PREPRINT UCRL- 81124

CONF-780565--1

Lawrence Livermore Laboratory

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MAY 15, 1978

SESA 1978 SPRING MEETING, WICHITA, KS
MAY 15-19, 1978

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A method is described for the measurement of the acoustic velocity across the diameter of a 1 mm diam liquid metal column before instability and breakup of the column occurs.

ABSTRACT

Present techniques for measuring sound velocity in liquid metals have been limited by the use of transducers which cannot survive in extreme temperature conditions. These methods also require relatively long measurement times. An optical noncontacting method has been developed which may be used for extremely short experimental times and very high temperatures and pressures. This technique is being incorporated into an isobaric expansion apparatus in which a 1 mm diam wire sample in a high pressure argon gas environment is resistively heated to melt within a time period of only a few microseconds. Before instability of the liquid column occurs, thermal expansion, enthalpy, and temperature are measured. The addition of the sound velocity measurement permits a more complete determination of the thermophysical properties of the liquid metal.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-Eng-48.

INTRODUCTION

The dilatation and shear wave velocities are usually measured by techniques employing piezoelectric transducers as in the through-transmission and pulse-echo methods.[1] There are several obvious limitations to this and similar approaches. First, flat and smooth specimen surfaces are required to permit direct contact with the transducers. Second, the specimen thickness and radius must be such that transducer ringing, edge effects, and successive echoes of the main pulse do not overlap so that signal interpretation becomes difficult. Finally, piezoelectric transducers do not survive well in severe environments and require relatively long measurement times.

These difficulties were encountered when trying to find a method to measure the acoustic velocity across the diameter of a 1 mm diam column of liquid metal under high pressure. This sound velocity measurement is needed to provide additional thermophysical property data for liquid metals obtained from an isobaric expansion apparatus.[2] In this experiment a specimen about the diameter of a common paperclip and 25 mm long is subjected to rapid resistance heating by current dumped from a large capacitor bank. Required measurements are recorded a few microseconds following specimen melt and before instability and breakdown of the molten column occurs. The isobaric expansion apparatus allows determination of pressure, density, enthalpy, temperature and electrical resistivity to be made simultaneously. These data can be used to determine specific heat and the bulk thermal expansion coefficient for the liquid. Measurement of sound velocity would allow the additional determination of the Gruneisen parameter, the specific heat at constant volume, and the

adiabatic and isothermal compressibility of the liquid metal. A successful solution to the acoustic velocity measurement was developed using a noncontact optical technique consisting of pulsed laser deposition loading and displacement interferometry. A high power, Q-pulsed laser beam is focused on one side of the specimen, initiating a stress pulse traveling across the diameter.[3,4] The stress pulse arrival on the opposite side of the specimen diameter is recorded using a Michelson displacement interferometer. The measured transit time of the stress pulse and the diameter of the metal column leads directly to the acoustic velocity.

NONCONTACT TESTING USING LASERS

The absorption of radiation from a high energy, Q-pulsed laser in a thin surface layer of a target material can produce a relatively large stress pulse which propagates into the material. The rapid vaporization of the target surface skin produces a strong transient pressure build up against the target surface due to recoil from the blowoff of the plasma. The plasma blowoff in turn drives a compressive stress pulse into the solid. Moderate size lasers producing several Joules of energy have induced stress pulses with amplitudes approaching the yield stress of many metals and durations on the order of 100-200 nanoseconds. The latter is equivalent to a pulse length of about 1 mm in most metals.

Completely noncontact testing is made possible by using a Michelson displacement interferometer to sense the stress wave arrivals at the specimen surface . This surface becomes the moving mirror of the interferometer. A single frequency, CW laser is focused to a point on the lateral surface of the rod. The interference of the reflected signal beam with the reference beam from a fixed mirror produces a series of

light and dark fringes. Slight movement of the surface causes fringe movement to occur which can be accurately monitored with a photomultiplier tube (PMT) and associated instrumentation. A displacement of $\lambda/2$ where λ is the laser wavelength, produces a fringe shift of one cycle. For an argon-ion laser operating at 0.5145 μm, a displacement of only 0.2572 μm, will result in a fringe movement of one cycle. In the present application times of arrival of transient displacements, rather than the displacement amplitudes, are required. Therefore, displacements producing a fraction of a fringe cycle movement can be easily detected.

