**DEVELOPMENT OF
NONDESTRUCTIVE EVALUATION TECHNIQUES
FOR HIGH-TEMPERATURE CERAMIC
HEAT EXCHANGER COMPONENTS**

**Third Annual Report
October 1979—September 1980**

by

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ABSTRACT

The goals of the present program are not only to develop hardware and procedures for efficiently inspecting ceramic heat-exchanger components in conventional ways, but also to develop advanced NDE techniques that will allow effective failure prediction. The main objectives in FY 1980 have been to (a) develop a computer-interfaced ultrasonic bore-side probe for pre-service and in-service inspection, (b) develop and assess techniques for inspection of SiC tubing by acoustic microscopy, and (c) carry out preliminary tests to compare ultrasonic, holographic, and infrared techniques with more conventional dye-penetrant and radiographic methods for inspection of butt joints in ceramic tubes.

Circumferential notches, 125 μm deep x 250 μm long, on the inner and outer surfaces of sintered and siliconized SiC tubes were successfully detected with an ultrasonic bore-side probe. The signal-to-noise ratios for the ultrasonic echoes were better than 10 to 1, which exceeded initial expectations for detection of small reflectors. The ultrasonic bore-side probe was able to detect and record the location of an outer-surface notch while scanning a portion of a SiC tube under microcomputer control. To detect laminar-type defects, a normal-incidence longitudinal probe of frequency ≥ 25 MHz will be necessary.

The acoustic microscope was modified to handle 30- as well as 100-MHz sound waves, since the lower-frequency waves give better penetration of SiC tube walls. The modification decreased the acoustic noise. The ability to detect a notch only 250 x 125 x 75 μm in size was demonstrated.

The difference in acoustic images generated with two types of insonification geometries was demonstrated. Circumferential geometry produces straight interference lines; axial geometry produces curved lines. Both axial and circumferential EDM notches were imaged using the more recently developed circumferential insonification geometry.

In a comparison of siliconized and sintered SiC tubes, the sintered material showed high attenuation but good beam coherence (i.e., weak signals but little distortion), while the siliconized material showed good transmission but poor coherence (i.e., strong signals but moderate distortion).

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A conceptual design was presented for inspection of tubes up to 7 feet in length by acoustic microscopy, using both through-transmission from the tube inner surface and reflection from the outer surface.

Efforts to examine a butt joint with dye-penetrant, radiographic, ultrasonic, and holographic-interferometry techniques revealed that while holography seemed to identify more clearly the presence of a crack-like inner-surface flaw, ultrasonic pulse-echo and pitch-catch techniques at 22 MHz also indicated the presence of an anomaly; the ultrasonic and holographic results agreed with regard to angular location of the flaw.

I. INTRODUCTION

High-temperature ceramic heat-exchanger components are of particular interest because they are lighter than their metallic counterparts, have better high-temperature mechanical properties and good corrosion resistance, and can be fabricated from inexpensive and abundant elements. As a result, the use of these ceramics at temperatures $>1000^{\circ}\text{C}$ (higher than metals can withstand) can lead to more efficient energy-conversion systems.

In recent years, significant progress has been made in the use of ceramics for structural applications. Silicon carbide (SiC), for example, is currently being considered for heat-exchanger tubing because of its excellent thermal-shock resistance, low coefficient of expansion, high thermal conductivity, and strength at high temperature.¹

The reliable use of ceramics as structural components, however, requires effective failure prediction and thus effective flaw-detection capabilities. The flaws with the most deleterious effects on the lifetime of SiC components are cracks and porosity. Many fracture origins are adjacent to the surface,² indicating that surface cracks are an important cause of failure. The size of critical cracks leading to fracture can be related to microstructural features such as grain size, and can be relatively small (an order of magnitude or more smaller than in comparable metallic parts). For example, to assure high reliability of ceramic heat-exchanger tubes, fracture mechanics analysis indicates that an inspection technique must be capable of detecting defects of the order of 100 μm in size.³ Thus, nondestructive evaluation (NDE) techniques that are satisfactory for metals may not be for ceramics. Depending on the component of interest, it may be necessary to develop or advance conventional NDE techniques for ceramic applications. Currently, the techniques most widely employed by industry for ceramic NDE are x-radiography (RT) and fluorescent dye penetrant testing (PT). However, efforts are under way at Argonne National Laboratory (ANL) and several other institutions to advance NDE techniques for structural ceramics. The techniques studied outside ANL include high-frequency ($>50\text{-MHz}$) ultrasonic testing,⁴ microfocus x-radiography,⁴ microwave NDE,⁵ acoustic surface-wave testing,⁶ photoacoustic microscopy,⁷ acoustic emission detection,⁸ and overload proof testing.⁹

The purpose of the present ceramic NDE program is to compare the effectiveness of several conventional and unconventional NDE techniques for flaw detection in specific high-temperature ceramic components. The investigation encompasses many NDE techniques, concentrating on those not under

extensive evaluation at other institutions. The techniques under study at ANL have included dye-enhanced radiography, acoustic microscopy, conventional ultrasonic testing, acoustic-emission detection, acoustic impact testing, holographic interferometry, infrared (IR) scanning, internal friction measurements, and overload proof testing. No single technique is expected to serve as a universal flaw detection method; several techniques will be required to thoroughly assess ceramic components in a cost-effective way. Gross flaws should be detectable by simple, inexpensive techniques such as PT; smaller flaws may be detectable by ultrasonic testing, but may require more sophisticated techniques such as acoustic microscopy for imaging. After the investigation of many NDE techniques, one or more promising methods will be developed further for the specific ceramic components of interest. The current effort involves SiC heat-exchanger tubes; previous ceramic NDE efforts at ANL have involved silicon nitride gas-turbine rotors.¹⁰

The efforts described in the four quarterly reports issued in FY 1980¹¹⁻¹⁴ are summarized in the present annual report, which discusses the development of a computer-interfaced ultrasonic bore-side probe for pre- and in-service inspection of SiC tubes; advances in acoustic microscopy techniques, including a conceptual design for preservice inspection of tubes up to seven feet in length; and progress in evaluating NDE techniques (including acoustics, holographic interferometry, IR scanning, RT, and PT) for ceramic joint assessment.

II. SAMPLES

The SiC tubes used in the present study were obtained from several sources. Siliconized (Carborundum SKT and Norton NC430) and sintered (Carborundum) α -SiC tubes were obtained from the Garrett AiResearch Manufacturing Division's high-temperature heat-exchanger program; tubes with overlap joints were provided by Solar Turbines International; and butt-jointed NC430 tubes were obtained from the Norton Co. Hot-pressed SiC bars were also purchased from the Norton Co. They are nominally 150 x 6 x 6 mm in size (square cross section), with the surface ground smooth. The characteristics of some of the tube and bar samples are listed in Table I, and photographs are presented in Fig. 1. A micrograph of the joint in an NC430 butt-jointed tube is shown in Fig. 2. The joint was made by pressing the two halves of the tube together with a slip in between and then firing the tube. The joint is relatively fine-grained and about 150 μ m wide. SiC grains, 100-200 μ m across, can also be seen in the micrograph. Optical micrographs of other tubes were presented in the previous annual report.¹⁵

III. COMPUTER-INTERFACED ULTRASONIC BORE-SIDE PROBE

One of the objectives of the present program is to develop a design for an ultrasonic bore-side probe that can be used for both pre- and in-service inspections of SiC tubes, and that can be interfaced to a microcomputer for rapid inspection and data analysis. The probe should be capable of detecting and locating defects (cracks or voids) $\sim$ 100 μ m in size in tube walls and joints. Other, more sophisticated techniques (acoustic microscopy and holographic interferometry) may be used in conjunction with the ultrasonic probe to characterize the anomalies that are found.

