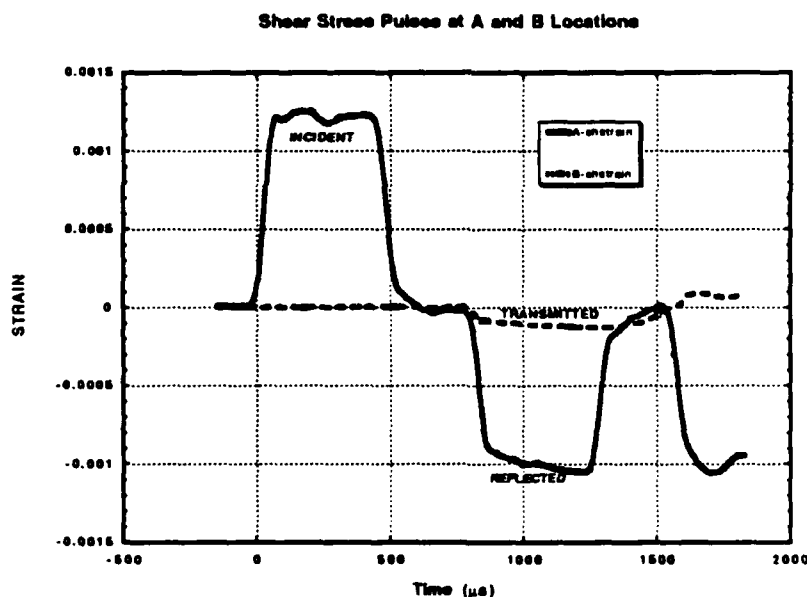
Figure 9. Shear Stress Pulses at A and B Gage Locations.

Before each test, by tuning the pot that varies the magnitude of the power supply voltage, the calibration factor is set for each bridge to output the calculated voltage for the calibration resistor.

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ACQUISITION AND ANALYSIS OF STRESS PULSES

Traces of the stress pulses in both input and output bars are captured at the A gage (incident and reflected) and B gage (transmitted) using the digital oscilloscope. The oscilloscope is triggered by the trace at gage A off the incident pulse: a threshold crossing with a prescribed delay of -150 μs.

The waveforms, captured by the digital oscilloscope, are transferred to a microcomputer (AT compatible) via an RS232 serial port using a computer program written in WaveForm Basic language (see Appendix B for the listing of the program).

Shifting of the waveforms in time space, computation of strain rate (Equation 7), stress (Equation 12), strain (by numerically integrating strain rate) waveforms from captured data at A and B, and the plotting of the stress-strain curves are performed using a computer program (written in TBASIC language). The listing of the computer program is given in Appendix B.

EXPERIMENTS

In this section of the report, preliminary experiments that have been conducted with the THBar are discussed. Also, axial and bending pulses that are generated by the clamp are presented and discussed in this section of the report.

Material

Test specimens were machined from oxygen-free-high-conductivity (OFHC) copper (99.99% copper). OFHC material was received as one inch diameter rods in the work hardened condition. Before machining the specimens, copper rods were annealed at 400°C vacuum for one hour. This annealing heat treatment produced grains of an average size of 45 μ.

Specimen Geometry

Geometry of the test specimen is shown in Figure 10. Gage section of the test specimen is a thin wall tube (0.38 mm wall thickness) of 0.254 mm gage length and of outside (D_{so}) and inside (D_{si}) diameters of 10.16 mm and 9.40 mm, respectively. A thin wall tube is sandwiched between two hexagonal flanges which are used to attach the specimen to the elastic input and output bars of the test system. Before testing the specimens, a fine line, parallel to the axis of the specimen, is scribed on the inside wall of the specimen.

The geometry of the specimen is identical to the one used at Brown University by Duffy.[9] In this short gage length specimen, an almost homogeneous state of strain is achieved after a few reflections of the loading shear stress pulse. In this specimen geometry, although the plastic zone starts at the flange-gage section interface, the plastic zone is contained until it spreads gradually through the specimen and engulfs the whole gage section.[12]

12. LEUNG, E. K. C. *An Elastic-Plastic Stress Analysis of the Specimen Used in the Torsional Kolsky Bar.* J. Appl. Mech., v. 47, 1980, p. 278.
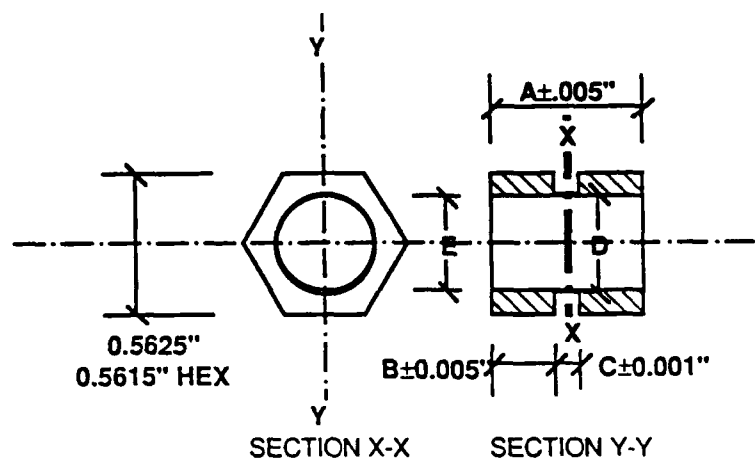
DIM   INCHES

A   0.600
B   0.250
C   0.100
D   0.400±0.0005 DIA
E   0.370±0.0005 DIA

UNSPECIFIED TOLERANCES = ±0.005

Figure 10. Test specimen for Torsional Hopkinson Bar.

Tests

Three OFHC specimens were tested at three different strain rates, 400, 800, and 1200 s^{-1}, using the THBar. The specimens were attached to the slotted end of the bars by screws. The tests were initiated, as discussed earlier, by first clamping the bar and then twisting it by the loading assembly using the hydraulic hand pump at the loading arrangement. While clamping the bar, it was made certain that the clamp would apply its two clamping forces symmetrically opposing each other, thus cancelling any lateral force components that would apply any bending to the bar. The amount of twisting was indicated by a digital mili-voltmeter that is attached to the strain gage bridge at the location C (C gage). The clamp was released by further hand pumping of the hydraulic cylinder at the clamp. Shear stress pulses at the A and B gages were captured by the digital oscilloscope.