A typical arrangement for noncontact testing is shown in Fig. 1. The energy from a Q-pulsed laser is deposited on the surface of the specimen, driving a stress pulse into it. The photodiode triggers a digital delay unit which triggers the scope sweep after a preset delay time. The far surface of the specimen acts as the moving mirror of the Michelson interferometer shown. The transient displacement is converted to a voltage output by the PMT and the output recorded on a fast response oscilloscope.

TIME INTERVAL MEASUREMENT CONSIDERATIONS

The transit time of a stress pulse through 1 mm of liquid metal is only a few hundred nanoseconds. Therefore, inherent delays in the scope triggering and vertical input, transit time through the PMT, electrical and optical path travel time, and effective start time of the stress pulse can have a significant effect on the measured transit time. For example, the trigger circuit and vertical amplifier of the scope used in this study had electrical delay times of 40 ns and 80 ns, respectively and the PMT had a transit time of 30 ns. The timing was calibrated by placing a thin plate of high purity oxygen free copper of known dilatational velocity in place of the specimen of Fig. 1 and adding a second

slideglass beamsplitter at the high energy input to provide a marker fiducial superposed on the photomultiplier signal output from the interferometer. This procedure provided data on the stress initiation time and eliminated all timing considerations except the difference in optical path lengths. Results were recorded using a high frequency response oscilloscope. The details of the timing calibration are shown in Fig. 2. The optical path from the first beam splitter to the PM tube was .46 m shorter than the air path via the interferometer, so the Nd-G laser pulse appeared 1.5 ns early on the oscilloscope record shown. The average value for the velocity of sound at room temperature for copper was taken to be 4740 m/sec for compressional waves in an infinite medium.[5] The copper plate was 0.91 mm thick, so the expected transit time was 192 ns. Therefore, the apparent time of start of the stress pulse on the record is obtained by measuring back 190.5 ns from the breakout of the interferometer signal, as indicated by the arrows. Thus, the effective time of stress wave initiation is at about the half-amplitude point of the beginning of the Nd-G laser pulse. Similar results were obtained from tests on thin sheets of aluminum, steel, and beryllium. The nominal sweep rate shown was 50 ns/div. The results appear to be repeatable to within ~ ±5 ns.

It was necessary to make a compromise in choosing the spot size used for the energy deposition on the 1 mm diameter specimen rod. A very precisely focused spot results in a sharp signal arrival, but the peak displacement amplitude is greatly reduced because energy from the Nd-G laser is expended in drilling a hole in the specimen. A broadly focused beam on the other hand leads to a strong displacement signal, but signal arrival becomes distorted. The best compromise for 1 mm diameter samples appears to be a spot size of ~ 0.5 mm diameter.

The interferometer was adjusted so that the two arms had nearly equal path length and beam intensity. This results in large, high contrast fringes at the photomultipler tube. The displacement signal sensitivity depends upon the position of the fringe pattern at the precise instant of the test. If it is close to a maximum or minimum, the sensitivity is low. This problem can be eliminated by using a quadrature system with the second signal shifted 90° so one detector will always respond at high sensitivity.

EXPERIMENTAL PROCEDURE

To test the proposed technique an aluminum mock-up of the inner portion of the isobaric expansion pressure cell was fabricated. This held the sapphire pressure windows and one of the sample-holding anvils complete with electrodes and cylindrical current return cap used in the actual system. The hardware is shown in Fig. 3.

