AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

**DEVELOPMENT AND EVALUATION OF A WORKPIECE
TEMPERATURE ANALYZER FOR INDUSTRIAL FURNACES**

By: J. W. Berthod

June 1993

Work Performed Under Contract No. DE-FC07-89ID12875

**Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Sponsored by the Office of the Assistant Secretary
for Conservation and Renewable Energy
Office of Industrial Technologies
Washington, D.C.**

**Prepared by
The Babcock & Wilcox Company
Research and Development Division
Alliance Research Center
Alliance, Ohio 44601**

TABLE OF CONTENTS

	<u>Page</u>
1.0 EXECUTIVE SUMMARY	-1-
1.1 INTRODUCTION	-1-
1.2 BACKGROUND	-1-
1.3 GOAL	-2-
1.4 WORK PERFORMED	-2-
1.5 SUMMARY OF RESULTS	-2-
1.6 CONCLUSIONS AND RECOMMENDATIONS	-3-
2.0 TEST PLANS AND TEST REPORTS	-4-
2.1 PROOF-OF-CONCEPT TEST PLAN	-5-
2.1 JOHNS HOPKINS UNIVERSITY PROOF-OF-CONCEPT TEST REPORT	-14-
2.3 PHASE IA TEST PLAN	-37-
2.4 JOHNS HOPKINS UNIVERSITY PHASE IA TEST REPORT	-46-

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

The current industrial practice for controlling the operation of steel processing furnaces relies on measurements of furnace gas temperature and workpiece surface temperature¹. If the workpiece internal temperature is desired, it must be estimated from calculations which use the gas temperature and workpiece surface temperature to infer the average internal temperature of the workpiece. This can lead to considerable errors in estimation. The desirability of an effective workpiece temperature analyzer is reflected in the ongoing effort in industry to use non-contact methods to accurately measure the temperature distribution of a steel workpiece as it undergoes processing inside a furnace². Energy savings, improved product quality and productivity improvements are just a few of the benefits that would be expected from a WPTA system.

The results reported here are significant. The technology of laser generation and detection of ultrasound is very promising for measurement of the internal temperature of hot steel workpieces. Results show the feasibility of making such measurements at temperatures above 1250°C (2282°F).

1.2 BACKGROUND

In July 1989, Babcock & Wilcox (B&W) was contracted by the United States Department of Energy (DOE) to perform Phase I of a Research & Development (R&D) program on a Workpiece Temperature Analyzer (WPTA) System for Industrial Furnaces. The objective of the Phase I effort was to develop, evaluate and recommend remote acoustic concepts for measuring the internal temperature of steel workpieces undergoing processing within an industrial furnace. In addition, the Phase I effort was to determine the economic benefits which would be derived from such a system and the steel industry's interest in the commercial availability of a WPTA. The results and conclusions drawn from the Phase I effort were to be used to determine the desirability of pursuing this concept for further development, laboratory testing, prototype construction, and field testing.

The Steel Industry Survey, which included the economic analysis was reported in February, 1990 (DE91-013138). The Phase I Concept Development and Technical Evaluation was completed and reported in March, 1990 (DE91-013285). A Phase I Final Report was completed in April, 1991 (DE91-01319). The Final Report included results of proof-of-concept tests, two reports related to the attenuation of ultrasound in hot steel, a summary of acoustic attenuation effects by Dr. Donald M. Boyd, and a laser safety white paper.

¹ T. A. Gasper and H. W. Lownie, "Research Options for the Development of Sensors to Measure the Thermal State of Solid Steel Bodies," Final Report PNL-4592, DE83007253, Battelle Columbus Laboratories, February 1983.

² A. S. Chance, H. R. Hazard, A. Levy, A. C. Thekdi, and E. W. Ungar, "Combustion Research Opportunities for Industrial Applications," Final Report DOE/ID-10204, May 31, 1988.

The purpose of this Test Report is to summarize the results of additional laboratory tests recently performed and to compile all the past test results in one report volume.

1.3 GOAL

The overall program goal of this multi-phase project is to commercialize a WPTA system whose industrial use would offer significant advantages in terms of energy savings and other manufacturing and processing cost savings compared to conventional techniques. The goals for the Phase I effort were to determine whether a WPTA system would be commercially justified and, if so, to conceptually develop a system which could reliably measure the internal workpiece temperature in an industrial environment. Both these goals were met. In addition, laboratory tests were conducted which demonstrated the feasibility of generating and detecting ultrasonic waves in metal alloys at high temperatures. The goal for the second series of Phase IA laboratory tests was to extend laser generation and detection of ultrasound to as high a temperature as possible.

1.4 WORK PERFORMED

Proof-of-concept tests were performed using equipment based on the preliminary design of the WPTA. Typical steel billets were supplied by the Timken Company. Tests were performed at Johns Hopkins University. The purposes of these tests were to determine whether ultrasound energy could be generated, propagated through and detected in typical steel specimens at temperatures up to approximately 1020°C (1868°F). Additional objectives of this testing were to identify the optimum laser power density, to define the laser energy versus surface displacement relationship, and to identify the frequency range for optimum detection.

Additional follow-on tests were conducted in 1992 at Johns Hopkins University. The purpose of these tests was to extend the upper temperature limit for laser generation and detection of ultrasound, with the goal of achieving operation at or above maximum steel forging temperatures. In addition, the WPTA performance limits (sample thickness, maximum temperature) and methods to circumvent these limits were identified, and a steel specimen specially prepared by DOE was tested.

1.5 SUMMARY OF RESULTS

For the proof-of-concept tests, five cylindrical specimens of alloy 8620 were tested. These specimens ranged in diameter from approximately 73 mm (2.9 inches) to 267 mm (10.5 inches). These specimens were subjected to a series of laser ultrasound experiments. All specimens were subjected to room temperature tests by generating ultrasound across the diameter via a nominal 1.0 Joule Nd-YAG laser and detecting the ultrasound using a Michelson interferometer setup. One specimen with a nominal 73 mm diameter and one specimen with a nominal 124 mm diameter (4.9 inches) were also tested at temperatures up to approximately 1020°C (1868°F).

The results of the proof-of-concept tests indicated that, at room temperature, the ultrasound transmission was easily detected even

passing twice through the thickest specimen (total travel about 21 inches) with a signal-to-noise ratio of at least 10 to 1. However, as the temperature was increased, the signal was lost. It was postulated that the attenuation increased faster than exponentially so that the echo from even the smallest diameter specimen was undetectable above 700°C (1292°F).

In the subsequent follow-on tests, ultrasound detection was performed with the preferred Fabry-Perot interferometer rather than the Michelson interferometer used previously. The Fabry-Perot interferometer is preferred because of its ability to work on non-specular surfaces. Nominal 6 mm (0.25 inch) thick samples of alloy 8620 (two samples) and alloy 4620 (one sample) were tested. One of the alloy 8620 samples was prepared in the DOE Idaho National Engineering Laboratory metallurgical laboratory.

In the follow-on tests, laser generated ultrasound was detected at temperatures above 1250°C (2282°F). This temperature is believed to be the maximum internal metal temperature required for reheating in any present-day forging operation. This result is the first known demonstration of laser generation of ultrasound at such extreme temperatures.