Table I. Samples Used in the Present Study

Material	Type of Specimen	Dimensions	Defect	Example
Hot-pressed SiC (Norton NC203)	Bar	6 x 6 x 150 mm	Cracks, Knoop inden- tation, natural flaws	
Siliconized SiC (Carborundum SKT)	Tube	25 mm OD 3 mm wall 200 mm long	Natural flaws	
Siliconized SiC (Norton NC430)	Tube	~25 mm OD 3 mm wall 200 mm long	Natural flaws, EDM notches, holes	J
Sintered SiC (Carborundum)	Tube	~25 mm OD 3 mm wall 200 mm long	Natural flaws, EDM notches holes	SRI
Siliconized SiC (Norton NC430)	Tube with butt joint at center	~25 mm OD 3 mm wall 200 mm long	Natural flaws (crack in joint)	J6
SiC	Tube with overlap joint	Outer tube: ~25 mm OD ~3 mm wall Inner tube: ~18 mm OD ~3 mm wall	Poor bonding

Fig. 1. Three SiC Tubes Used in the Present Investigation. (Top) Siliconized tube; (center) NC430 tube with butt joint at center; (bottom) tube with overlap joint of Corning #0080 glass adhesive.

Fig. 2. Optical Micrograph of a Butt Joint (Arrow) in an NC430 Tube. The joint is about 150 μm wide; the SiC grains are $\sim 100\text{--}200\mu\text{m}$ across. Excess slip is visible on the outer surface of the tube (left).

Figure 3a shows a schematic representation of the probe in its simplest configuration. From the transducer, an ultrasonic beam (~ 3 mm dia) is directed axially down the water-filled tube. A mirror rotating at, typically, 500 r/min sweeps the ultrasonic beam around the tube wall. Depending on the mirror angle θ , either normal-incidence longitudinal waves (which detect wall thinning and delaminations) or axially propagating shear waves (which detect circumferential cracks) can be generated. To generate circumferential shear waves for detection of axial cracks, a small reflector must be placed on the mirror to shift the beam off the center line; this mode has not yet been tested. An ultrasonic frequency of 22 MHz is currently used, but higher frequencies may eventually be necessary to increase the resolution for normal-incidence longitudinal-wave testing.

The apparatus for manipulating the ultrasonic bore-side probe is also shown in Fig. 3. Figure 3b shows the entire apparatus; Fig. 3c is a closer view of the probe and SiC tube. A stepping motor drives a threaded rod, which moves the probe up and down via a housing riding on two rails. Microswitches limit the vertical travel. The system can be manipulated manually or through the microcomputer arrangement described below. Ultrasonic reflections from the two posts that connect the upper and lower parts of the probe mount are used to mark the angular positions of the probe. Because one post has a square cross section and the other is triangular, they produce signals of different amplitudes which can easily be distinguished. Because the posts block part of the tube inner surface during inspection, a complete scan requires two passes (one up and one down) with an intervening 90° rotation of the probe.

A schematic of the entire system is shown in Fig. 4. A small dc power supply drives the motor that rotates the mirror. A pulser-receiver is used for flaw detection. The flaw-signal analog output is connected to an oscilloscope or strip chart recorder and a microcomputer (National Semiconductor RMC-80/14 and Teletype Model 43 terminal). Details of the computer interfacing and mechanical arrangement, along with data on the capabilities of the probe, are discussed in the following sections. Other details of the system are discussed in Ref. 15.

A. Detection Sensitivity

1. Longitudinal Waves

Three flat-bottom holes were drilled in the outer wall of a SiC tube, as shown schematically in Fig. 5, to simulate laminar-type defects. The ability of the ultrasonic bore-side probe to detect these holes is illustrated in Fig. 6. The large peak at the left side of each trace is the reflection from the water/tube interface. Multiple backwall reflections, due to reverberation of the normal-incidence longitudinal waves in the tube wall, can also be seen beyond the hole echo. Unfortunately, the interface and multiple-reflection echoes are rather wide, making it difficult to isolate signals from flaws near the tube inner surface. With the present system and a 3-mm wall thickness ($0.5\text{-}\mu\text{s}$ round trip transit time in the wall), the first mm of the tube wall will be virtually unexaminable with longitudinal waves. Thus, laminar-type defects within the first mm of the wall will have to be detected by shear waves in a pitch-catch mode or by a system having shorter pulses and higher frequency. A short-pulse, 50-MHz transducer has been ordered from Panametrics

and will be compared with the present one for effectiveness in detecting such flaws.

The results from Fig. 6 suggest that (a) laminar-type flaws $\sim 500 \mu\text{m}$ in diameter can be readily detected by the current system, and (b) the beam is focused so sharply owing to the curvature of the tube that under the right circumstances, 1-mm-dia and larger reflectors in the middle of the wall may reflect virtually all of the beam, significantly reducing the amplitude of multiple reflections from the backwall.

2. Shear Waves

For this series of experiments, the position of the mirror was adjusted to generate shear waves in the tube wall at ~ 45 - 55° to the tube diameter, an angle empirically shown to provide optimal detection of circumferential notches. Data were obtained from SiC tubes J (siliconized) and SRI (sintered) in which electron-discharge-machined (EDM) notches had been placed as shown schematically in Fig. 7. Figures 8a and b show the radio-frequency signals from circumferential outer-surface notches 3 and 4 (500 and 125 μm deep, respectively) in Tube J. In both cases, the notches were detected from a 1/2 V position (as defined in Fig. 8c), using an Aerotech UTA-3 pulser-receiver with an attenuation of 0 dB. The water/tube interface signals appear at the left in Figs. 8a and b. Scales are indicated in the photographs. Figure 8d shows the frequency spectrum obtained from Fig. 8a, employing a Hewlett-Packard spectrum analyzer. The horizontal scale is 0-50 MHz. The peak lies at 23 MHz, about as expected.

Figure 9 shows the ultrasonic echo signals (arrows) from notch 3 in Tube J, detected from the 1/2 V and 1-1/2 V positions (att. 22 and 12 dB, respectively) with a Sonic Mark III pulser-receiver in the video output mode. Again, the signal at the left is from the water/tube interface. Figure 10 shows the signals from notch 4 in Tube J, detected from the 1/2 V and 1-1/2 V positions with a Sonic Mark IV pulser-receiver. Figure 11 shows the signals from circumferential inner-surface notches 7 and 8 in Tube J (500 and 125 μm deep, respectively), detected from the 1 V position with the Sonic Mark IV.

Similar results were obtained from the sintered tube SRI. Figure 12 shows the ultrasonic echo signal from circumferential outer-surface notch 4 (125 μm deep), detected from the 1/2 V position with a Sonic Mark III pulser-receiver. An unidentified natural anomaly was found in tube SRI within a few millimeters of the 125- μm notch; its signal is shown in Fig. 13.