RESULTS AND DISCUSSION

Captured shear pulse traces, at A and B strain gage locations, for one of the tests is shown in Figure 9. As shown in the figure, this instrument produces an approximately constant incident pulse. Rise time of the incident shear wave generated by the clamp is about 45 μs.

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Axial and bending strain pulses at the A gage are given with the shear strain pulse in Figure 11a for the same test. Axial and bending strain pulses that are generated by the clamp are appreciably smaller than the shear strain pulse (less than 10%).

For the same test, after transforming measured shear, axial, and bending strain pulses at the B gage to corresponding stresses through the specimen, are shown in Figure 11b. In the above conversion of axial and bending strains at B gage to stresses, the following expressions are used:

$$\sigma_a(t) = \frac{ED^2}{(D_{so}^2 - D_{si}^2)} \epsilon_{aT}(t)$$ (17)

and

$$\sigma_b(t) = \frac{ED^3 D_{so}}{(D_{so}^4 - D_{si}^4)} \epsilon_{bT}(t)$$ (18)

where σ_a and σ_b are axial and bending stresses at the specimen, respectively, ϵ_{aT} and ϵ_{bT} are axial and bending strains transmitted to the output bar, respectively, and E is the Young's modulus of the bar. Bending and axial stress peaks that are transmitted through the specimen are less than the static yield of the annealed OFHC copper. Moreover, the bending stress pulse travels through the specimen after the end of the shear pulse; flexural wave speed for the aluminum bar supported at locations L ($\approx$ 1300 mm) apart is approximately equal to 2.9 D/L ($\approx$ 0.06) times the shear wave speed of the bar for the zeroth overtone (free end condition is assumed). However, the axial pulse travels faster ($\approx$ 1.6 times) than the shear pulse and, therefore, it reaches the specimen earlier.

The captured stess pulses at gages A and B for the tests are transferred to the microcomputer. The reduction of these data are accomplished using the computer program in Appendix B. The resulting output from the program, stress-strain plots at the three different strain rates, 400, 800, and 1200 s^{-1} are shown in Figure 12. Computed shear strain rate, stress and strain as a function of time for the three tests are shown in Figures 13, 14, and 15, respectively.

Shear stress-strain curve of the OFHC copper at the quasi-static shear strain rate of 1 x 10^{-3} s^{-1} is also shown in Figure 13.* Stess-strain curves for copper at strain rates of 400, 800, and 1200 s^{-1} shows a strain rate sensitivity of this material in the range of rates that are used in the tests. At higher strain levels ($\approx$ 35%), under high strain rate conditions, stress levels seem to be independent of the strain rates. This may be due to the thermal softening of the material at higher strains and strain rates. However, no deformation shear bands were present in the gage section. High strain rate, shear stress-strain data (below 35% strain level) correlate favorably with the trend from the quasi-static rate data from a servohydraulic test machine.

It is noted from Figure 13, after a 60 μs time interval, strain rate data as a function of time for the three tests show that the strain rate remained reasonably constant during the test. This 60 μs time interval corresponds to a strain of approximately 1 to 5%, depending upon the strain rate (see Figure 15).

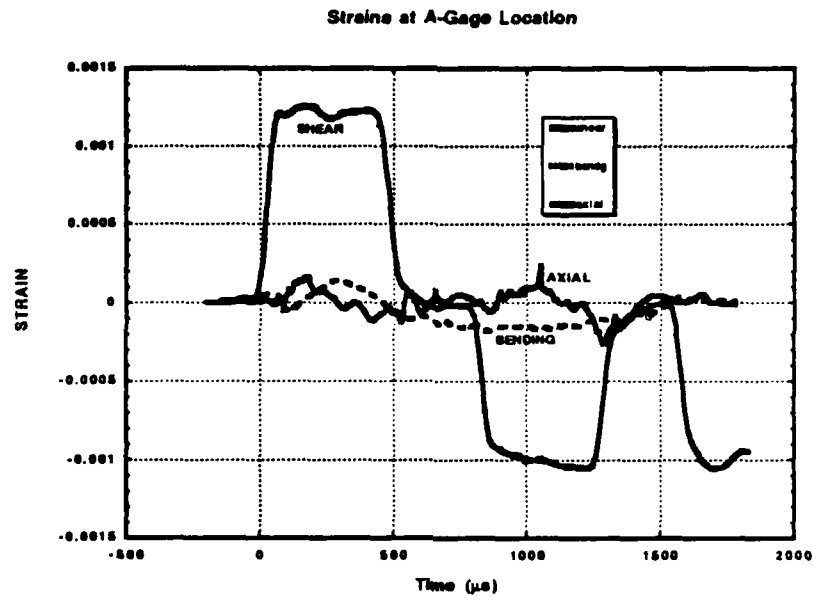*WEERASOORIYA, T. Unpublished Research, 1989.

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Strains at A-Gage Location

Figure 11a. Shear, Axial, and Bending Pulses at the A Gage Location.