1.6 CONCLUSIONS AND RECOMMENDATIONS

The feasibility of high-temperature WPTA operation was demonstrated, but the sample thicknesses (0.25 inch) were too thin to be practical for forging operations where minimum workpiece thickness is about two inches. However, it is straightforward to identify system improvements that could be made, and to predict the metal thickness through which laser generated ultrasound measurement could be used to obtain internal metal temperature to 1250°C (2282°F). The system improvements are listed below and could be implemented with known methods by Johns Hopkins University in the present WPTA laboratory test setup.

- Increase energy of generation laser
- Perform signal averaging
- Repetitively pulse generation laser

With these improvements, we conservatively estimate that laser generated ultrasound could be detected through a three-inch specimen of alloy 8620 at 1250°C (2282°F).

B&W recommends that DOE fund additional work to do further investigation of laser generation of ultrasound prior to initiation of Phase II development of a WPTA prototype. The scope of these additional investigations should include demonstration of the system improvements listed above.

The remainder of this report includes a description of Phase I tests and test results followed by a description of Phase IA tests and test results. Test plans for each phase are presented to show the test set-up and approach.

2.0 TEST PLANS AND TEST REPORTS

2.1 PROOF-OF-CONCEPT TEST PLAN

DEVELOPMENT AND EVALUATION
of
A WORKPIECE TEMPERATURE ANALYZER FOR INDUSTRIAL FURNACES

TEST PLAN
FOR
PROOF-OF-CONCEPT TESTING

Revision 1, MARCH 1990

Sponsored by

The U. S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, Idaho 83402

Work performed under Contract DE-FO07-89ID12875

Work performed by

THE BABCOCK AND WILCOX COMPANY
Research and Development Division
Alliance Research Center
Alliance, Ohio 44601

BACKGROUND

The Babcock & Wilcox Company (B&W) has been contracted by the U.S. Department of Energy (DOE) to develop a concept for a Workpiece Temperature Analyzer (WPTA) System. The WPTA would be used in the steel processing industry to measure average internal workpiece temperature. Its use during manufacturing processes such as reheat and continuous casting is expected to result in substantial energy savings as well as general cost savings and product quality improvements. The WPTA concept developed by B&W relies upon the laser generation of ultrasound at the surface of the workpiece and laser detection of the return echo of the ultrasound. Using the time-of-flight of the ultrasound, the known workpiece thickness, and the specific material calibration data of ultrasound velocity versus workpiece temperature, the average internal temperature can be determined. Because of the significant signal losses expected from diffraction and material attenuation, a "proof of concept" test is required to show that sufficient signal will be generated for detection by the WPTA system's interferometer. B&W has asked The Johns Hopkins University Center for Nondestructive Evaluation (CNDE) to perform the "proof-of-concept" testing outlined below.

SPECIMENS

The Timken Company has been chosen as the industrial host for follow-on field testing of the WPTA design. The specimens identified in Table 1 will be supplied by The Timken Company for the "proof-of-concept" testing of the WPTA at The Johns Hopkins University. All specimens will be alloy 8620. This alloy has grain growth characteristics typical of the range of Timken steels. The following outlines the planned test program.

EQUIPMENT

The ultrasound will be generated by a Q-switched Nd:YAG laser, Quantel Model YG 621, available at The Johns Hopkins University (JHU). This laser is very similar to the Quantel Model YG 682 Q-switched ND:YAG laser planned for use in the WPTA system. The JHU laser has a maximum output energy of 1.2 Joules, while that proposed for the WPTA system has a maximum output energy of 1.5 Joules. In the JHU tests, the ultrasound will be detected by a Michelson interferometer setup which is available at the University. In contrast, the WPTA system will use a confocal Fabry-Perot interferometer. Appendix A discusses the rationale for using the Michelson interferometer for the JHU tests in lieu of the actual Fabry-Perot. At least one room temperature test will be run using a Fabry-Perot, on loan from the University of Arizona, in parallel with the Michelson interferometer. This test will be used to confirm the Fabry-Perot sensitivity.

Babcock & Wilcox (B&W) will supply an electrically heated furnace, capable of temperatures up to 1090°C (1994°F), for heating the specimens. The general test arrangement is shown in Figure 1 and the furnace details are shown in Figure 2. In order to minimize oxidation and provide a reflective target for the Michelson interferometer, a cover gas, such as Nitrogen or Argon, will be fed to

the furnace. The cover gas may need to be preheated to prevent a cooling action inside the furnace. B&W will work with JHU in setting up a preheater system. It is expected that passing the cover gas through a coil of tubing as it enters the furnace will provide sufficient preheating to prevent a cooling effect from the gas. The cylinders of gas required as the gas supplied will be provided by JHU.

TEST MATRIX

The test matrix for The Johns Hopkins University tests is provided in Table 2. The values of the laser energy, laser power density and specimen temperature are nominal. The actual values obtained will be as close as practical to those presented in Table 2. The test matrix may have to be modified as the initial data is obtained in order to meet the objectives of the test program. The following outlines the intent of the various tests outlined in Table 2.

1. Test Nos. 1 through 5 are intended to determine the optimum laser power density which will provide the maximum ultrasound generated surface displacement. This optimum power density will be used in subsequent tests. A variation in laser power density with a fixed laser energy will require the variation of the impingement spot size.
2. Test Nos. 6 through 9 are intended to verify that increasing laser energy will result in a proportional increase in generated surface displacement. A variation of laser energy while holding a constant power density will be accomplished through the use of neutral density filters and a variation of impingement spot size.
3. Test No. 10 will determine whether the maximum laser energy and the optimum laser power density will provide a measurable surface displacement at the maximum furnace temperature of 1090°C (1994°F).
4. Runs 11 and 12 will repeat specimen A's room temperature and 1090°C (1994°F) data points, but on specimen B. This will provide an indication of repeatability between identical samples.
5. Runs 13 through 16 will repeat three room temperature ((22°C) (72°F)) data points and one hot ((1090°C) (1994°F)) data point, previously obtained on specimen A, but on specimen C. Specimen C is a five inch diameter specimen whereas specimen A is three inches in diameter. The hot data point will confirm that the maximum laser energy and the optimum laser power density will provide a measurable surface displacement at 1090°C(1994°F) on the minimum diameter specimen processed in the Timken reheat furnace.
6. Runs 17 through 19 will repeat the same three room temperature test points obtained on specimens A and C, but on specimen D. Specimen D is a seven inch diameter specimen. Specimen D is too large for the furnace and, therefore, will only be tested cold.

7. Runs 20 through 22 will repeat the same three room temperature test points obtained on specimens A, C and D, but on specimen E. Specimen E is a 10 inch diameter specimen and is also too large for the furnace. The hot test results from specimens A, B and C will be used to extrapolate the expected hot results from specimens D and E.
8. the results of the entire test program are expected to also provide information on the relative amount of signal loss from diffraction and from attenuation. This information will help confirm our ability to predict at least diffraction losses for various test specimen thicknesses.

RESULTS

The measurement results obtained from the Michelson interferometer will be in the form of measured surface displacements, in nanometers, for each of the test runs. These measured surface displacements will be tabulated along with the actual test parameters obtained for each run. In addition, a spectrum of the frequency content of the resulting displacement will also be obtained in order to better define the frequency band and bandwidth to be set on the WPTA confocal Fabry-Perot interferometer. If necessary, a number of Nd:YAG firings may be used to obtain an average displacement and also an average frequency spectrum.