By use of the Sonic Mark III analog output, strip-chart recordings showing a 360° scan of the tube can be made as the ultrasonic mirror rotates. As mentioned earlier, signals from the probe-mount posts (180° apart) are used as reference points. Figure 14 shows the strip-chart recordings (one complete revolution each) for all four circumferential notches in Tube J. The arrows indicate the notch signals; the other large signals are from the posts. Figure 15 shows a strip-chart recording for the sintered tube SRI, indicating the presence of notch 4 (arrow). Again, the broad signals are from the probe-mount posts. The signal just to the left of the notch signal is from an unidentified reflector; several small, spurious signals from unidentified sources are also present.

These results show that the ultrasonic bore-side probe operating at 22 MHz is very sensitive to the presence of artificial reflectors (circumferential EDM notches) on the order of 125 x 250 μm in size. The signal-to-noise ratio of >10:1 is better than expected, because the fortuitous geometry and high velocity of sound in the SiC tube cause a sharp focusing of the ultrasonic beam as it passes from the water to the tube wall. Detection sensitivities for axial notches will be established in future reports.

B. Detection of Mode-converted Shear Waves

One difficulty with the ultrasonic bore-side probe, when normal-incidence longitudinal waves are employed for wall-thickness measurements or detection of laminar-type defects, is the generation of mode-converted shear waves. Because of the curvature of the tube, the edge of the beam is not normal to the tube wall. This portion of the beam mode-converts to a shear wave inside the tube wall; if the refracted angle is not too large this shear wave can reflect off the tube outer wall, mode-convert back to a longitudinal wave at the ceramic-water interface, and be received by the transducer, as shown schematically in Fig. 16. At and beyond the critical angle for longitudinal waves, a relatively large fraction of the beam energy is mode converted to shear waves, and a large echo may appear. This critical angle occurs in SiC at 7.13° from the normal; in the tube, this corresponds to a 1.2-mm shift of the ultrasonic beam from the line of normal incidence. Since the beam is about 3 mm in diameter, we may expect this spurious echo to appear on the A-scan. This has been observed experimentally, as shown in Fig. 17a. Here, the transit time for the first longitudinal backwall echo after the initial echo from the water/ceramic interface is

$$\begin{aligned}\Delta t_{L_1} &= 2 \times 0.3 \text{ cm} / 12 \times 10^5 \text{ cm s}^{-1} \\ &= 0.5 \mu\text{s} \quad .\end{aligned}$$

The shear wave appears at

$$\begin{aligned}\Delta t_{S_1} &= 2 \times 0.3 \text{ cm} / 7.65 \times 10^5 \text{ cm s}^{-1} \\ &= 0.78 \mu\text{s} \quad ,\end{aligned}$$

and the second longitudinal backwall echo at $1.0 \mu\text{s}$; successive backwall echoes are $0.5 \mu\text{s}$ apart. The transducer and mirror alignment is critical, and slight movements of the probe can result in the loss of this shear-wave signal. As a result, the mode-converted shear wave may appear intermittently during an inspection and mask, or be misinterpreted as, a legitimate flaw signal.

From the above discussion, one may predict that if the beam width is sufficiently reduced, the mode-converted shear wave will not be detected. Therefore, the mirror of the bore-side probe was partially masked with Apiezon Q to reduce the width of the ultrasonic beam to $\sim 1 \text{ mm}$. Figure 17b shows a typical A-scan using the masked mirror, with three longitudinal-wave backwall echoes; no mode-converted shear-wave echo is seen. Reducing the beam width caused only a 5-dB reduction in the signal amplitude of the first backwall echo.

A longitudinal-wave echo produced by an actual defect can sometimes be distinguished from a spurious mode-converted shear wave by its reoccurrence throughout the entire decay pattern. This is illustrated in Fig. 17c (mirror masked as above), which shows the presence of a relatively strong laminar-type reflector $\sim 750 \mu\text{m}$ beyond the tube inner wall.

C. Computer Interfacing

The initial effort in writing the software for the National Semiconductor RMC-80/14 microcomputer has been completed and preliminary data have been obtained using the computer and ultrasonic probe. The general arrangement of the system is shown in Fig. 4. The microcomputer memory has 4 kilobytes each of RAM and ROM. The software was written in PLM language using the Intellac system. The program goes into ROM and is then loaded into the computer. The microprocessor instructions are communicated to the stepping motor via a translator board. Ultrasonic flaw signals and angular position signals are transmitted to the computer via the interface board. The stepping motor rotates a lathe-bed-type screw which allows the probe to be translated up and down. A small variable-voltage power supply is used to rotate the ultrasonic mirror.

The system operates in the following manner: The stepping motor is instructed to move a certain number of steps. After reaching this initial axial position, the computer waits for a signal indicating that the mirror has reached its initial angular position. This signal comes from the analog output of the gate, set on the reflection from the probe-mount posts. The computer then looks at the analog output from the gate of the pulser-receiver, set for detection of flaws; for example, at an echo transit time associated with outer-surface defects. This operation is carried out after every vertical movement of the probe. The vertical displacement between angular scans is determined by an instruction to the computer.

The total angular time for one revolution of the mirror is divided into several steps. The number of steps is decided by the operator. After each angular time interval, the computer looks for a flaw signal and stores it if it is above a specified threshold level. For example, if it is determined from an oscilloscope monitoring periodic echoes from the probe mounting posts, or calculated by the computer, that the motor is rotating once every 120 ms and that the angular time interval should be 1 ms, then the computer looks for a flaw signal after every 1 ms or three degrees of rotation. This can happen, for example, after every 10 steps of the motor. Thus, the probe is translated a fixed distance before it scans angularly for defects. Flaw signals are recorded after every 360° angular scan and printed out on the teletype. The Sonic Mark III output is operated in the "stretched" mode so as to hold the flaw signal long enough to assure that the computer will detect its presence.

An example of the instruction sequence and output is shown in Fig. 18. The information given to the computer is (1) "current position" of stepping motor, (2) "initial (vertical) position" desired (200 steps per revolution of stepping motor and 16 steps/mm of axial travel), (3) "final position" of stepping motor, (4) "position step" or number of steps of stepping motor between angular scans, (5) "number of points" or number of times data are taken at

each revolution, (6) "minimal recordable signal" (in units of 0.0025 V), (7) "motor inactive time", time between two consecutive steps of stepping motor in ms (determines vertical speed), (8) "amplifier gain" (in computer) of flaw signal, (9) "angle reference level" (the threshold for identifying angular position of mirror), and (10) instruction for computer to scan, operate manually, or produce output data.

A study was carried out to indicate the capability of the bore-side probe to detect an EDM notch while under complete microcomputer control. In this example, the probe was inserted into siliconized SiC Tube J (Ref. 15) and moved over an axial range of 13 mm. The computer printout correctly indicated the location of notch 3 (a circumferential, 500- μ m-deep x 1250- μ m-long outer-surface EDM notch) to within 0.25 mm. The printout is shown in Fig. 18. The mirror was rotating at a rate of 5 r/s. Flaw information was acquired after every 6° of angular displacement (about every 1.5 mm of circumferential travel), and angular scans were taken at 312- μ m (0.012-in.) or 5-step axial intervals.