A top view of the mock-up pressure cell containing the 1 mm diam specimen is shown in Fig. 4 with the associated optical setup. The energy from a high-power, Q-switched Nd-G laser (8J, 30 ns) is directed through a collimating aperature (1), a sapphire pressure window (2), and then is focused by lens (3) on a spot (0.2 mm diameter) on the surface of the 1 mm diam cylindrical sample (4). A stress pulse is generated in the sample by surface pressure produced from plasma blowoff.

The stress pulse propagates to the diametrically opposite surface which acts as the moving mirror of the Michelson interferometer. Light from an argon ion laser is directed through lens (5), the sapphire window (2), aperature (6) and focused on the sample (4). Figure 5 shows a close up view of the specimen and holder. The interferometric beam enters from the right side and the high energy beam from the left. The self-illuminating plasma blowoff appears just to the left of the specimen. The laser beam reflection

from the specimen is combined with a reference beam from the other leg of the interferometer. The sudden fringe shift produced in the interferometer when the stress pulse arrives is observed with a pulsed photomultiplier tube. The time of energy deposition is determined from a fiducial generated as described in the timing calibration (Fig. 2). The transit time for the pulse is determined by displaying the signals on a fast oscilloscope. The samples diameter during the transit time can be accurately determined from a streak camera record so that the propagation velocity can be calculated. The energy density deposited by the Nd-G laser must be restricted so that the weak shock wave generated will have a velocity close to the longitudinal sound speed.

A variety of solid metals were tested in the mock-up system including tungsten, tantalum, copper, iron and lead. The principal operational differences were due to the different reflectivities and surface conditions of the samples. Adequate interferometric fringes for reasonably good signal-to-noise data were obtained for each solid metal. The accurate location of the high-energy deposition spot directly opposite the spot viewed by the interferometer was found to be very important. The stress pulse amplitude is rapidly reduced if this alignment is not good and the distance traveled by the stress pulse becomes different from the specimen diameter.

LIQUID LEAD TEST

To check out the method for acoustic velocity measurement in liquid metals, lead specimens were chosen for testing due to the relatively low energy required to obtain melt. Experiments were first conducted on solid lead rods and subsequently on lead rods liquefied by the high current

pulse from a 20-kV capacitor bank discharge. The stress transit time measurement was made a few microseconds following melt. Typical specimen voltage and current histories are shown in Fig. 6. The initiation of specimen melt begins about 8 μs after dumping the capacitor bank across the specimen. Melt is completed about 1.5 μs later and the capacitor bank is shorted at 12 μs. At 5 μs after bank crowbar, the acoustic velocity measurement is made. This time was chosen to be sufficiently long for the liquid column to come to thermal equilibrium but before instability and breakup occur.

Scope data traces are shown in Fig. 7 for solid and liquid lead tests. As in the timing calibration, the fiducial is simply a reference marker for the occurance of the high-energy laser pulse. The measured acoustic velocity across the 1 mm diam of the solid specimen was found to be 2.38 mm/μs, slightlyhigher than an average value of 2.21 mm/μs taken from Ref. 5. As would be expected, there was a considerable drop in velocity for the liquid lead test. The measured liquid-lead acoustic velocity of 1.80 mm/μs agreed very well with a published value at melt of 1.78 mm/μs.[6]

Some surface motion was noted to occur before the arrival of the stress pulse in all the liquid-lead tests. This was probably due to small perturbations induced by the rapid melting of the specimen. In several tests the disturbance was severe enough to obscure the clear arrival of the stress pulse. This problem may be alleviated by waiting longer after crowbar to make the acoustic velocity measurement.

CONCLUSIONS

The noncontact method described using laser energy deposition and displacement interferometry provides a unique method for the measurement of acoustic velocity in liquid metals. This approach yields information not obtainable by conventional techniques. The capability is being permanently installed as an integral part of an isobaric expansion experiment apparatus. This addition will provide a more complete determination of the thermophysical properties of liquid metals.