CONCLUSIONS

The above outlined program is felt to provide the basic information required to verify that the WPTA system proposed by B&W will be capable of generating ultrasound displacement amplitudes on hot, thick specimens of sufficient magnitude for detection by the WPTA's confocal Fabry-Perot interferometer. The program will further help define the optimum Nd:YAG laser power density and the frequency band and frequency bandwidth settings for the Fabry-Perot interferometer for the field tests at The Timken Company.

TABLE 1 - TEST SPECIMENS*

<u>Specimen</u>	<u>Approximate Dimensions</u>	<u>Approximate Weight</u>
A	2-7/8" O.D. x 6" long cylinder	11 lbs
B	2-7/8" O.D. x 6" long cylinder	11 lbs
C	4.75" O.D. x 10" long cylinder	50 lbs
D	6.5" O.D. x 14" long cylinder	132 lbs
E	10.5" O.D. x 21" long cylinder	540 lbs

*All specimens are alloy 8620 with the following constituents.

C	.18 - .23%
Cr	.40 - .60%
Mn	.70 - .90%
Ni	.40 - .70%
Mo	.15 - .25%
Fe	Remainder

Austenitic grain size is 1 to 3 (250 μ m to 64 μ m)

All specimens are rolled from square billets.
Specimens are not all from same heat.

TABLE 2 - TEST MATRIX

TEST NO.	SPECIMEN	LASER ENERGY (J)	LASER POWER DENSITY* (W/cm ²)	TEMP. (°C)
1	A	1.2	1.0x10 ⁸	22 (72°F)
2	A	1.2	2.0x10 ⁸	22
3	A	1.2	3.0x10 ⁸	22
4	A	1.2	4.0x10 ⁸	22
5	A	1.2	5.0x10 ⁸	22
6	A	0.1***	1.0x10 ⁸	22
7	A	0.2***	1.0x10 ⁸	22
8	A	0.4***	1.0x10 ⁸	22
9	A	0.8***	1.0x10 ⁸	22
10	A	1.2	OPTIMUM**	1090 (1994°F)
11	B	1.2	OPTIMUM**	22
12	B	1.2	OPTIMUM**	1090
13	C	1.2	1.0x10 ⁸	22
14	C	1.2	5.0x10 ⁸	22
15	C	1.2	OPTIMUM**	22
16	C	1.2	OPTIMUM**	1090
17	D	1.2	1.0x10 ⁸	22
18	D	1.2	5.0x10 ⁸	22
19	D	1.2	OPTIMUM**	22
20	E	1.2	1.0x10 ⁸	22
21	E	1.2	5.0x10 ⁸	22
22	E	1.2	OPTIMUM**	22

* Varied by adjusting impingement spot size.

** Maximum response case of 1, 2, 3, 4 or 5 x 10⁸ W/cm² tests on specimen A.

*** Varied through use of neutral density filters.

APPENDIX A

RATIONALE FOR USING A MICHELSON INTERFEROMETER FOR JHU TESTS

A Michelson interferometer is planned for use in making the ultrasound-generated displacement measurements in the Johns Hopkins University (JHU) WPTA feasibility tests. There are several reasons for using the Michelson interferometer in lieu of the confocal Fabry-Pérot interferometer, which is planned for use as part of the WPTA system. These are:

1. The Michelson interferometer is more sensitive than the Fabry-Pérot and therefore should provide displacement data over the entire range of test parameters. Some of the displacement levels generated during the test may be lower than would be obtained in an actual WPTA application. The use of the Fabry-Pérot interferometer for these tests would provide a "not measurable" result rather than a quantifiable value. It is necessary to know the actual levels obtained in order to identify methods for generating increased levels. Although more sensitive than a Fabry-Pérot, the Michelson interferometer is a laboratory device which requires a highly polished specimen surface and, therefore, it would not be suitable for use as part of the WPTA system.
2. JHU does not have a Fabry-Pérot interferometer available but does have a Michelson interferometer setup and has extensive experience in using the Michelson to obtain calibrated displacement measurements.
3. The cost of assembling a Fabry-Pérot interferometer with an argon ion laser identical to the one planned for the WPTA would be prohibitively expensive for use in the feasibility tests. In order to at least obtain some verification of the Fabry-Pérot sensitivity, the University of Arizona has loaned B&W a confocal Fabry-Pérot for use in parallel with the Michelson interferometer on one or two room temperature test runs. The loaned unit will most likely be used in conjunction with a helium neon laser source available at B&W rather than the argon ion laser planned for the WPTA. These test runs will be used to confirm the calculated sensitivity of the confocal Fabry-Pérot which will be used in the WPTA.
4. The operating principles and minimum sensitivity versus operating parameters of the Fabry-Pérot are well documented and readily calculated. Also, Monchalin from Canada, has worked extensively with confocal Fabry-Pérot interferometers in the measurement of laser generated ultrasound and his work is widely published. His measurement results are directly applicable to the WPTA. Using this base knowledge, the results obtained from the Michelson interferometer can be directly correlated with the known Fabry-Pérot sensitivity.

FIGURE 1
TEST SET-UP FOR JOHNS HOPKINS TESTING

FIGURE 2
TEST FURNACE DETAILS

DYNA-TROL FURNACE
MODEL P212-C25
1090°C MAX.
110/220V SINGLE PHASE
17.8 AMPS, 3940 WATTS

(NOTE: DOOR WILL BE FITTED WITH 1" DIAMETER SAPPHIRE WINDOW)

2.1 JOHNS HOPKINS UNIVERSITY PROOF-OF-CONCEPT TEST REPORT

**LASER ULTRASONICS FOR WORKPIECE TEMPERATURE ANALYSIS:
A FEASIBILITY STUDY**

**Prepared for the Babcock and Wilcox Company
Research and Development Division
Alliance Research Center**

J.W. Wagner, J.B. Deaton, Jr. and J.B. Spicer

**Center for Nondestructive Evaluation
Johns Hopkins University
Baltimore, MD 21218**

September, 1990

(Revised April, 1991)

SUMMARY

The experimental study described in the following report was conducted to establish the feasibility of using laser-ultrasonics testing to infer remotely the temperature of steel samples of different diameters.

BACKGROUND

An incident laser pulse simultaneously excites several different acoustic modes in the target material. In particular, longitudinal and shear components travel outward from the source location in all directions through the bulk material, while Rayleigh waves propagate along the surface. For this project, we were interested primarily in the longitudinal wave that is launched normal to the surface (i.e. 'on epicenter'). The amplitude of this longitudinal pulse depends strongly on the incident power density of the laser source. Accordingly, the first objective of this investigation was to determine the optimum power density necessary to maximize the amplitude of the longitudinal wave that propagated normal to the surface. At low power densities, thermoelastic expansion of the material near the surface is the dominant generation mechanism. At a traction-free surface, there is no normal force to oppose the thermal expansion, so the amplitude of the longitudinal displacement on epicenter is relatively weak. As the power density is increased however, ablation of the surface material results. The momentum transfer accompanying ablation does contribute a strong force normal to the surface; consequently, the amplitude of the epicentral longitudinal wave is enhanced significantly. Previous work [1] has established that there is an optimum laser power density at which the longitudinal pulse amplitude is maximized within the ablative regime. As the power density rises above this optimum level, the laser-generated plasma absorbs an increasingly greater portion of the incident laser energy, and the acoustic amplitude actually decreases.