The computer output shown in Fig. 18 indicates flaw signals at axial positions 970 and 975 for the first scan, and positions 965 and 970 for the second scan. Maximum flaw amplitudes of 105 and 117 units (equivalent to an analog output of $\sim$ 0.25 V) are indicated in the two passes of the EDM notch. The threshold level was set at 100 amplitude units. The analog output of the ultrasonic pulser-receiver was set for a gate that would only transmit flaw signals for reflectors near the tube outer wall. The "stretched" mode was employed, which means that the notch signal was held for about 20 ms; thus, the 1250- μ m-long notch, which should only be detected at one angular position, was recorded at several angular positions. (This assures that the notch will not be missed in a scan.) The notch was seen at more than one axial position because the beam spans about 3 mm of axial length (about 50 axial positions). Maintaining a threshold level of about 0.25 V prevented the notch signal from being recorded at even more locations. Since the signals are not recorded continuously and the motor driving the mirror does not maintain a constant speed (the speed varies by $\sim$ 20%), the output data is not entirely reproducible. Improvements are planned to minimize these problems. Comments next to the computer printout provide more details regarding this computer program and test. Although this scan was slow (2 mm/s), in principle it could be carried out at a rate of 500 mm/s (20 in./s). Work is progressing on modifications of the system to allow for this more rapid inspection rate.

Figure 19 shows a plot of the output data from the computer for detection of outer-surface circumferential notches 3 (1250 μ m long x 500 μ m deep) and 4 (250 x 125 μ m). In this example, the computer acquired data at approximately every 5° of angular rotation. The threshold level was set low so that the EDM-notch echo signal was "stretched" in time and recorded over almost 40° of angular displacement. Computer data were converted to angular degrees. (The data were acquired at two different axial positions with a relative rotation of the probe housing to generate a relative angular shift of the time plots). The data show the expected drop in signal amplitude with angular position, and proper relative signal strength.

D. Reproducibility of Axial Motion of Probe

The stepping motor that drives the probe axially has 400 steps/in. of vertical travel; thus, each step or count of the motor moves the probe up or

down by 64 μm (0.0025 in.). The system was checked to establish whether an axial position could be reproduced to within $\sim 100\ \mu\text{m}$. Figure 20 shows the traces obtained (a) at the position of hole "c" (1.5-mm-dia) in Tube J, (b) after the probe was lowered $\sim 13\ \text{mm}$, and (c) after the probe was returned to the original position. These movements were controlled by the microcomputer. The echo pattern obtained after the probe traversed 13 mm and returned is virtually the same as the original. Other tests with longer axial motions lead to the same conclusion: The system, as currently designed, can be returned to a location with an error of less than 100 μm .

IV. ACOUSTIC MICROSCOPY

The fundamentals of acoustic microscopy and its application to NDE of ceramic components have been discussed in previous reports.^{10,15} In the previous annual report,¹⁵ it was concluded that acoustic microscopy could be adapted to preservice inspection of tubing and that the acoustic-microscope system could, in principle, be used for industrial applications. It would probably be most valuable as a means of characterizing indications found by other techniques, such as conventional ultrasonic testing. Acoustic microscopy may also be useful for general materials characterization in cases where microstructural variations can be related to variations in acoustic transmission properties. In this regard, it may be especially useful for examining ceramic butt joints, since variations in acoustic transmission across joints may be correlated with variations in bond quality.

The instrument used in the present investigation was the Sonoscan Sonomicroscope 100, which can be operated at ultrasonic frequencies of about 30-500 MHz. At 100 MHz, the ultrasonic wavelengths are of the order of 120 μm for longitudinal and 75 μm for shear waves in SiC.

Ultrasonic energy creates mode-converted shear waves in the specimen. The transmitted acoustic energy imparts a slight oscillatory mechanical motion to the top surface of the sample. These oscillations have the same frequency as the incident wave, but vary in amplitude depending on the acoustic attenuation properties of the underlying material. These disturbances are detected, point by point, by a rapidly scanning focused laser beam (40,000 image points per micrograph), which drives an optoacoustic receiver. The resultant acoustic image is displayed on a TV monitor. If the sample has a smooth surface finish, the acoustic image can be produced with the light specularly reflected from the surface. Otherwise, a mirrored coverslip is placed in acoustic contact with the top surface of the sample, using water as a couplant, and light reflected from the coverslip is used to form the acoustic image; this was the case for all samples in the present investigation.

Data may be presented in the form of both single-frequency and frequency-modulated acoustic-amplitude micrographs. In both types of picture, the lighter regions correspond to low-attenuating zones while darker regions correspond to more highly attenuating zones. The distinction between the two image types lies in their sensitivity to image features arising from coherent sound scattering. When single-frequency insonification is employed, sound scattered from elastic discontinuities can combine at the detector to produce high-contrast features termed acoustic speckle; the amount of speckle is related to the degree of scattering. In some applications, the speckle is a

MODE	θ
LONGITUDINAL	45°
SHEAR (AXIAL)	49°
SHEAR (CIRC.)	45° WITH 1-mm OFFSET

(a)

Fig. 3. (a) Schematic Drawing of Ultrasonic Bore-side Probe; (b) Photograph of Probe Mounted on Stand; (c) Close-up View of Lower Part of Stand.

Fig. 3 (continued)

Fig. 4. Schematic Representation of Ultrasonic Bore-side Probe and Associated Electronics.

Fig. 5. Schematic Drawing Showing Locations of Flat-bottom "Reference" Holes in Siliconized SiC Tube J (Norton C430).

Fig. 6. Ultrasonic Echoes from Flat-bottom Holes A, B, and C of Fig. 5. Peaks marked with lowercase letters are signals from the respective holes; the large peaks at the left are reflections from the water/tube interface.

NOTCH*	TYPE	LENGTH (μm)	DEPTH (μm)
1	OD AXIAL	1250	500
2	OD AXIAL	250	125
3	OD CIRC.	1250	500
4	OD CIRC.	250	125
5	ID AXIAL	1250	500
6	ID AXIAL	250	125
7	ID CIRC.	1250	500
8	ID CIRC.	250	125

* NOTCH WIDTH 75 μm

Fig. 7. Schematic Showing Placement of Axial and Circumferential EDM "Reference" Notches in SiC Tubes J (Siliconized) and SRI (Sintered).

Fig. 8. Radio-frequency Signals (Arrows) from (a) 500- μ m-deep and (b) 125- μ m-deep Outer-surface Notches in Siliconized Tube J, Detected with an Aerotech UTA-3 Pulser-Receiver from 1/2 V Position as Defined in (c); Frequency Spectrum Obtained from Signal (a) is shown in (d). Horizontal scale in (d) is 0-50 MHz; the peak in the spectrum is at 23 MHz.

Fig. 9. Ultrasonic Echo Signals (Arrows) from the 500- μ m-deep Outer-surface Notch in Tube J, Detected from the (a) $1/2$ V and (b) $1-1/2$ V Position Using a Sonic Mark III Pulser-Receiver. Attenuations are 22 and 12 dB, respectively.

(a)

(b)

Fig. 10. Ultrasonic Echo Signals (Arrows) from the 125- μ m-deep Outer-surface Notch in Tube J, Detected from the (a) 1/2 V and (b) 1-1/2 V Position Using a Sonic Mark IV Pulser-Receiver. Attenuations are 12 and 6 dB, respectively.

(a)

(b)

Fig. 11. Ultrasonic Echo Signals (Arrows) from the (a) 500- and (b) 125- μm -deep Inner-surface Notches in Tube J, Detected from the 1 V Position Using a Sonic Mark IV Pulser-Receiver. Attenuations are 10 and 6 dB, respectively.

Fig. 12. Ultrasonic Echo Signal (Arrow) from the 125- μ m-deep Outer-surface Notch in Tube SRI, Detected from the 1/2 V Position Using a Sonic Mark III Pulser-Receiver. Attenuation is 8 dB.