**Stresses Transmitted Through the Specimen
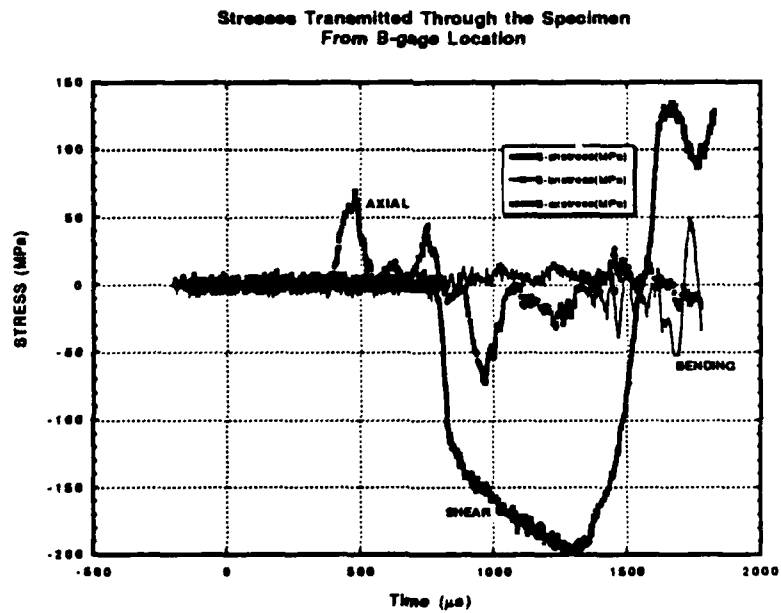From B-gage Location**

Figure 11b. Shear, Axial, and Bending stresses through the specimen
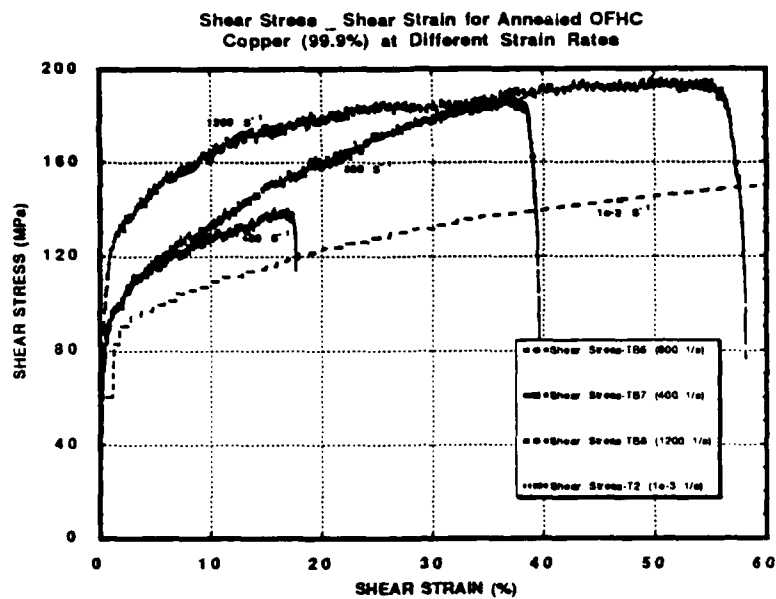from captured strain pulses at the B Gage Location.

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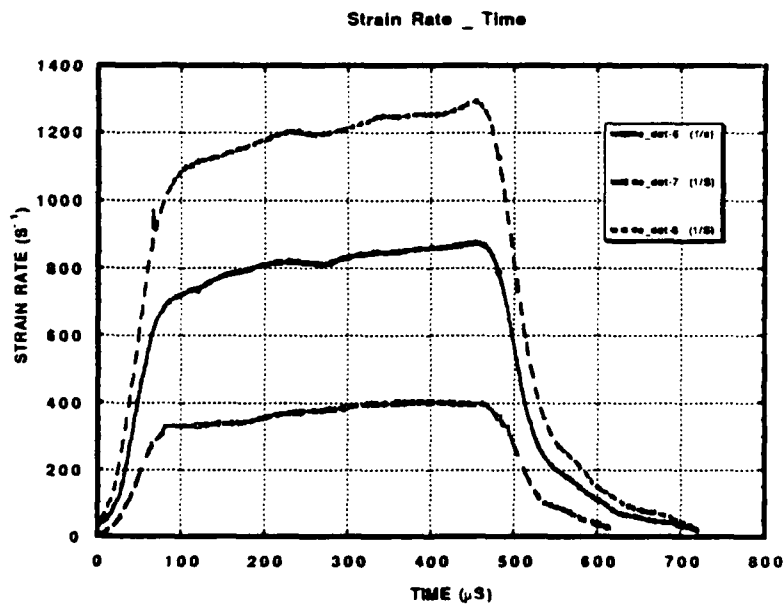**Figure 12. Shear stress-strain data at different strain rates.**

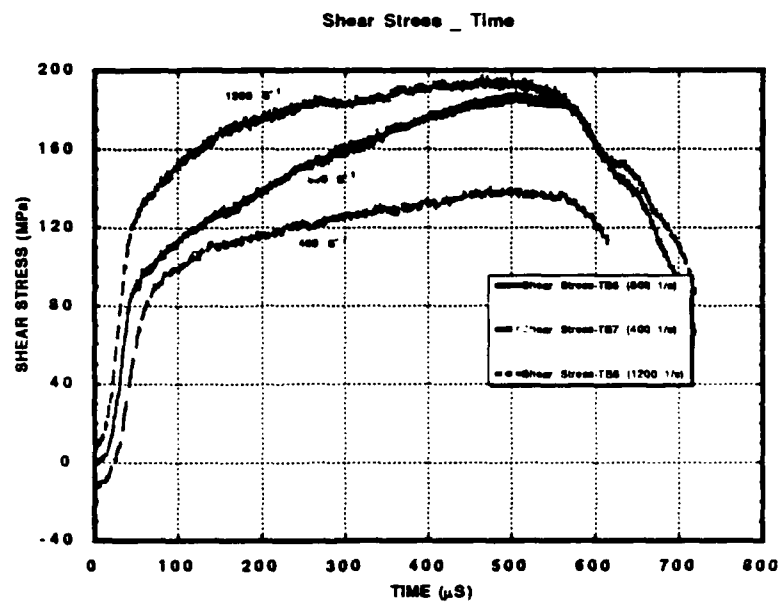**Figure 13. Strain rate as a function time for the three tests.**

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Shear Stress _ Time

Figure 14. Stresses as a function of time for the three tests.