LASER ULTRASONICS EQUIPMENT

To generate the ultrasonic signals, we used a Quantel Model 581C Q-switched Nd:YAG laser. After passing through an amplifier stage the Q-switched pulse was emitted with a nominal energy of 1 J, a pulse width of about 9 nsec (FWHM), and a spot diameter of about 9 mm at a wavelength of $1.06 \mu m$.

The laser generated acoustic signals were detected with a path-stabilized Michelson interferometer using a 10 mW linearly polarized Helium-Neon (He-Ne) laser as the light source. The reference mirror for the interferometer was mounted on a piezoelectric element driven by a feedback loop. This pathlength stabilization scheme helped provide immunity to low frequency environmental disturbances (room vibrations,

air turbulence, etc.). The experiments were conducted on a Newport Corp. optical table to further isolate the interferometer from any room vibrations. The maximum bandwidth of the interferometer was limited by the response of the photodetectors to about 20 MHz.

Absolute calibration of this interferometer was a straightforward process once the probe beam was aligned on the sample with the stabilization loop disabled. Repeatedly tapping on the optical table introduced large random variations in the optical path lengths. The resulting signal was displayed on an oscilloscope (50 Ω termination) to measure the peak-to-peak amplitude, V_o (referred to as the 'full scale response' of the interferometer). This voltage represented the output corresponding to a net difference of $\lambda / 4$ between the path lengths of the reference and probe legs. The surface displacement, δ , could be calculated in terms of the signal voltage from the interferometer, V_{sig} , the laser wavelength, λ , and the full scale response according to the following expression:

$$\delta = \frac{\lambda}{2\pi V_o} V_{sig} \quad (1)$$

TEST SAMPLES

The Timken Company provided several cylindrical steel samples (Alloy 8620) for this project. The sample designations and dimensions were as follows:

- Sample A: 2 7/8" diameter by 6" long,
- Sample B: 2 7/8" diameter by 6" long (identical to Sample A),
- Sample C: 4 7/8" diameter by 10" long,
- Sample D: 6 1/2" diameter by 14" long,
- Sample E: 10 1/2" diameter by 21" long.

As with any Michelson interferometer, a highly reflective sample surface was necessary to return sufficient optical power to the photodetectors for good SNR. The steel samples tested were rolled from square billets, and the surface provided was too rough to be tested with a Michelson interferometer. To produce a polished detection surface, a flat (about 3/4" wide and running the length of the cylinder) was ground off in the machine shop. This machined surface was then sanded with progressively finer grit paper (240, 320, 400, 600 grit) and finally polished to a mirror-like finish with diamond paste. The resulting finish yielded a nearly specular reflection of the interferometer probe beam which allowed sufficient light to be returned to the interferometer.

ROOM TEMPERATURE TESTING

Experimental Procedure:

The sample was placed upright on the optical table and the interferometer was positioned so that the probe beam struck the polished region of the sample at a working distance of about 6". Because there were variations in reflectivity across the polished surface, it was necessary to monitor the full scale response of the interferometer to ensure that the probe spot was at a region of high reflectivity. The source beam from the Nd:YAG laser was then directed with a right angle prism to a point on the sample that was diametrically opposite from the location of the probe beam. In this way, the ultrasound was detected after a single pass through the sample.

To vary the spot diameter of the laser source, a plano-convex focusing lens (25 cm focal length) was mounted on an optical rail so that the lens-to-sample distance was adjustable and reproducible. When working with the unfocused beam, a fused silica window was substituted for the lens so that the energy striking the sample remained about equal to that delivered with the lens in place. Several approximations were made when calculating the incident power density. The peak power in the pulse was computed assuming the energy (measured with a Scientech model 365 meter) arrived in a 9 nsec pulsewidth. For each lens setting a spot 'diameter' was estimated from the burn pattern recorded on thermally sensitive paper, and the power was assumed to be uniformly distributed over the area of the spot. To facilitate realistic comparison of the results for various samples, the same series of lens positions was used in each test. This ensured that the similar set of power densities was delivered to each of the samples, even though the absolute accuracy of the power density calculations might be somewhat suspect.

Experimental Results:

The first experiment determined the optimum power density for the various steel samples. With the focusing lens (or flat window) in place, the energy in the Nd:YAG pulse reaching the sample averaged about 0.8 J. Figure 1 shows the amplitude of the laser generated longitudinal pulse (in nm of surface displacement) plotted as a function of the incident power density for samples A, C, D, and E. Notice that for each sample, the optimum power density (maximum in signal amplitude) is around 200-300 MW/cm^2 . This optimum power density was achieved with a spot diameter of 6-8 mm with 0.8 J/pulse of energy in the laser source. This implies that for somewhat higher pulse energies, the optimum power density could be delivered with an unfocused beam. Operating without a focusing lens would simplify the experimental system and, more importantly, eliminate the energy loss associated with the lens.

In the next experiment, waveforms were recorded from sample A at several different pulse energies. A stack of microscope slides inserted in the path of the Nd:YAG beam provided a convenient means for attenuating the energy delivered to the sample. Figure 2 shows the measured signal amplitude as a function of incident power density for the nominal source energies of 0.42, 0.6, and 0.8 J/pulse. It is clearly desirable to operate at the highest possible pulse energy in order to maximize the amplitude of the longitudinal pulse. However, as this data illustrates, the optimum power density remains about the same, independent of the pulse energy. Therefore, when increasing the pulse energy, it is necessary to increase the laser spot size commensurately so as to maintain the optimum power density value.

Representative waveforms are included to illustrate the pertinent features of the laser generated signals recorded in the various samples, as depicted in figures 3-6 (for samples A,C,D, and E respectively). These signals were generated at the optimum power density with a nominal pulse energy of 0.8 J. Recall that this required the generating beam to be weakly focused to a 6-8 mm spot diameter. The complete waveform records the arrival the longitudinal wave (P), the shear wave (S), the first longitudinal echo (3P), which made three passes through the sample, and finally the Rayleigh wave (R), which travelled around the surface of the sample. In addition, expanded views are included for each sample detailing the longitudinal pulse as well as the longitudinal echo and Rayleigh wave, which arrived close together. No longitudinal echo was detected in the thickest sample (E) because of ultrasonic attenuation.

Figure 7 shows typical waveforms generated in samples A and B (both nominally 2 7/8" diameter). In both cases the source laser struck the sample at time $t = 0$. The similarity of the longitudinal arrival in these two samples indicates that sample-to-sample repeatability can be delivered with this laser ultrasonics technique. The slight difference between the arrival times for the two signals indicates a difference of perhaps 3 mm between the ultrasonic pathlengths. The possibility that the sound did not travel along a true diameter of these samples may account for this discrepancy. When this technique is implemented on-line, the ultrasonic pathlength in the sample must be precisely controlled in order to make dependable velocity calculations.

For each sample, the frequency spectrum of the first longitudinal arrival was computed using the Fast Fourier Transform (FFT) algorithm. The results are shown in Fig. 8 for the different sample diameters. Since the higher frequencies experience greater attenuation, it follows that the thinner samples transmit signals of greater bandwidth. From these results, it would appear that a bandwidth of 10 MHz on the interferometer is adequate for detecting the longitudinal pulses. Operating with a higher bandwidth will only decrease the signal-to-noise ratio of the system. Operation at bandwidths down to 1 MHz may be possible and will improve the signal-to-noise ratio.