Fig. 13. Ultrasonic Echo Signal (Arrow) from an Unidentified Natural Flaw at the Outer Surface of Tube SRI. Experimental arrangement same as for Fig. 12. Attenuation is 8 dB.

Fig. 14. Strip-chart Recordings Showing Ultrasonic Signal Indications (Arrows) from Four Circumferential Notches in Tube J. The other large signals are reflections from the probe-mount posts, located 180° apart.

Fig. 15. Strip-chart Recording Showing Ultrasonic Signal Indication (Arrow) from 125- μ m-deep Circumferential Outer-surface Notch in Tube SRI. Broad signals are from the probe-mount posts. One other significant signal, next to the notch signal, has not yet been identified.

Fig. 16. Schematic Representation Showing Conversion of Longitudinal Waves into Shear Waves, and Reconversion to Longitudinal Waves, at Water/Tube-wall Interface.

Fig. 17. "A-scans" of a SiC Tube, Employing a Sonic Mark III Pulser-Receiver and Ultrasonic Bore-side Probe Operating at 20 MHz. (a) Multiple longitudinal backwall echoes $0.5 \mu\text{s}$ apart (1-4) and mode-converted shear wave (S): (b) multiple longitudinal backwall echoes with the ultrasonic bore-side probe mirror masked to reduce the beam width to $\sim 1 \text{ mm}$; (c) multiple longitudinal backwall echoes (1-9) and multiple reflections (r) from a laminar-type reflector

```

PROBE
PROGRAM NAME (0 TO QUIT)
I

CURRENT POSITION
0000'

INITIAL POSITION
00000
1 | FINAL POSITION
  | 01200
2 | POSITION STEP
  | 00005
3 | NUMBER OF POINTS
  | 00060
4 | MINIMUM SIGNAL
  | 00100
5 | MOTOR INACTIVE TIME
  | 00025

AMPLIFIER GAIN (1,2,4,8)
00001

6 | ANGLE REFERENCE LEVEL
  | 00400
7 | PROGRAM NAME (0 TO QUIT)
  | S

8 - COUNTS PER REVOLUTION= 00062
9 - SAMPLE PERIOD= 00001
  CURRENT POSITION=00970 00040-00102c
  CURRENT POSITION=00975 00057-00105

10 | PROGRAM NAME (0 TO QUIT)
    | S

COUNTS PER REVOLUTION= 00074
SAMPLE PERIOD= 00001
CURRENT POSITION=00965 00035-00102
CURRENT POSITION=00970 00057-00113 00050-00117 00059-00104

```

1. Distance of 25 mm between initial and final positions.
2. Tube scanned after every 0.3 mm of axial motion.
3. 60 data points per revolution.
4. A signal with amplitude ≥ 100 units (= 0.25 V of analog output from pulser-receiver) indicates presence of a flaw.
5. 25-ms pause between steps of motor.
6. Signal from support rib provides trigger for marking 0° point of each angular rotation.
7. Start of Scan 1.
8. Time after trigger signal for one rotation of mirror, as calculated by computer (1 count = 3 ms).
9. Axial position (a), angular position (b), and amplitude (c) of first above-threshold signal in Scan 1.
10. Start of Scan 2.

Fig. 18. (Left) Computer Printout of Two Microcomputer-controlled Ultrasonic Scans of SiC Tube J, Indicating Same Notch at Location 970-975 (Scan 1) and 965-970 (Scan 2). (Right) Explanations of Numbered Lines in Printout.

Fig. 19. Comparison of Ultrasonic Signal Levels for Large and Small Notches as Recorded by the Microcomputer.

Fig. 20. Ultrasonic Echoes from (a) 1.5-mm-dia Hole in Tube J, (b) Region of Tube 13 mm Below 1.5-mm-dia Hole, and (c) 1.5-mm-dia Hole After Computer-controlled Traverse Back to Original Position. Traces (a) and (c) are virtually identical.

Fig. 20.

valuable characterization parameter, while in other applications (e.g., NDE), speckle produces an unwanted background. By sweeping the acoustic frequency over a variable bandwidth of, for example, a few MHz around 100 MHz, the contribution of speckle features to the images can be minimized. Thus, frequency-modulated amplitude micrographs are often used in NDE applications where speckle might mask underlying flaws. In the present work, only frequency-modulated amplitude micrographs are shown.

In addition to displaying the acoustic amplitude distribution throughout the field of view, the Sonomicroscope provides an acoustic-interference mode of operation which provides access to acoustic phase information. The phase information is presented pictorially as dark bands (interference fringes, $\sim 100 \mu\text{m}$ apart). For acoustically homogeneous and flat samples, these bands are parallel to one another and are equally spaced. For samples that are elastically inhomogeneous, the interference lines are distorted by the localized variations in the sound velocity and/or sample thickness. These variations are, in turn, related to variations in either the bulk density or elastic modulus of the sample constituents. Quantitative sonic-velocity data are obtained by measuring the fringe displacements. Acoustic interferograms presented in this investigation are oriented so that fringe shifts to the left and right correspond, respectively, to areas of lower and higher ultrasonic velocity.

A. Effect of Microstructure on Acoustic Imaging

In a very general way, SiC tubes can be classified in terms of their acoustic transmission properties. The two properties that are important in microscopy are attenuation and beam coherence. Attenuation refers to the ability of a sample to conduct sound. From a microscopist's standpoint, only a level of sound transmission sufficient to produce images is required. For example, at 100 MHz the system dynamic range is 60 dB. Good images require a dynamic range of at least 20 dB; thus, samples with attenuation >40 dB are not well suited for imaging at 100 MHz and a lower acoustic frequency (say, 30 MHz) would have to be used. Beam coherence is a somewhat more elusive parameter. It refers specifically to the background interference encountered in transmitting sound through a structure, and can be qualitatively estimated by the continuity of the interferogram fringes.

Beam coherence has a strong influence on the visibility of flaws in the midst of the background structure, and has emerged as an important parameter in the characterization of SiC. Observations indicate that the presence of porosity in SiC increases the attenuation but does not have a deleterious influence on beam coherence. Thus, porous sintered material, though attenuating, generally retains beam coherence and can be imaged very easily at 100 MHz (as long as the attenuation does not exceed 40 dB). On the other hand, some SiC tubes (siliconized) with large grain structures and/or substantial amounts of unreacted material have been found to render the sound field incoherent. These materials, though not highly attenuating, are difficult to image at 100 MHz and lower acoustic frequencies are desirable.

B. Operating the Acoustic Microscope at 30 MHz

As discussed above, by reducing the operating frequency of the acoustic microscope to 30 MHz, interference from the intrinsic background structure of

SiC tubes may be reduced and thus the detection of flaws may be enhanced. The resolution will be reduced at 30 MHz, but not necessarily to the point where 100- μ m defects would be missed.

A standard 100-MHz scanning laser acoustic microscope was modified for 30-MHz operation. The laser-beam scanning electronics and a portion of the optics remained unchanged. Modifications to the microscope included:

- (1) 30-MHz drive unit for the transducer.
- (2) 30-MHz photodiode and preamplifier.
- (3) Extended optical track to accommodate longer focal length lenses.
- (4) Fabrication of one new circuit board for the receiver module.
- (5) 30-MHz transducers with elements 10 x 14 mm in size, larger than the normal 100-MHz elements (4 x 5 mm). The active element of the 30-MHz transducer is quartz and is mounted in a stainless steel housing which also accommodates the matching network. A rectangular housing was designed to fit tightly into the bore of the tubes.