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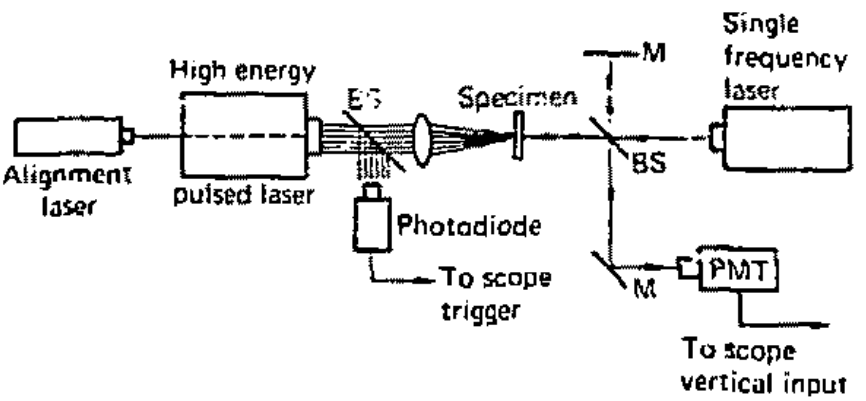

Fig. 1. Typical noncontact test setup using high energy and CW lasers.

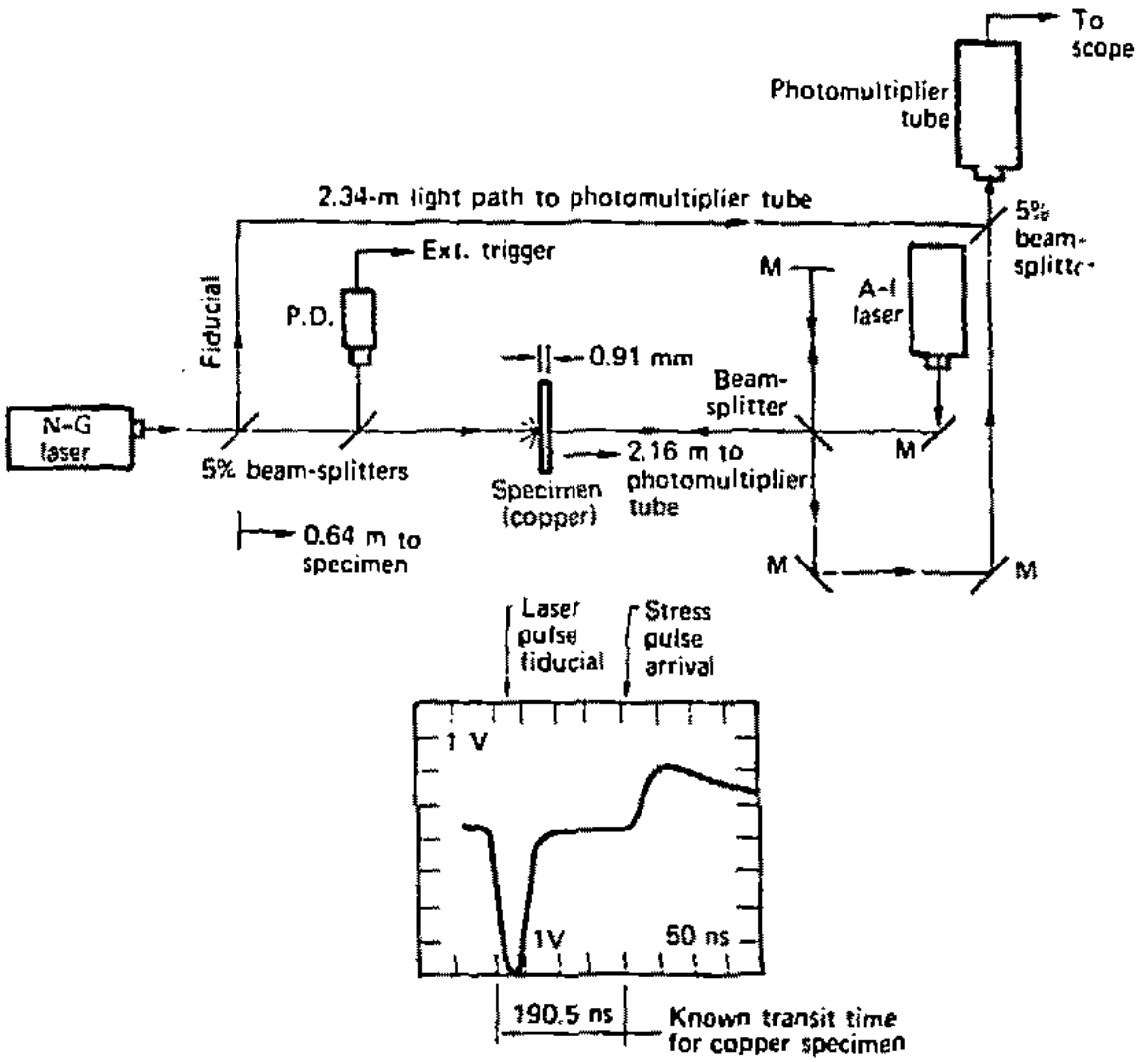

Fig. 2. Stress-initiation time calibration.

Fig. 3. Photograph of isobaric expansion test