HIGH TEMPERATURE TESTING

The second phase of this project involved testing the two smaller samples (A and C) inside a furnace at elevated temperatures to determine how such an environment might affect the performance of the laser-ultrasonics system.

Experimental procedure:

Babcock and Wilcox supplied a small electrically heated furnace (Dyna-trol Model P212-C25) with a maximum operating temperature of 1090 C. A 1" diameter opening through the center of the furnace door provided the only access to the sample for the generation and detection beams. Argon gas was piped into the furnace through a coil of copper tubing and blown directly across the region of the sample surface under interrogation. It was hoped that the flow of inert gas would delay the high temperature oxidation of the reflective surface. Two thermocouples were fed into the furnace. The first thermocouple monitored the internal air temperature and provided feedback to the temperature controller. The second thermocouple was embedded in a hole drilled down the center of a witness piece identical in size to the actual sample. The witness piece was used because any hole drilled in the actual sample might perturb the path of the ultrasound. The internal temperature of the sample was assumed to be similar to that of the witness piece since they were placed side-by-side in the furnace.

The test sample was placed at the front of the furnace chamber in between the door and the witness piece. Both the generation and probe beams had to enter the furnace through the single port in the door. This requirement led to several experimental complications. It was difficult to bring both laser beams in through the same small opening. A right angle prism mounted in front of the access port directed the source beam in through the lower portion of the opening. The probe beam from the interferometer came in just above the prism and through the upper portion of the opening in the furnace door. The working distance for the interferometer was about 8.5", right at the outer limit for this particular instrument. Alternatively, we might have used a dichroic mirror (e.g. a mirror that reflected the Nd:YAG beam while transmitting the He-Ne beam), but alignment of the interferometer would have been more difficult. Care also was taken to ensure that the source spot did not overlap the location of the interferometer probe beam, since ablation of the surface material destroyed the reflectivity after only a few pulses. In this configuration the acoustic pulse had to travel twice through the sample thickness, doubling the attenuation. The final, and most troublesome side effect of same-side generation and detection proved to be the laser generated sound wave launched from the sample surface into the surrounding air. The 1 J pulse from the Nd:YAG laser generated an audible 'snap' upon hitting the sample. This sharp sound (similar to the detonation of a small firecracker) was uncomfortably loud so

it was no surprise that the interferometer detected a powerful airborne acoustic disturbance. This shock wave lasted for several tens of microseconds, and its large amplitude completely obscured the arrival of any of the much smaller ultrasonic pulses. To eliminate the influence of the shock wave, a 1 MHz highpass filter was placed on the output of the interferometer. Unfortunately, the filter also blocked a significant portion of the frequency content of the ultrasonic pulse, as was evident from the detected waveforms. However, the only other highpass filter available at the time, with a cutoff frequency of 20 KHz, did not eliminate the effect of shock wave from the signal and may have had a detrimental effect on the signal-to-noise ratio. It is likely that a cutoff frequency between 20 KHz and 1 MHz would provide the optimum performance, and a filter of this type will be used if future work is performed.

Experimental results:

The first high-temperature test was conducted on sample C (4 3/4" diameter). For this experiment, we abandoned the idea of placing the sapphire window over the access port in the furnace door. We discovered that the window significantly reduced the amount of light returning to the interferometer, which compromised the sensitivity of the system even at room temperature. About 1.2 J/pulse of laser energy was delivered to the sample in an unfocused beam (9 mm spot dia.). After recording a room temperature signal, the furnace was set for continuous heating and data was taken about every 100 C of increase in furnace temperature. Figure 9 shows representative longitudinal arrivals recorded for a series of temperatures up to 700 C. The scale on the vertical axis is 100 mV per division. Each trace is labelled with the air temperature first, followed by the temperature of the witness piece. With the furnace heating continuously, the temperature of the witness piece lagged the air temperature by a significant margin.

Note that as the temperature increased, the arrival time for the acoustic pulse was delayed increasingly. This result is consistent with previous work that indicated a decrease in ultrasonic velocity with increasing temperature [2]. Unfortunately, oxidation of the sample surface ended our experiment before the target temperature of 1000 C was attained. Once the air temperature approached 400 C, the sensitivity of the interferometer began decreasing steadily until finally no signal could be detected at a temperature of 700 C. Note also that the longitudinal waveforms in Fig. 9 exhibit a bi-phasic behavior, while those recorded for the earlier room temperature tests (Figs. 3a, 4a, 5a, 6a) were sharper mono-phasic pulses. This distortion resulted from the 1 MHz highpass filter on the interferometer output, as was previously discussed.

In the next experiment, sample A (2 7/8" diameter) was tested according to the procedure just described. This time, however, the sapphire window was mounted over the access port in the furnace door. The surface finish on this sample was better than that on sample C, resulting in better performance for the interferometer, even with the window in place. Losses through the window dropped the energy in the unfocused laser

source to about 1 J/pulse. As before, the furnace was set to heat continuously, and this time data was taken for each increase of 100 C in the temperature of the witness piece (not the air). Figure 10 shows typical longitudinal waveforms recorded over a temperature range extending to 700 C. The vertical scale is 100 mV/division and each trace is labelled with the air temperature followed by the temperature inside the witness piece. The arrival of the longitudinal pulse was delayed with increasing temperature, again indicating that the sound velocity decreased as the temperature increased. The sensitivity of the interferometer began falling as the temperature reached 400 C. The window may have helped retard surface oxidation, because signals were still barely detectable at 700 C. Beyond this temperature, however, no ultrasonic features could be resolved.

When studying Figs. 9 and 10 it appears that the ultrasound suffered significant attenuation at elevated temperatures. Recall, however, that the sensitivity of the interferometer was plummeting while the temperature increased. It is helpful to consider the ratio of the peak-to-peak amplitude of the longitudinal arrival over the full-scale response, V_o , of the interferometer at each temperature. In Fig. 11 this normalized 'surface displacement' ratio is plotted against temperature for the data shown in Fig. 10, revealing that the acoustic amplitude appears to have increased at the higher temperatures. This might have resulted from additional surface constraint provided by the high temperature oxide film. Another explanation for this behavior might be that less laser energy was required to ablate the target material at high temperatures. This possibility suggests that the optimum laser power density likely varies with temperature. The dependence of the optimum power density on temperature was not investigated during this preliminary study, but it certainly deserves future consideration.

In the final stage of this preliminary study, piezoelectric detection was combined with laser generation of ultrasound to obtain ultrasonic data at temperatures above 700 C, beyond the operating range of the interferometer. A fused quartz buffer rod (10 1/2" long by 1/4" diameter) was used to isolate the piezoelectric transducer from the hot steel sample. After some trial and error, it was discovered that glass microscope slides would melt and adhere to the steel surface as its temperature approached 650 C. The quartz buffer rod was then passed through the opening in the furnace door and pushed into the layer of molten glass to form a high temperature bond. The source laser beam was positioned to strike the sample adjacent to the base of the buffer rod. In this configuration, the laser generated ultrasound passed twice through the sample and then travelled the length of the buffer rod before arriving at the transducer. A Panametrics 2.25 MHz transducer was held against the end of the rod to record the resulting acoustic signal. A layer of light oil was applied to the end of the rod to couple the ultrasound into the transducer. The data collected at temperatures up to 1025 C is presented in Fig. 12. The ringing observed in these signals was an artifact of the piezoelectric transduction. The arrival times were significantly longer than those in Fig. 10 because the ultrasound travelled the additional distance through the buffer rod. The arrival time clearly increased

with temperature, as expected. The amplitude of the detected acoustic echo diminished with increasing temperature, until the signal was barely resolvable at a temperature of 1025 C. During the course of this testing, the temperature was raised from about 650 C to 1000 C, lowered back to about 650 C and finally raised again to the 1025 C. The variation in signal amplitude was reproducible as the temperature cycled up and down, indicating that the bond between the buffer rod and the sample remained intact. Nevertheless, it is premature to conclude that material attenuation was solely responsible for the loss in signal as the temperature approached 1000 C. Other factors, such as a deterioration in coupling efficiency at the various interfaces may have contributed to these results. Such uncertainties highlight the problems with conventional piezoelectric ultrasonic testing. Improvements in the non-contact laser ultrasonics system (e.g. switching to a high-power Fabry-Perot interferometer) will provide the means to determine the true extent of acoustic attenuation that may occur at elevated temperatures.