The new transducer design is compatible with the scanning system developed for the 100-MHz probe. Straightforward adaptation of the transducer mounting fixture permits implementation of the 30-MHz system. However, in the present study, the new transducer was mounted on a long arm which was inserted into the tube sections. This approach was ideally suited for the characterization of short tube segments, and permitted the rapid evaluation of four different tube segments. Longer segments would be most easily examined using a helical scanning system similar to that previously developed, or by insonification from outside the tube (as discussed below, in Section IV.C.2).

Below is a short description of four tubes analyzed in this study, which were characterized and ranked in terms of their attenuation and beam coherence.

Tube No. 1, sintered (Norton). This tube was not analyzed at 100 MHz. At 30 MHz, transmission and beam coherence were generally good and the interferogram fringes continuous, although regions with incoherent zones were found.

Tube No. 2, sintered (Carborundum). At 100 MHz, the majority of the tube exhibited incoherent propagation; only four zones around the circumference showed good beam coherence. Numerous zones with indications of laminar flaws were found. At 30 MHz, beam coherence was typically better than with Tube No. 1. Numerous laminar flaws were encountered and attenuation was comparable to that found in Tube No. 1.

Tube No. 3, siliconized (Carborundum). No results are available on the intact tube at 100 MHz. At 30 MHz, the tube showed a high level of transmission and the most beam incoherence of any of the four tubes investigated at this frequency. Laminar flaws were also detected in this tube.

Tube No. 4, sintered (Carborundum). This tube was examined at 100 MHz and found to be 30 dB more attenuating than the cleanest zones of Tube No. 2. Attenuation was $\sim$ 10 dB higher than for the other tubes. Beam coherence was

typically very good. Some zones of incoherent propagation were encountered.

All the micrographs described below were obtained at 30 MHz, using circumferential through-wall insonification (see Section IV.C.1 below). The field of view is 10.0 x 7.6 mm. Amplitude micrograph TA3-28 (Fig. 21) shows a typical region of Tube No. 1. This area is relatively free from grain structure and has good acoustic transmission. Amplitude micrograph TA3-29 (Fig. 22) depicts a defective region in Tube No. 1. The defective region appears as a dark clump in the center, where a continuous vertical bright area would normally be seen. In the interference mode, the fringes appear scrambled in this area. Micrograph TA3-13 (Fig. 23) is an interferogram of an area of Tube No. 3 with uniform acoustic transmission. The fringes are relatively straight through the region of best transmission. Micrograph TA3-2 (Fig. 24) shows an example of a flaw or anomalous region encountered in Tube No. 3. The fringes are straight at the top and bottom portions of the field but are scrambled in the center. Micrograph TA1-26 (Fig. 25) is an interferogram of a region of Tube No. 4 with good acoustic transmission. The straight fringes are indicative of the homogeneity of this area of the sample. Micrograph TA1-8 (Fig. 26) is an amplitude micrograph showing the longitudinal EDM notch in Tube No. 4 in the area of best transmission. This 1-mm-long notch is located on the outer surface of the tube. Micrograph TA2-4 (Fig. 27) shows a circumferential EDM notch on the outer surface of Tube No. 4; it appears as a dark horizontal line in the bright region. Micrograph TA2-10 (Fig. 28) shows a dark horizontal line in the area of best transmission, corresponding to a naturally occurring crack or flaw in Tube No. 4. Notice the similarity between this reflector and the circumferential EDM notch in Fig. 27.

C. Comparison of Sound-transmission Configurations

The above results, and those of previous work,¹⁵ have demonstrated the feasibility of through-wall inspection (with circumferential insonification from the inner to the outer surface) for cracks and other structural elastic inhomogeneities in short, water-filled SiC tube segments. However, other insonification geometries are possible. In the following paragraphs, studies on the use of several different geometries are discussed. Also, tests of acoustic lenses fabricated at ANL are described, and the observations compared with results obtained without lenses.

1. Through-wall Imaging

(a) Comparison of Axial and Circumferential Insonification

Through-wall insonification may utilize either an axial or circumferential geometry; these are shown schematically in Figs. 29 and 30, respectively. Both geometries produce bright-field acoustic images that are similar in size and general appearance to optical images. Early efforts in acoustic microscopy were carried out using axial insonification geometry, and successful detection of laminar flaws and cracks in tubes was initially demonstrated using this configuration. Circumferential insonification geometry was later found to be useful for revealing EDM notches in otherwise intact tubes.

In axial through-wall insonification (Fig. 29), sound impinges on the inner surface of a tube with the transducer tilted about the y-axis, so that sound traveling through the tube has both x and z vector components. A typical image produced using this axial insonification geometry is shown in Fig. 31. The two primary characteristics of images obtained using axial insonification are (1) an aperture limited by the tube curvature, and (2) curved fringes. The aperture is caused by the large sonic-velocity difference between the water couplant and the SiC tube, in conjunction with the curved geometry. In the micrographs, the bright horizontal zone in the center (~ 3 mm wide) represents the usable portion of the image. Large phase shifts and mode conversion occur in the portions of the sound field above and below this high-transmission band, making these regions useless for flaw detection. The curved fringes are interpreted in terms of transit time through the sample. A single fringe traces out a semicircular trajectory as one follows it from the top to the bottom of the micrograph. The point farthest to the right represents the zone of shortest transit time. Above and below this point the transit time increases, as indicated by the leftward curvature of the fringe. The gentle curvature is attributable to the tube geometry; deviations from this curvature represent local nonuniformities.

Circumferential through-wall insonification geometry (Fig. 30) differs from the axial geometry discussed above in that the transducer is tilted about the z-axis (parallel to the tube axis) and the sound propagating through the tube has no z-axis component. This configuration appears to enhance the visibility of EDM notches without reducing the sensitivity of the system to laminar flaws. Images obtained with the two configurations exhibit some similar characteristics; however, the interferogram fringe pattern is quite different. Typical 30-MHz images obtained in the circumferential configuration are shown in Figs. 21-28, 32, and 33. The sound is still aperture-limited; however, in this case the central high-transmission band is vertical. On either side of this lighter band, the propagation is decreased and substantial phase shifts occur. Therefore, only the central portion is used for flaw characterization. The acoustic interferograms contain straight vertical fringes; however, the fringe spacing gets progressively smaller from right to left. This is the results of refraction of the sound by the tube wall and indicates a steeper angle of incidence on the coverslip as one goes from right to left across the field of view (see Fig. 30). The steeper the incident angle measured from the coverslip normal, the finer the fringe spacing.

In general, imaging of flaws in the SiC tubes by circumferential through-wall insonification was relatively tolerant of the insonification angle. However, visibility varied (particularly for outer-surface notches) as the flaw was rotated through the fixed sound field. This effect is illustrated in the series of micrographs shown in Fig. 34; these were taken with circumferential insonification in the vicinity of the EDM notch shown in Fig. 33a. The notch is located at the right edge, center, and left edge of the sound field in Figs. 34a, b, and c, respectively. The notch is readily detected when positioned at either edge of the sound field, but not when positioned in the middle. This effect is much more dramatically illustrated during real-time viewing on the monitor; the notch is visible "coming and going", but disappears when in the center of the field.