Strain _ Time
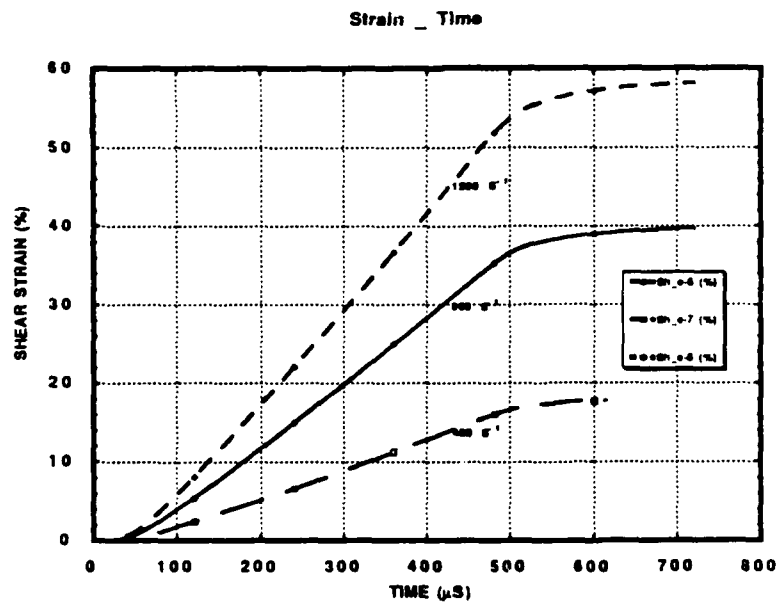
Figure 15. Strain as a function of time for the three tests.

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The maximum shear strain rate that can be achieved in this THBar configuration, with the specimen of gage length of 2.54 mm and the present clamp, is 1400 s^{-1}. This maximum limit is due to the inability to apply a higher clamping force to prevent the slipping of the bar at the clamp for higher input torques; i.e., fracture load of the present aluminum fracture pin is low. In future tests, strain rates up to 2500 s^{-1} can be reached with the present specimen geometry with a new clamp that is being designed.

CONCLUSIONS

A THBar apparatus was developed and constructed at MTL. This apparatus can be used to generate constant shear stress-strain data at high strain rates, up to 1300 s^{-1}, for the development and evaluation of constitutive models that will improve the description of the shear behavior of the materials. In addition, the shear stress-strain data generated by this apparatus can be compared with the data generated by the compression or tension Hopkinson bars, using the equivalent stress-strain relationships such as von Mises. These comparisons will allow the evaluation of existing equivalent stress-strain relationships, as well as the development of better ones.

The effect from the bending and axial pulses generated by the release of the clamp is determined to be negligible. Strain rates remain reasonably constant after 60 μs (i.e., 5% strain at the highest achievable strain rate).

The apparatus is being improved to have additional capabilities. A motor drive is being developed and constructed to rotate the output bar at the far end, therefore, allowing quasi-static tests, as well as strain rate jump (sudden jump of strain rate from the quasi-static to a higher rate in the same or opposite direction) tests to be conducted. A new clamp is being developed to achieve strain rates up to 2500 s^{-1}. In addition, shear bands can be generated in some materials with this new clamp.[13]

ACKNOWLEDGMENTS

13. HARTLEY, K. A., DUFFY, J., and HAWLEY, R. H. *Measurement of the Temperature Profile During Shear Band Formation in Steels Deforming at High Strain Rates.* J. Mech. Phys. Solids, v. 35, no. 3, 1987, p. 283.