REFERENCES

1. R.J. Dewhurst, D.A. Hutchins, S.B. Palmer, and C.B. Scruby; *J. Appl. Physics* **53**; p. 4064 (1982).
2. R.J. Dewhurst, C. Edwards, A.D.W. McKie, and S.B. Palmer; in *Review of Progress in Quantitative Nondestructive Evaluation*; ed. by D.O. Thompson and D.E. Chimenti (Plenum, New York, 1988) p. 1615.

Figure 1: Amplitude of the laser generated longitudinal pulse vs. power density for the various samples. Laser pulse energy = 0.8 J. Sample A: 2 7/8" dia.; Sample C: 4 3/4" dia.; Sample D: 6 1/2" dia.; Sample E: 10 1/2" dia. The dashed lines do not represent any mathematical fit.

Figure 2: Amplitude of the laser generated longitudinal pulse vs. power density for nominal laser pulse energies of 0.8, 0.6 and 0.42 J/pulse. Ultrasonic signals were generated and detected in Sample A (2 7/8" diameter). Dashed lines do not represent a mathematical fit to the data.

(3a)

(3b)

(3c)

Figure 3: Representative laser generated signal detected in sample A (2 7/8" dia.). A) Entire waveform, including the first longitudinal arrival, P, the shear arrival, S, the first longitudinal echo, 3P, and the Rayleigh arrival R. B) The first longitudinal arrival. C) The first longitudinal echo and the Rayleigh arrival. Nominal laser energy was 0.8 J/pulse.

(4a)

(4b)

(4c)

Figure 4: Typical laser generated signal detected in sample C (4 3/4" dia.). a) Entire waveform showing the first longitudinal arrival, P, the shear arrival, S, the first longitudinal echo, 3P, and the Rayleigh arrival, R. b) The first longitudinal arrival. c) The first longitudinal echo and the Rayleigh arrival. Nominal laser energy was 0.8 J/pulse.

(5a)

(5b)

(5c)

Figure 5: Typical laser generated signal detected in sample D (6 1/2" dia.). The nominal laser energy was 0.8 J/pulse. a) Entire waveform showing the first longitudinal arrival, P, the shear arrival, S, the first longitudinal echo, 3P, and the Rayleigh arrival, R. b) Expanded view of the first longitudinal arrival. c) Expanded view of the first longitudinal echo and the Rayleigh arrival.

(6a)

(6b)

(6c)

Figure 6: Typical laser generated signal detected in sample E (10 1/2" dia.). The nominal laser energy was 0.8 J/pulse. a) Entire waveform showing the first longitudinal arrival, P, the shear arrival, S, and the Rayleigh arrival, R. b) Expanded view of the first longitudinal arrival. c) Expanded view of the Rayleigh arrival. Note that the first longitudinal echo is not detected in this thick sample.

Figure 7: Comparison of laser generated longitudinal pulses detected in samples A and B (both 2 7/8" dia.). Nominal laser energy = 0.8 J/pulse. (In both cases, the laser source struck the samples at time, $t = 0$.)

Figure 8: Frequency spectra for the laser generated longitudinal pulse for the various samples. Nominal laser energy = 0.8 J/pulse. Sample A: 2 7/8" dia.; sample C: 4 3/4" dia.; sample D: 6 1/2" dia.; sample E: 10 1/2" dia.

Figure 9: Longitudinal pulse waveforms generated in sample C (4 3/4" dia.) and detected with the interferometer. Laser source had a nominal energy of 1.2 J and a spot diameter of 9 mm. Each trace is labeled by 'furnace temperature/witness piece temperature'. Vertical scale = 100 mV/div.

Figure 10: Longitudinal pulse waveforms generated in sample A (2 7/8" dia.) and detected with the interferometer. Laser source had a nominal energy of 1 J/pulse and a spot diameter of 9 mm. Each trace is labeled by 'furnace temperature/witness piece temperature'. Vertical scale = 100 mV/div.

Figure 11: Normalized results for the high temperature testing of sample A (2 7/8" dia.). Plotted on the vertical axis is the ratio of the peak-to-peak amplitude of the longitudinal pulse in Fig. 10 versus the full-scale voltage response of the interferometer.

Figure 12: Longitudinal waveforms generated in sample A (2 7/8" dia.) and detected with a 2.25 MHz piezoelectric transducer through a fused quartz buffer rod. The laser source had a nominal energy of 1 J/pulse and a spot diameter of 9 mm. Each trace is labeled by 'furnace temperature/witness piece temperature'. The vertical scale = 100 mV/div.

Appendix: Calibration comparison of The Johns Hopkins interferometer versus the Babcock and Wilcox shaker table and accelerometer.

For calibration comparison of the interferometer to the accelerometer, three trials of the following test protocol were performed:

- 1) The shaker table with the attached accelerometer and optical reflector were aligned with the interferometer to provide optimum signal-to-noise for optical detection of the displacements of the reflector.
- 2) The shaker table was turned-on. The drive voltage to the shaker table at 10 kHz was adjusted until the accelerometer signal voltage obtained the values given in the first column of Table A1.
- 3) It was found that the shaker table imparted substantial displacements to the optical reflector at frequencies well below the selected drive frequency of 10 kHz. These displacements destabilized the interferometer making accurate readings of the signal voltage at 10 kHz difficult. The signal voltages were estimated as accurately as possible. The calculated displacements corresponding to these voltages (see main body of report) are given in the third column of Table A1.

Table A1: Calibration comparison of The Johns Hopkins interferometer versus the Babcock and Wilcox shaker table and accelerometer. 8/90.

Accelerometer Voltage at 10 kHz (Volts p-p)	Converted Accelerometer Output at 10 kHz (nm): 2.5 nm/(V p-p)	Converted Interferometer Output at 10 kHz: Peak-to-Peak Sample Displacement (nm)	Ratio of Accelerometer Output to Interferometer Output (nm/nm)
0.40	1.0	0.93	1.1
0.70	1.8	1.8	1.0
12.5	31	30	1.0

Note: The accelerometer output for the 0.40 V p-p data reading for the accelerometer voltage was a distorted sinusoid.