The explanation for these observations lies in the fact that as the notch is rotated, the propagation angle of the interrogating sound wave relative to

the notch varies continuously. At some orientation the sound wave is exactly parallel to the notch axis and thus the reflection is difficult to observe. Additionally, copious mode conversion at the notch makes this flaw type a strong radiator of acoustic energy, which in certain orientations will add to the incident beam and mask its presence. The latter statement is supported by the ability of the system to produce dark-field images. These can be obtained because the laser detection method is sensitive to the incident angle of sound impinging on the coverslip. Thus, dark-field images are produced by placing the notch in a region of the sound field that is not normally detected by the laser beam. Acoustic energy is scattered by the flaw into the angular-acceptance aperture of the laser scanner, as illustrated in Fig. 35. In this situation, the flaws (Fig. 36) appear bright. In the normal transmission mode (Fig. 33) the flaws are dark because we are detecting the energy they have removed from the interrogating beam.

(b) Focusing Effects Observed with Circumferential Insonification

The schematic diagram of Fig. 30 shows the refraction (focusing) of the sound field that accompanies circumferential insonification. (The actual situation is even more complicated than that shown; as discussed in Section IIIB, normal-incidence longitudinal waves mode-convert to shear waves at the tube inner surface, forming two foci, one for shear waves and one for longitudinal waves. In practice, the two sound fields overlap spatially.) Two features in the acoustic images may be attributed to the curved tube geometry: (1) The sound field is apertured by critical-angle considerations at the input surface, and (2) the focusing of the sound field by the tube wall leads to distortion in the images of buried flaws. This will influence the interpretation of flaw type as well as the estimation of flaw size. Three regions of the sound field should be considered: (1) above the focal zone, near the outer surface; (2) at the focal zone; and (3) below the focal zone, near the inner surface. For flaws in region (1), the images resemble those obtained from the planar insonification. However, as flaws successively closer to the focal zone are detected, increasingly magnified images are obtained. At the focal zone, the projected image of a flaw may fill the entire field of view of the micrograph. For example, a flaw might be indicated by transformation of the entire field of view from light to dark. In region (3), the images will be inverted and magnified. Structures in the images arising from flaws in this zone possess the unique characteristic that as the tube is rotated in one direction, the structures move in the opposite direction.

An acoustic lens can be used to convert the incident plane wave into a cylindrically diverging wave and thus compensate for this focusing effect, as illustrated in Fig. 37. By matching the curvature of the sound field to the curvature of the tube inner wall, the critical-angle aperturing effect and complex image characteristics associated with the focused sound field can be eliminated. What we are doing is converting the cylindrical component imaging problem into the more familiar plane-wave imaging problem. A large body of data exists for flaw characterization in ceramics using planar insonification; the lens approach would permit us to take full advantage of this data base.

Diffusing lenses were fabricated from aluminum bar stock, which is easily machined and has a sufficiently clean acoustic structure to allow testing of the lens concept. The lenses were placed on top of a standard 30-MHz sound

cell in the configuration shown in Fig. 37. The acoustic amplitude micrograph and interferogram in Fig. 38 illustrate the divergent sound field produced by and aluminum lens with a 10-mm radius of curvature. The speckle in the pictures results from grain-boundary scattering in the lens. Although the curvature of the lens matches that of the inner surface of the SiC tube, the curvature of the sound field is not sufficient to fully compensate for the tube geometry, owing to the large sonic velocity difference between aluminum and SiC.

The effect of the lens on the acoustic image of a tube segment is shown by a comparison of Figs. 39 (without lens) and 40 (with lens). In Fig. 40, the sound field is wider and the fringes are straighter; however, greater sound-field curvature (more diffusing of the beam) is still needed. Additionally, artifactual sound-field structure arises from grain structure in the aluminum, reverberation in the lens, and reverberation in the space between transducer and lens. All of these limitations can be overcome by better lens design, better material choice, and direct bonding of the piezoelectric element to the lens.

Other lenses made from glass and silicon nitride were fabricated at ANL and tested in a similar fashion to the aluminum lens. These materials were acoustically clean and therefore did not contribute to the image; however, reverberation was a more serious problem because these lenses were much thinner than the aluminum lens.

We conclude that the concept is viable but that appropriate lens design is essential to realize the desired experimental results. Specific conclusions are as follows:

- (1) The aluminum lens produced the expected result, i.e., flattening of the sound field.
- (2) Reverberation of sound in the lens produced a significant amount of artifactual structure in the image, but this can be eliminated by careful design.
- (3) Reverberation of sound in the space between the lens and the transducer also produced artifacts, but this can be eliminated by bonding the piezoelectric element directly to the lens.

2. Reflection Imaging

Axial and circumferential insonification geometries can also be used in the external mode, with both the transmitting transducer and the receiving scanning laser located outside the tube. Both methods are useful for flaw characterization, as demonstrated below.

(a) Axial Insonification

From a standpoint of image quality, axial insonification appears to be superior to circumferential insonification for reflection imaging. With axial insonification, the sound is transmitted through the tube, reflected from the inner surface, and detected at the coverslip, as shown schematically in Fig. 41. Figures 42 through 44 show, respectively, a "clean" zone, a buried inclusion, and axial outer-surface notches in tube SRI, all imaged by axial insonification.

(b) Circumferential Insonification

Figure 45 illustrates the geometry for external circumferential insonification. Figures 46 and 47 schematically illustrate the propagation of shear waves and longitudinal waves in a SiC tube undergoing such insonification. Successful use of the technique requires a smooth tube surface. In practice, the axial positions of the tube and coverslip were fixed and the tube was rotated about its long axis. Empirically, we found that for a given circumferential location of the transducer, a transducer alignment could be found which produced a good image of the notches. The movements of the transducer holder were too imprecise to allow accurate measurement of the angles. However, the image quality could be easily reproduced and did not appear to require a unique combination of transducer location and angulation. For precise location of buried flaws, both angles and working distance (separation between transducer and sample) need to be accurately measured.

Interpretation of the images produced by external circumferential insonification requires an understanding of the propagation paths followed by the sound. The sound reaching the coverslip appears to segment into three distinct fields; an interpretation of their origins is shown in Fig. 48, and Figs. 49 and 50 illustrate the characteristics of the three sound fields. Sound field #1 probably corresponds to that portion of the incident energy which passes through the tube wall, is reflected from the inner surface, and impinges on the coverslip. Sound field #2 appears as a bright vertical band directly to the right of sound field #1. It is not clear why sound field #2 appears as a well-defined unit; however, the large longitudinal notch in the tube appears as a dark zone (circled). The lack of shadowing, together with the invariant visibility and shape of the flaw indication as the flaw is rotated through the field, suggests that this bright zone results from specular reflection of sound from the outer surface of the tube (Fig. 48). Sound field #3, visible in Fig. 50, also results from the specular reflection of sound from the outer tube surface. Clearly, only sound field #1 will be of use in probing the interior of the sample.

Figure 51 shows an image of the large axial EDM notch. The image was produced using circumferential insonification, with the notch in sound field #1. The width of the shadow indicates a steep propagation angle relative to the notch. This insonification method may be suited for measuring crack extension.