APPENDIX A. COMPUTER PROGRAM TO TRANSFER WAVEFORMS
FROM DIGITAL OSCILLOSCOPE TO COMPUTER

```
10   TRANSFER (D@,"a2")
20   REM SELECT FIRST AND LAST POINTS BY OPERATOR-FOR A-GAGE DATA
30   SETFXP
40   SETLXP
50   AGAGE@ = CUT (D@)
60   TRANSFER (D@,"b2")
65   REM USE AGAGE WINDOW TO CUT B-GAGE DATA
70   BGAGE@ = CUT (D@)
75   REM PLOT SELECTED A-GAGE AND B-GAGE DATA
80   PLOT AGAGE@
90   PLOT BGAGE@
95   REM STORE DATA IN AN ASCII FILE
100  ASTORE AGAGE@,BGAGE@,"TBARDATA"
110  CLEAR ALL
120  CLOSE
130  END
```

```
  1   !     HOPKINSON TORSIONAL BAR DATA ANALYSIS PROGRAM
  2   !        WRITTEN BY TUSIT WEERASOORIYA (November 1989)
  3   SET KEY ON I GOTO 100
  4   PRINT "Plot STRESS_STRAIN CURVE on_",Gin$
  5   SET VIEWPORT 0,130,0,100 I INPUT PROMPT "NEW PAPER AND RETURN":A$
  6   Xmax = 0.6 I Xmin = 0 I Ymax = 250 I Ymin = 0
  7   CLEAR I CALL Stress_strain I IF Gin$="L" THEN COPY I END
  8   PRINT "Plot EPDOT_TIME on_",Gin$
 10   SET VIEWPORT 0,130,0,100 I INPUT PROMPT "NEW PAPER AND RETURN":A$
 11   CLEAR I CALL Epdot_t I IF Gin$="L" THEN COPY I END
 12   PRINT "Plot STRAIN_TIME on_",Gin$
 13   SET VIEWPORT 0,130,0,100 I INPUT PROMPT "NEW PAPER AND RETURN":A$
 14   CLEAR I CALL Epsilon_t I CALL X_ticlab(1.E+06,1,"Time(uSec)")
 15   CALL Y_ticlab(100,1,"Strain(%)") I IF Gin$="L" THEN COPY I END
 16   PRINT "Plot STRESS_TIME on_",Gin$
 17   SET VIEWPORT 0,130,0,100 I INPUT PROMPT "NEW PAPER AND RETURN":A$
 18   CLEAR I CALL Sigma_t I CALL X_ticlab(1.E+06,1,"Time(uSec)")
 19   CALL Y_ticlab(1,1,"Stress(MPa)") I IF Gin$="L" THEN COPY I END
 20   A$ = H$ & ".MOD" I PRINT "Saving Stress_Strain curve data in ",A$,"..."
 21   GOTO 4180 I END
 24   INP PRO "Send graphics to the Plotter, Laserwriter, Screen (P/L/S) : ":Gin$
 25   Gdevice$ = "" I IF Gin$="P" THEN Gdevice$ = "HPPLT=COM1:"
 26   IF Gin$="L" THEN Gdevice$ = "IBMPRN=D:" I SET GRAPH DEVICE Gdevice$
 27   SET TEXT SIZE 2,2 I SET LINE COLOR 1 I CALL Menu I END
 28   IF Gin$="L" THEN COPY I END
 40   CLEAR I CALL Menu
 41   END
100   ! -----------------------------------------------------------
105   INIT I CLEAR
110   Lf$ = CHR$(10) I Ashift$ = "Y" I Gin$ = "S" I Gdevice$ = ""
120   PRINT Lf$
210   OPEN #6:"LPT1","W"
220   Gin$ = "S" I INP PRO "Send graphics to the Plotter/Laser/Screen (P/L/S) : ":Gin$
225   SELECT CASE Gin$
230   CASE "P"
232       Gdevice$ = "HPPLT=COM1:"
233   CASE "L"
234       Gdevice$ = "IBMPRN=D:"
235   CASE ELSE
236       Gdevice$ = ""
237   END SELECT
238   SET GRAPH DEVICE ""
240   SET TEXT SIZE 2,2 I SET LINE COLOR 1
250   INPUT PROMPT "Enter data from file or Default file (F/D) : ":A$
260   IF A$="F" THEN
265       PRINT "Enter the Nicolet Data File Name (ex: d:\fname) "
270       INPUT PROMPT " (DO NOT ENTER EXTENSION-assumed .PRN) : ":H$
280   ELSE
290       H$ = "TB003"
300   END IF
310   He$ = H$ & ".PRN"
330   Dbar = 1.0 I Dout = 0.4 I Din = 0.37 I Lspec = 0.1 ! inches
335   Cl = 5036 I Cs = 3100 ! m/sec.
340   OPEN #7:He$,"F"
350   A$ = "K"!INP PRO "Bar and Spec. dimensions from file or keyboard-inches (F/K) : ":A$
360   IF A$="F" THEN
370       INPUT #7:Dout,Di,Lspec
380   ELSE IF A$="K" THEN
```

```
390      !INPUT PROMPT "Enter Dout, Din and Spec. length (in.): ":Dout,Din,Lspec
400   ELSE
410      GOTO 350
420   END IF
425   Dmspec = (Dout+Din)/2.0 I Th = (Dout-Din)/2.0 I Th = Th*0.0254
430   Dbar = Dbar*0.0254 I Dmspec = Dmspec*0.0254 I Lspec = Lspec*0.0254
435   Calib_a = 25000*(0.1*Dmspec/(0.385*Lspec))
436   Calib_b = 4.E+04*(0.385^2*0.015*0.0254^3/(Dmspec^2*Th))
440   Rbar = Dbar/2 I Areab = Pi/4*Dbar^2 I Areas = Pi/4*Dmspec^2
460   Delb = 48.5*0.0254 I Delc = 48.5*0.0254 I Dela = 59*0.0254
465   E = 7.1E+10 I G = 2.69E+10 ! MPa
470   Ro = 2800 I Adelt = 5.E-05
475   Cl = SQR(E/Ro) I Cs = 3100 ! CS =SQR(G/Ro) - m/sec.
477   Tshift = 2*Delb/Cs
480   Iread = 4094
490   ! READ NICOLET TWO WAVE-FORMS-----------------------------------
495   DIM Temp[2,Iread] I Temp = 0
507   ON EOF(7) GOTO 590
510   INPUT #7:T0,Temp[1,1],T0,Temp[2,1]
520   Xmin = T0/1.E+06 ! Seconds
530   Ofset1 = Temp[1,1] I Ofset2 = Temp[2,1]
545   INPUT #7:T,Temp[1,2],T,Temp[2,2]
546   Delt = (T-T0)*1.E-06 ! Seconds
560   FOR I = 3 TO Iread
570      INPUT #7:T,Temp[1,I],T,Temp[2,I]
580   NEXT I
590   CLOSE 7
595   Imax = I-1
597   DIM Wform[2,Imax],Temp0[Imax] I Wform = 0 I Temp0 = 0
600   FOR I = 1 TO Imax
610      Wform[1,I] = Temp[1,I]-Ofset1
620      Wform[2,I] = Temp[2,I]-Ofset2
630      Temp0[I] = Wform[1,I]
660   NEXT I
661   DELETE Temp
662   DIM Ep[3,Imax] I Ep = 0
670   ! -----------------------------------------
680   Xmax = T/1.E+06-Xmin I Xmin = 0 I Txmax = Xmax I Txmin = Xmin
690   Xran = Xmax-Xmin
700   CLEAR
760   CALL D_windows
780   Delt = Xran/(Imax-1) I Tmax = Txmax I Imaxp = INT(Tmax/Delt)
790   CALL P_MIN(Temp0,Ymin,Ypos) I Ymax = -Ymin ! CALL P_MAX(Temp0,Ymax,Ypos)
800   IMAGE 2D,6(4D.4D)
810   Delx = ABS(Xmax-Xmin) I Dely = ABS(Ymax-Ymin)
820   SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.1*Dely,Ymax+0.1*Dely
830   ! DRAW TWO NICOLET WAVEFORMS IN ACTUAL TIME SPACE-------------
840   SET VIEWPORT 0,65,50,100 I SET LINE COLOR 1 I SET LINE STYLE 0
850   MOVE GDU 129.2 I SET TEXT ALIGN 5,3 I SET TEXT SIZE 1.5,1.5
860   PLOT TEXT GDU H$ I SET TEXT ALIGN 0,0 I SET TEXT SIZE 2,2
870   CALL X_ticlab(1.E+06,1,"Time(uSec)") I CALL Y_ticlab(100,1,"Strain(%)")
880   AXIS Xinc,Yinc,0,0,3,3
890   FOR J = 1 TO 2
900      SET LINE COLOR J+1 I SET TEXT COLOR J+1
910      FOR I = 1 TO Imax
920         X = Xmin+(I-1)*Delt
930         Y = Wform[J,I]
940         IF I=1 THEN MOVE X,Y ELSE DRAW X,Y
950      NEXT I
960      IF J=1 THEN Title$ = " Ea,"
970      IF J=2 THEN Title$ = " Eb"
990      MOVE GDU 30+J*12,90
1000     PLOT TEXT GDU Title$
1010  NEXT J
```

```
1015   ! SHIFT REFLECTED AND TRANSMITTED WAVEFORMS AT B BY TRAVEL TIME
1017   MOVE Tshift,Ymin/2 I DRAW Tshift,Ymax/2
1020   IF Ashift$="Y" THEN
1022       PRINT "Twice the Time (uS) from A -> Specimen ";Tshift*1.E+06;