2.3 PHASE IA TEST PLAN

REVISED

Development and Evaluation of a
Workpiece Temperature Analyzer

Phase Ia - Test Plan

J. W. Berthold

September 1992

Sponsored by:

The U.S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, Idaho 83402

Contract DE-FC07-89ID 12875

Work Performed by:

The Babcock & Wilcox Company
Research and Development Division
Alliance Research Center
Alliance, Ohio 44601

BACKGROUND

The Babcock & Wilcox Company (B&W) has been contracted by the U.S. Department of Energy (DOE) to develop a concept for a Workpiece Temperature Analyzer (WPTA) System. The WPTA would be used in the steel processing industry to measure average internal workpiece temperature. Its use during manufacturing processes such as reheat and continuous casting is expected to result in substantial energy savings as well as general cost savings and product quality improvements. The WPTA concept developed by B&W relies upon the laser generation of ultrasound at the surface of the workpiece and laser detection of the return echo of the ultrasound. Using the time-of-flight of the ultrasound, the known workpiece thickness, and the specific material calibration data of ultrasound velocity versus workpiece temperature, the average internal temperature can be determined.

In 1990, tests performed at The Johns Hopkins University (JHU) showed the feasibility of time-of-flight of laser generated ultrasound for obtaining internal temperatures. During those tests, unexpectedly large attenuation of the ultrasound signals was observed in alloy 8620 at temperatures above 700°C (1292°F). The additional tests outlined in this test plan will examine alloy 8620 again, and one other alloy, 4620, at temperatures as close as possible to the melting temperature.

SPECIMENS

One test alloy, 8620, is supplied by the Timken Company, the industrial host for follow-on field testing of the WPTA design. The other alloy, 4620, is being purchased. One test specimen made from alloy 8620 will be prepared by DOE.

EQUIPMENT

The ultrasound will be generated by a Q-switched Nd:YAG laser, Quantel Model YG 621, available at The Johns Hopkins University (JHU). This laser is very similar to the Quantel Model YG 682 Q-switched Nd:YAG laser planned for use in the WPTA system. The JHU laser has a maximum output energy of 1.2 Joules, while that proposed for the WPTA system has a maximum output energy of 1.5 Joules. In the JHU test, the ultrasound will be detected by a Michelson Interferometer setup which is available at the University. Alternately, a recently acquired Fabry-Perot Interferometer may be used by JHU if this new interferometer has been debugged and is operating properly. The Fabry-Perot Interferometer is the instrument preferred for ultrasound detection in a WPTA system. Correlations between the Michelson and Fabry-Perot Interferometers have already been performed to determine the measured amplitudes of ultrasound generated motion. Therefore, either interferometer could be used for these tests.

For heating the specimens, Babcock & Wilcox (B&W) will lend to JHU a radiantly heated parabolic clamshell furnace capable of temperatures to 1650°C (3002°F). This furnace is an R-I Controls Model 4068-12-25 containing twelve 5kw lamps. The furnace accommodates quartz tubes along its axis as shown in Figure 1. Specimens will be located in these specially designed quartz tubes (see Figure 2) that provide for both inert gas circulation to prevent specimen oxidation, and quartz windows that allow access for the

ultrasound generation and detection laser beams and viewing by a remote fiber optic radiation pyrometer. This noncontact radiation pyrometer, a Mikron Model M668 will also be lent to JHU by B&W so that specimen temperatures can be measured. Although a fiber optic radiation pyrometer is being planned for these measurements, a thermocouple and "witness" sample may also be used for temperature measurement as was done by JHU in earlier tests. Cylinders of inert gas, to purge the quartz tube, will be provided by JHU.

The general test arrangement is shown in the block diagram Figure 3. The ultrasound generation laser will enter one end of the quartz tube and the detection laser beam will enter the other end. Thus, measurements on ultrasound time of flight will be made from a single pass through the specimen.

TEST PROGRAM

Based on the previous test results reported by JHU in 1990, the generation laser spot size will be adjusted to obtain optimum laser power density for ultrasound generation in the specimens. To ensure detectable signals from the Interferometer/Detection Laser during the tests, every effort should be made to limit the overall Interferometer and processing electronics bandwidth to 1 MHz or less. B&W is willing to lend JHU electronic filters, if needed, to help accomplish suitable bandwidth limiting.

The intent of the tests is to measure the following for each of the specimens in Table I:

- t - time-of-flight of laser generated ultrasound through the length vs specimen temperature T. Nominal specimen lengths from 1/4 to three inches may be measured.
- A - amplitude (vs specimen temperature T) of interferometer output signal produced by ultrasound modulation of detection laser beam.
- T - specimen temperature from the low end limit of approximately 400°C (752°F) imposed by the radiation pyrometer up to the high end limit of approximately 1650°C (3002°F) imposed by the capability of the furnace.

The quantities t, A and T should be recorded at temperature intervals of 50°C (122°F) over the temperature range so that for each specimen, a data set is generated consisting of 26 points with each point containing the values for t, A and T. JHU should provide a conversion factor to convert quantity A to estimated specimen surface displacement amplitude.

RESULTS

The results of the test program are expected to provide information on ultrasound absorption in steel alloy materials up to temperatures near the melting point. This information will help us to predict ultrasound attenuation levels for different phase states in different alloys.

The 26-point data set for each specimen should be tabulated along with test parameters and other information deemed relevant by JHU. All the information and test results should be compiled in a summary report.

Table I. Test Specimens

<u>Specimen</u>	<u>Alloy</u>	<u>Approximate Cylindrical Dimensions</u>
A	8620	1.5" x 3"
B	4620	1.5" x 3"

Figure 1
WORKPIECE TEMP.
TEST SET-UP

Figure 2
WORKPIECE TEMPERATURE
SPECIMEN CONTAINER 2-7-91

FIGURE 3 TEST SETUP FOR JHU TESTS

C1299/d45

2.4 JOHNS HOPKINS UNIVERSITY PHASE IA TEST REPORT

Laser Ultrasonic Testing of Steel at Elevated Temperatures for Temperature Determination

**J.W. Wagner and R.D. Huber
The Johns Hopkins University
Center for Nondestructive Evaluation
Baltimore, Maryland 21218**

October 1992

HIGH TEMPERATURE LASER ULTRASONICS

Introduction

The results of the WPTA Phase I proof-of-concept tests performed in 1990 indicated that, at room temperature, the ultrasound transmission was easily detected even passing twice through the thickest specimen (total travel about 21 inches) with a signal-to-noise ratio of at least 10 to 1. However, as the temperature was increased, the signal was lost. It was postulated that the attenuation increased faster than exponentially so that the echo from even the smallest diameter specimen was undetectable above 700 °C (1292 °F).

In the subsequent Phase IA follow-on tests described in this report, ultrasound detection was performed with the preferred Fabry-Perot interferometer rather than the Michelson interferometer used previously. The Fabry-Perot interferometer is preferred because of its ability to work on non-specular surfaces. In the follow-on tests, laser generated ultrasound was detected at temperatures above 1250 °C (2282 °F).

The results reported here are significant. The technology of laser generation and detection ultrasound is very promising for measurement of the internal temperature of hot steel workpieces. Results show the feasibility of making such measurements at temperatures above 1250 °C (2282 °F).