hardware. Specimen and anvil on right are inserted into current return cap in center and combined unit is placed into aluminum mockup of pressure cell on left.

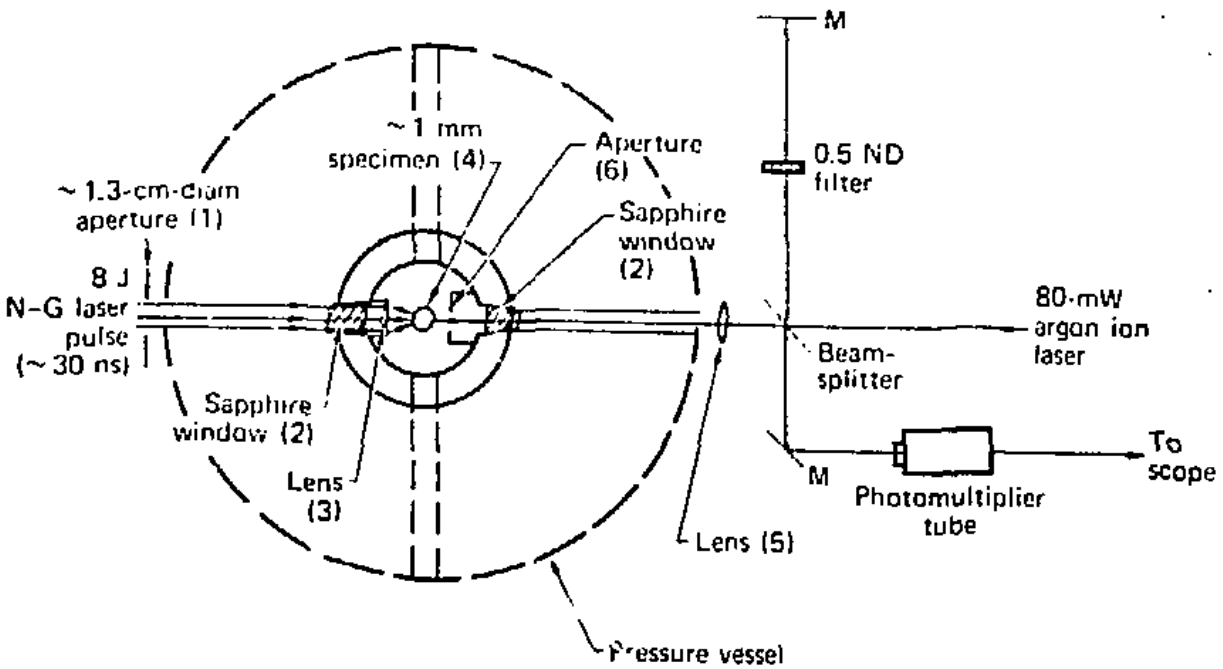

Fig. 4. Top view of isobaric expansion pressure cell and optical arrangement for acoustic velocity measurement.