1024       INPUT PROMPT "Change the time (Y/N) ?":Ashift$
1026       IF Ashift$="Y" THEN
1028           INPUT PROMPT "Enter Time (uS) = ":Tshift I Tshift = Tshift/1.E+06
1030       ELSE
1032           SET GRAPH DEVICE Gdevice$
1034       END IF
1039       GOTO 700
1040   END IF
1042   Ishift = INT(Tshift/Delt)
1045   FOR I = Ishift TO Imax
1050       J = I-Ishift+1
1060       Ep[2,J] = Wform[1,I]
1065       Ep[3,J] = Wform[2,I]
1070   NEXT I
1072   FOR I = 1 TO Imax
1073       Ep[1,J] = Wform[1,I]
1074   NEXT I
1080   Itest = Imax-Ishift+1
1110   ! PLOT THE SHIFTED WAVEFORMS---------------------------------------
1120   SET VIEWPORT 0,65,0,50 I SET LINE COLOR 1 I SET LINE STYLE 0
1130   MOVE GDU 129,2 I SET TEXT ALIGN 5,3 I SET TEXT SIZE 1.5,1.5
1140   PLOT TEXT GDU H$ I SET TEXT ALIGN 0,0 I SET TEXT SIZE 2,2
1150   CALL X_ticlab(1.E+06,1,"Time(uSec)") I CALL Y_ticlab(100,1,"Strain(%)")
1160   AXIS Xinc,Yinc,0,0,3,3
1170   FOR J = 1 TO 3
1180       SET LINE COLOR J+1 I SET TEXT COLOR J+1
1190       FOR I = 1 TO Itest
1200           X = Xmin+(I-1)*Delt
1210           Y = Ep[J,I]
1220           IF I=1 THEN MOVE X,Y ELSE DRAW X,Y
1230       NEXT I
1240       IF J=1 THEN Title$ = " E-ins,"
1250       IF J=2 THEN Title$ = " E-ref,"
1260       IF J=3 THEN Title$ = " E-trn"
1270       MOVE GDU 30+J*12,90 I PLOT TEXT GDU Title$
1280   NEXT J
2330   !EpIns, EpRef, EpTm and (EpIns+EpRef)--------------------------------
2340   SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.1*Dely,Ymax+0.1*Dely
2350   SET VIEWPORT 65,130,0,50 I SET LINE COLOR 1 I SET LINE STYLE 0
2360   MOVE GDU 129,2 I SET TEXT ALIGN 5,3 I SET TEXT SIZE 1.5,1.5
2370   PLOT TEXT GDU H$ I SET TEXT ALIGN 0,0 I SET TEXT SIZE 2,2
2380   CALL X_ticlab(1.E+06,1,"Time(uSec)") I CALL Y_ticlab(100,1,"Strain(%)")
2390   PLOT AXIS Xinc,Yinc,0,0,3,3
2400   FOR J = 1 TO 4
2410       SET LINE STYLE 0 I SET LINE COLOR J+1 I SET TEXT COLOR J+1
2420       FOR I = 1 TO Itest
2430           X = Xmin+(I-1)*Delt
2440           IF J<>4 THEN Y = Ep[J,I] ELSE Y = -(Ep[1,I]+Ep[2,I])
2450           IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
2460       NEXT I
2470       IF J=1 THEN Title$ = " EpIns,"
2480       IF J=2 THEN Title$ = " EpRef,"
2490       IF J=3 THEN Title$ = " EpTm,"
2500       IF J=4 THEN Title$ = " EpIns+EpRef"
2510       MOVE GDU 5+(J-1)*23,90 I PLOT TEXT GDU Title$
2520   NEXT J
2525   IF Gin$="L" THEN COPY else INPUT PROMPT "New paper AND Press ENTER":A$
2540   CLEAR I CALL D_windows
2550   ! Computation of Sigma, Epdot AND Epsilon----------------------------
2555   DELETE Wform,Temp0
```

```
2560    DIM  Sigma[Itest],Epdot[Itest],Epsilon[Itest],Asigma[Itest]
2570    FOR I = 1 TO Itest
2580        Asigma[I] = -Calib_b*(-(Ep[1,I]+Ep[2,I])+Ep[3,I])/2
2590        Sigma[I] = -Ep[3,I]*Calib_b        ! ((G*dbar) / ( (8*dmspec^2) *th) )
2600        Epdot[I] = -Calib_a*Ep[2,I]        ! ((2*Cs*dmspec)/(lspec*dbar))
2610    NEXT I
2620    ! Compute Epsilon by Integrating Epdot----------------------------
2630    Epsilon[1] = (Epdot[1]+Epdot[2])*0.5*Delt
2640    FOR I = 2 TO Itest-1
2650        Epsilon[I] = Epsilon[I-1]+Delt*0.5*(Epdot[I]+Epdot[I+1])
2660    NEXT I
2670    Epsilon[Itest] = Epsilon[Itest-1]
2680    ! Epdot-Time Plot-----------------------------------------------
2690    SET VIEWPORT 0,65,50,100 I CALL Epdot_t
2700    ! Sigma-Time Plot-----------------------------------------------
2710    SET VIEWPORT 0,65,50,100 I CALL Sigma_t
2720    SET VIEWPORT 65,130,50,100 I CALL X_ticlab(1.E+06,1,"Time(uSec)")
2730    CALL Y_ticlab(1,1,"Stress(MPa)") I CALL Sigma_t
2740    ! Epsilon-Time Plot--------------------------------------------
2750    SET VIEWPORT 0,65,50,100 I CALL Epsilon_t
2760    SET VIEWPORT 65,130,0,50 I CALL X_ticlab(1.E+06,1,"Time(uSec)")
2770    CALL Y_ticlab(100,1,"Strain(%)") I CALL Epsilon_t
2780    ! Sigma-Epsilon plot------------------------------------------
2790    SET VIEWPORT 0,65,0,50
2800    CALL P_MIN(Sigma,Ymin,Ypos) I CALL P_MAX(Sigma,Ymax,Ypos)
2810    CALL P_MIN(Epsilon,Xmin,Ypos) I CALL P_MAX(Epsilon,Xmax,Ypos)
2825    CALL Stress_strain
2826    IF Gin$="L" THEN COPY I PRINT Lf$ I PRINT "F10 for Menu"
2827    END
2828    ! Sigma-Epsilon plot------------------------------------------
2829    SUB Stress_strain
2830        Delx = ABS(Xmax-Xmin) I Dely = ABS(Ymax-Ymin)
2840        SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
2850        SET LINE STYLE 0 I SET LINE COLOR 1
2860        CALL X_ticlab(100,1,"Strain(%)") I CALL Y_ticlab(1,1,"Stress(MPa)")
2870        AXI Xinc,Yinc,0,0,3,3 I SET LIN STY 0 I SET LIN COL 5 I SET TEX COL 5
2880        FOR I = 1 TO Itest-1
2890            X = Epsilon[I] I Y = Sigma[I]
2900            IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
2910        NEXT I
2920        ! SET LINE STYLE 1 I SET LINE COLOR 1
2930        ! FOR I = 1 TO itest-1
2940            ! X = Epsilon[I] I Y = Asigma[I]
2950            ! IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
2960        ! NEXT I
2970        Title$ = "Sigma(MPa)_Epsilon(%)" I SET TEXT COLOR 1
2980        SET LINE STYLE 0 I MOVE GDU 40,90 I PLOT TEXT GDU Title$
2990        MOVE GDU 129,2 I SET TEXT ALIGN 5,3 I SET TEXT SIZE 1.5,1.5
3000        PLOT TEXT GDU H$ I SET TEXT ALIGN 0,0 I SET TEXT SIZE 2,2
3020    END SUB
3690    ! ----------------------------------------------------------
3700    SUB D_windows
3710        CLEAR I SET LINE STYLE 0 I SET LINE COLOR 2
3720        SET VIEWPORT 0,130,0,100 I SET WINDOW 0,130,0,100
3730        MOVE 0,0 I DRAW 0,0;130,0;130,100;0,100;0,0
3740        MOVE 65,0 I DRAW 65,100 I MOVE 0,50 I DRAW 130,50
3750    END SUB
3760    ! ----------------------------------------------------------
3770    SUB X_ticlab(Xmul,Tcol,Xlabel$)
3780        SET TEXT COLOR Tcol I SET CLIP OFF
3790        X = LOG10(Xmax) I Xinc = INT(X) I Xinc = 10^Xinc
3800        IF Xmax>5*Xinc THEN
3810            Xiinc = 2
3820        ELSE IF Xmax>2.5*Xinc THEN
```