Experimental Considerations

Laser ultrasonic tests were conducted on several steel samples which were of differing alloy composition. Samples were cut from 1.25 " diameter bars into lengths of approximately 0.25", and were placed in a furnace and heated to temperatures in excess of 1250 °C (2282 °F). A pulsed Nd:YAG laser was used to generate ultrasound on one face of the samples, and a Fabry-Perot interferometer was used to detect the resulting ultrasound on epicenter on the opposite face of the samples. The Nd:YAG laser had a pulse duration of around 9 ns, and the footprint of the generating beam at the steel disk face was a 3 mm X 5 mm oblong shape with energies up to 450 mJ. Waveforms were captured which gave the travel time of the longitudinal mode of the ultrasound propagating through the known thickness, from which longitudinal velocity could be calculated. A thermocouple with one end placed in a witness sample with dimensions similar to the test sample was used to measure the temperature. The witness sample was cut from the same stock as the test sample.

Figure 1 shows the experimental set-up for the high temperature ultrasonic tests. Details of the interferometer system are shown in Figure 2. The steel samples were placed in a quartz tube which was then sealed, and the generating and detecting beams were sent through the quartz tube. The atmosphere in the quartz tube was 98% Ar and 2% H. The light source for the Fabry-Perot interferometer system was an Argon ion gas laser. The Fabry-Perot cavity

consists of two confocal spherical reflectors which are separated by their radii of curvature. The light which is transmitted through the cavity is focussed on a photodetector. A 514 nm line filter was used in front of the photodetector to block the extraneous light from the high energy pulse from the Nd:YAG laser which can obscure the ultrasonic signal. A path-stabilization scheme using a piezoelectric tube attached to one of the reflectors of the Fabry-Perot cavity was used to compensate for laser drift and low frequency fluctuations in the cavity length.

Alloys 4620 and 8620 were tested. The data for alloy 4620 is in appendix 1. The data shown for alloy 8620 (figures 3,4 and 5) is from a test which was run using the oven in temperature control mode. In this mode, the oven used the feedback from a thermocouple to maintain the desired temperature by adjusting the current being sent to the oven lamps. Data was taken at the desired temperature by firing the Nd:YAG laser and capturing the output of the interferometer system on a digital storage oscilloscope. The signal from a photodiode which sensed the Nd:YAG pulse was used to trigger a digital oscilloscope. The waveforms were transferred to computer to be plotted out. Single shot waveforms were captured at room temperature, at 100 °C (212 °F) intervals starting at 100 and ending at 1200 °C (2192 °F), and at 1237 °C (2259 °F) at which the maximum temperature for this test was reached.

In a previous study, a Michelson-type interferometer was used. Although Michelson interferometers out-perform Fabry-Perot interferometers for specularly reflecting surfaces, as surfaces become more diffusely reflecting, the performance of Michelson interferometers degrades more rapidly than that of a Fabry-Perot. This arises from the fact that unlike the Michelson arrangement, a Fabry-Perot interferometer can process multiple speckles which arise from diffuse scattering.

Experimental Results

The waveforms are shown in Figures 3 a-n. The temperature in degrees Celsius at which the waveform was obtained is listed in the lower left of each graph. The initial ultrasonic arrival which occurs in the waveforms is the 1P, a longitudinal wave which travels through the thickness of the sample. On most of the waveforms, the 3P longitudinal wave is seen. This is a longitudinal wave which has propagated 3 times through the thickness of the steel. On many of the waveforms, a shear wave (transverse wave) is seen between the 1P and 3P waves. Note that Rayleigh waves observed in the Phase I test were not observed in this test. The reason Rayleigh waves were not observed was because laser excitation and detection were performed on opposite sides of the sample. The difference in the polarity of the waveforms resulted from the correction scheme for the Fabry-Perot interferometer which was employed during these tests. The absence of a clear 3P arrival in the higher temperature waveforms results from increased attenuation of the ultrasound as the steel heats up, and decreased sensitivity of the interferometer as the sample surface

degrades. Figure 4 shows the dependence of acoustic velocity on temperature computed from the data shown in Figure 3. Although there appear to be changes in the slope of figure 4, it is statistically impossible to account for these changes from this single data set. A graph showing the temperature history of the steel specimen for this test is shown in Figure 5. Tests were also run on a 4620 alloy. The results on alloy 4620 are reported in appendix 1.

The face of the sample on which detection took place was polished to a mirror-like finish with a final polish using 0.05 μm diamond paste. As the sample was heated, the surface degraded. This degradation led to a decrease in the amount of light reaching the detector from the sample, and thus led to an apparent decrease in sensitivity. For this reason, a second amplifier stage was added to the generating laser for waveforms captured above 800 °C (1472 °F). This increased the energy per pulse of the generating laser from 250 mJ to 450 mJ.

After running the test, the test sample was examined. The face of the sample on which detection had taken place was found to have a slight blue coloration, and the face on which generation had taken place was found to have only a slight discoloration marking the location at which the generating beam struck the sample, ensuring that we were not in the heavily ablative regime. A further increase in the energy density could lead to larger displacements, but at a cost of increased surface damage. However, the extent of this surface damage may be several square mm, which for forging operation is inconsequential.

Prior to testing, the surface of the specimen on which detection was to take place was polished to a mirror-like finish. Upon heating in an air atmosphere, the surfaces of the steel alloys used in this study were found to oxidize considerably, drastically reducing the amount of laser light reflected to the Fabry-Perot cavity. In an attempt to reduce the oxidation, argon gas was used both to purge the quartz tube, and to flow through the tube during testing. This reduced the oxidation, but the surface of the specimens still degraded from a highly polished state to a diffusely reflecting blue hue. A gas mixture of 2% hydrogen, 98% argon was then tried. This mixture helped slow the degradation of the surface even more, but the surface still degraded to a diffusely reflecting blue hue.

Appendix 1 shows waveforms obtained for a 4620 alloy. These waveforms were generated using a heavily ablative source (power density $> 10^7 \text{ W/cm}^2$). The furnace was run in current control mode for this test, and this accounts for the temperatures listed on the graphs not being at even numbers as was the case when running the furnace in temperature control mode. The temperatures listed were obtained from a thermocouple output, with one end of the thermocouple being placed in a witness sample in the furnace.

Conclusions

The feasibility of high-temperature WPTA operation was demonstrated. These results are very significant. We believe this is the first known demonstration of laser generation and detection of ultrasound at such extreme temperatures. However, the sample thicknesses (0.25 inches) were too thin to be practical for forging operations where minimum workpiece thickness is about two inches. It is straightforward to identify system improvements that could be made, and to predict the practical metal thickness through which laser generated ultrasound measurement could be implemented with known methods by the Johns Hopkins University in the present WPTA laboratory test setup.

- Increase energy of generation laser
- Perform signal averaging
- Repetitively pulsed generation laser

With these improvements, we conservatively estimate that laser generated ultrasound could be detected through a three-inch specimen of alloy 8620 at 1250 °C (2282 °F).

Figure 1 Experimental Set-Up

Figure 2 Fabry-Perot Interferometer System

Figure 3 Laser Generated Signals Detected in Alloy 8620 (0.25" thick sample).

Refer to Figure 3a which shows the first longitudinal arrival 1P, the shear arrival S, and the first longitudinal echo 3P. Sample temperature is noted in each waveform in lower left corner. Nominal laser energy was 450 mJ per pulse.

Figure 4 Dependence of Longitudinal Velocity on Temperature
Data on alloy 8620 from figure 3 was used to obtain this graph.

Figure 5 Thermal Equilibration Data
Obtained from temperature measurement on alloy 8620 witness sample. Laser generation and detection data were taken during periods of constant temperature

Appendix 1

Tests on Alloy 4620

**DATE
FILMED**

8 / 18 / 93

END