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```
3830          Xiinc = 1
3840      ELSE
3850          Xiinc = 0.5
3860      END IF
3870      I = 0 I SET TEXT ALIGN 3,0
3880      DO
3890          MOVE I*Xinc,-0.05*Dely I PLOT TEXT GDU I*Xinc*Xmul
3900          IF (I+Xiinc)*Xinc>Xmax THEN EXIT
3910          I = I+Xiinc
3920      LOOP
3930      SET TEX ALI 3,3 I MOV Xmin+0.5*Delx,-0.1*Dely I PLO TEX GDU Xlabel$
3940      SET TEXT ALIGN 0,0 I SET CLIP ON
3950  END SUB
3960  ! --------------------------------------------------------------
3970  SUB  Y_ticlab(Ymul,Tcol,Ylabel$)
3980      SET TEXT COLOR Tcol I SET CLIP OFF
3990      Y = LOG10(Ymax) I Yinc = INT(Y) I Yinc = 10^Yinc
4000      IF Ymax>5*Yinc THEN
4010          Yiinc = 2
4020      ELSE IF Ymax>2.5*Yinc THEN
4030          Yiinc = 1
4040      ELSE
4050          Yiinc = 0.5
4060      END IF
4070      I = 0 I SET TEXT ALIGN 5,3
4080      DO
4090          MOVE 0,I*Yinc I PLOT TEXT GDU I*Yinc*Ymul
4100          IF (I+Yiinc)*Yinc>Ymax THEN EXIT
4110          I = I+Yiinc
4120      LOOP
4130      SET TEXT ALIGN 3,3 I SET TEXT ANGLE 90
4140      MOVE -0.17*Delx,Ymin+0.5*Dely I PLOT TEXT GDU Ylabel$
4150      SET TEXT ANGLE 0 I SET TEXT ALIGN 0,0 I SET CLIP ON
4160  END SUB
4170  ! --------------------------------------------------------------
4180  A$ = HS & ".MOD" I OPEN #7:A$,"F"
4190  FOR I = 1 TO Itest
4200      ! IF Epsilon[I]>0.6 OR Sigma[I]>100 THEN GOTO 4230
4210      PRINT #7:(i-1)*delt*1e6;Epsilon[I];Sigma[I];epdot[i]
4220  NEXT I
4230  CLOSE 7
4240  END
4250  ! --------------------------------------------------------------
4260  SUB Epdot_t
4270      CALL P_MIN(Epdot,Ymin,Ypos) I CALL P_MAX(Epdot,Ymax,Ypos)
4280      Xmax = Txmax I Xmin = Txmin
4290      Delx = ABS(Xmax-Xmin) I Dely = ABS(Ymax-Ymin)
4300      SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
4310      SET LIN COL 2 I SET LIN STY 0 I CAL X_ticlab(1.E+06,1,"Time(uSec)")
4320      CAL Y_ticlab(1,2,"Strain Rate(1/Sec)") I PLO AXI Xinc,Yinc,0,0,3,3 I SET TEX COL 2
4330      SET LINE STYLE 0 I SET LINE COLOR 2 I SET TEXT COLOR 2
4340      FOR I = 1 TO Itest
4350          X = Xmin+(I-1)*Delt I Y = Epdot[I]
4360          IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4370      NEXT I
4380      Title$ = "StrainRate_t"
4390      MOVE GDU 87,90 I PLOT TEXT GDU Title$
4400      MOVE GDU 129,2 I SET TEXT ALIGN 5,3 I SET TEXT SIZE 1.5,1.5
4410      PLOT TEXT GDU HS I SET TEXT ALIGN 0,0 I SET TEXT SIZE 2,2
4420  END SUB
4430  ! MENU --------------------------------------------------------------
4435  SUB Menu
4440      PRINT L$
4450      PRINT "F1  - Plot STRESS_STRAIN Curve"
```

```
4460        PRINT "F2 - Plot EPDOT_TIME Curve"
4470        PRINT "F3 - Plot STRAIN_TIME Curve"
4480        PRINT "F4 - Plot STRESS_TIME Curve"
4490        PRINT "F5 - Write STRESS_STRAIN Data to a Disk File"
4500        PRINT "F6 - Select Graphic Device"
4505        PRINT "F7 - Print Graph to the Laserwriter"
4510        PRINT "F10 - MENU"
4530    END SUB
4540    ! ------------------------------------------------------------------
4550    SUB Sigma_t
4560        CALL P_MIN(Asigma,Yi1,Ypos) I CALL P_MAX(Asigma,Ya1,Ypos)
4570        CALL P_MIN(Sigma,Yi2,Ypos) I CALL P_MAX(Sigma,Ya2,Ypos)
4580        Ymin = MIN(Yi1,Yi2) I Ymax = MAX(Ya1,Ya2)
4590        Delx = ABS(Xmax-Xmin) I Dely = ABS(Ymax-Ymin)
4600        SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
4610        SET LINE COLOR 3 I SET LINE STYLE 0
4620        Y = LOG10(Ymax) I Yinc = INT(Y) I Yinc = 10^Yinc
4630        X = LOG10(Xmax) I Xinc = INT(X) I Xinc = 10^Xinc
4640        PLOT AXIS Xinc,Yinc,0,0,3,3 I SET LINE COLOR 3 I SET TEXT COLOR 3
4650        FOR I = 1 TO Itest
4660            X = Xmin+(I-1)*Delt I Y = Sigma[I]
4670            IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4680        NEXT I
4690        Title$ = "Stress_Time" I SET LIN STY 0 I MOV GDU 87,85 I PLO TEX GDU Title$
4700        SET TEXT COLOR 1 I SET LINE COLOR 1
4710        FOR I = 1 TO Itest
4720            X = Xmin+(I-1)*Delt I Y = Asigma[I]
4730            IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4740        NEXT I
4750        Title$ = "AvStress_Time" I MOVE GDU 87,80 I PLOT TEXT GDU Title$
4760        MOVE GDU 129,2 I SET TEXT ALIGN 5,3 I SET TEXT SIZE 1.5,1.5
4770        PLOT TEXT GDU H$ I SET TEXT ALIGN 0,0 I SET TEXT SIZE 2,2
4780    END SUB
4790    ! ------------------------------------------------------------------
4800    SUB Epsilon_t
4810        CALL P_MIN(Epsilon,Ymin,Ypos) I CALL P_MAX(Epsilon,Ymax,Ypos)
4820        Delx = ABS(Xmax-Xmin) I Dely = ABS(Ymax-Ymin)
4830        SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
4840        SET LINE COLOR 4 I SET LINE STYLE 0
4850        PLOT AXIS Xinc,1,0,0,3,3 I SET TEXT COLOR 4
4860        FOR I = 1 TO Itest
4870            X = Xmin+(I-1)*Delt I Y = Epsilon[I]
4880            IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4890        NEXT I
4900        Title$ = "Strain_Time" I MOVE GDU 87,75 I PLOT TEXT GDU Title$
4910        MOVE GDU 129,2 I SET TEXT ALIGN 5,3 I SET TEXT SIZE 1.5,1.5
4920        PLOT TEXT GDU H$ I SET TEXT ALIGN 0,0 I SET TEXT SIZE 2,2
4930    END SUB
4940    ! ------------------------------------------------------------------
```

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THE MTL TORSIONAL SPLIT-HOPKINSON BAR -
Tusit Weerasooriya

Key Words

Torsion
Shear properties
Hopkinson bar

Technical Report MTL TR 90-27, May 1990, 29 pp-
illus, D/A Project: 2102040064-8929 P61102
AMCMS Code: 611102.H420011

A Stored Torque Split-Torsional Hopkinson bar (THBar) was developed (based on the principle of the one located at Brown University) and constructed at the U.S. Army Material Technology Laboratory (MTL). This report provides a detailed description of the THBar and its shear, axial and bending characteristics, and use of it to generate high strain rate shear stress-strain data of annealed OFHC copper (99.99% copper). With the present clamp of the THBar, shear stress-strain data can be generated for strain rates from 200 to 1300 s⁻¹. At the highest strain rate, a specimen can be deformed in shear to a maximum strain of 85% with the shear pulse of 655 µs. Three tests have been conducted for copper at strain rates of 400, 800, and 1200 s⁻¹. The shear stress-strain curves that have been generated at these three strain rates show a strain rate sensitivity for strains less than 35%; stress increases with strain rate for a constant strain. At higher strain rates and higher strains (greater than 35% strains), shear stress saturates to a constant value independent of the strain rate. High strain rate, shear stress-strain data correlate favorably with the trend found in the quasi-static rate data from a servohydraulic test machine.