D. Conceptual Design for Inspection of Seven-foot Lengths of Tubing

In this and previous reports, it has been shown that ceramic heat-exchanger tubes can be characterized with the acoustic microscope, and that complete characterization of flaws requires a dual operating frequency of 30 and 100 MHz. In particular, 100 MHz has shown the strongest potential for detailed analysis of inner-surface flaws by through-wall imaging, while 30 MHz is optimal for reflection imaging and for detecting outer-surface flaws. Reflection imaging offers an advantage in that the transducer assembly is outside the tube and nothing need be inserted. Also, we have observed substantial attenuation differences among the various samples tested, which may preclude the use of the 100-MHz system in some tube types.

The conceptual design described below is basically an extension of the system already employed to inspect short tube segments. The output of this system is simultaneously available in three forms: (1) CRT image in real time, (2) video print on thermal roll paper, and (3) output for direct computer interfacing. Of course, photographs of the CRT output are also available. Flaw characteristics and positions are stored in the memory for long-term follow-up of tube performance under service conditions. For purposes of discussion, the long-tube inspection system may be divided into the following components:

- (1) Transducers.
- (2) Through-wall transmission stage.
- (3) Reflection stage.
- (4) Tube-positioning apparatus.
- (5) Detection system.

The detection system, a scanning laser acoustic microscope, has been discussed above, as well as in previous reports of this series and in the open literature. The other elements of the system are described below.

1. Transducers

The piezoelectric elements used as ultrasonic transducers in acoustic microscopy can be rather delicate, owing to their high operating frequency. Therefore, backings will be used to provide mechanical support. For use in microscopy, the transducers must have uniform output over the field of view. Each will be electrically matched to a 50- Ω line for optimum performance. It is particularly important to accomplish the matching near the piezoelectric element so that cable length variations do not affect the output. Transducers have been fabricated with a piezoelectric element and matching network in a small watertight housing that will fit inside the tube.¹⁵ This is essential for through-transmission inspection. For reflection imaging, the size limitations on the transducer housing can be relaxed. The transducer for use inside the tube will also contain integral spring-loaded bearings to guide it along the inner surface as the tube position is indexed. Both transducers will be embodied within an articulation mechanism to allow for some flexibility during inspection of specific defects.

2. Through-wall Transmission Stage

The techniques developed for inspection of short tube segments should be adaptable to long tubes. The acoustic microscope produces images by scanning a laser beam over a plastic mirror (coverslip), which is in close proximity to the subject being visualized. The mirror surface, which has impressed upon it an optical phase replica of the acoustic image, acts as the receiving plane. For through-wall imaging, the source (transducer) is placed on the opposite side of the sample from the coverslip. In the case of a tube, the transducer is inserted within the tube bore, whereas the coverslip is on the outer surface. The acoustic energy must be coupled to the sample and coverslip with a fluid. This is accomplished by filling the tube with water. Caps on either end of the tube retain the water and provide ports for filling and emptying. The coverslip is acoustically coupled to the outer surface by a continuous but slow water stream dripping onto the tube in the vicinity of the coverslip. The water is retained by capillary action. Excess water is

captured in a tray below and recycled to the coverslip.

The transducer housing is mounted on a gimbal so that the transducer can be angulated both axially and circumferentially. This angle will be controlled externally; thus, circumferential insonification as well as axial insonification can be accomplished with a single transducer.

3. Reflection Stage

For reflection imaging, the transducer and coverslip will be located on the outer surface of the tube and coupled by means of a flowing stream of water, as shown in Fig. 52. No water need be placed inside the tube. The position and angle of the transducer with respect to the tube will determine the insonification technique, e.g., shear, longitudinal, or surface waves. Thus, it will be possible to change the imaging mode as needed to enhance and analyze different types of anomalies.

4. Tube-positioning Apparatus

In either stage configuration, the transducer and coverslip have to be adjusted with respect to the tube and to each other, and the tube then rotated and translated through the field of view. The movement through the field of view will be helical during scanning, but also adjustable for pure rotation or pure translation. Since the tubes to be inspected can be up to 7 feet long, a system up to 14 feet long will be required. The acoustic microscope itself will be modified in several ways. For example, the laser scan will be capable of 90° rotation to make the vertical scan axis parallel to either the circumference or the long axis of the tube. This is necessary in order to achieve the axial and circumferential insonification geometries described earlier. Also, the field of view and laser spot size will be switchable for the dual 30/100-MHz frequencies.

Figure 53 shows the overall design for an acoustic microscope system for through-wall imaging of long tubes. (For reflection imaging, the mechanism for filling the tube with water and sealing it, along with the rod for holding the transducer and matching network, would be replaced by the arrangement shown in Fig. 52.) The advantages and disadvantages of through-wall and reflection imaging have been discussed in previous sections. More experience with the two types of systems will be necessary to determine whether just one would be practical and adequate to obtain the flaw characterization desired.

V. NDE FOR CERAMIC JOINTS

The successful operation of ceramic heat exchangers will depend on the proper fabrication and adequate testing of ceramic-to-ceramic joints. Suitable NDE methods will be needed to detect, locate, and size flaws, detect regions of high stress or strain, and detect anomalies in the microstructure of the joint. In the preliminary efforts reported here, pitch-catch angle-beam shear-wave testing as well as RT, PT, and holographic interferometry have been examined for application to butt joints in NC430 tubes, and IR scanning has been used to inspect a glass-adhesive overlap joint in a SiC tube. The overlap joint is used where relative motion (or telescoping) of the overlapped

TA3-28

Fig. 21. Amplitude Micrograph of Homogeneous Section of Tube No. 1.

TA3-29

Fig. 22. Amplitude Micrograph of Defective Region of Tube No. 1.

Fig. 23. Interference Micrograph of Homogeneous Region of Tube No. 3.

Fig. 24. Interference Micrograph of Defective Region of Tube No. 3.

TA1-26

Fig. 25. Interference Micrograph of Homogeneous Region of Tube No. 4.

TA1-8

Fig. 26. Amplitude Micrograph Showing Axial EDM Notch (250 x 500 μm deep) on Outer Surface of Tube No. 4.

TA2-4

Fig. 27. Amplitude Micrograph Showing Circumferential EDM Notch ($\sim 1250 \times$ 500 μm deep) on Outer Surface of Tube No. 4.

TA2-10

Fig. 28. Amplitude Micrograph Showing Natural Flaw in Tube No. 4.

Fig. 29. Insonification Geometry Used to Generate Axially Propagated Through-wall Ultrasonic Waves for Detection by Acoustic Microscopy.

Fig. 30. Insonification Geometry Used to Generate Circumferential Through-wall Ultrasonic Waves for Detection by Acoustic Microscopy.

AT1 -32

AT1 -33

Fig. 31. Typical Acoustic Micrographs of SiC Tube Using Geometry of Fig. 29.

Fig. 32. Typical Amplitude Micrograph (30 MHz) of SiC Tube Using Geometry of Fig. 30.

Fig. 33. Acoustic Amplitude Micrographs of Axial EDM Notches (Circled) in the Outer Wall of SiC Tube SRI, Obtained Using Through-wall Circumferential Insonification. Notch dimensions: (a) 1250 μm long x 500 μm deep; (b) 250 μm long x 125 μm deep.

Fig. 34. Acoustic Amplitude Micrographs Taken in the Vicinity of the Notch Shown in Fig. 33a, with Through-wall Circumferential Insonification. The sketch below each micrograph shows the approximate location of the notch relative to the sound field and coverslip. The notch is visible in (a) and (c), but not in (b).

Fig. 35. Schematic Illustrating the Geometry and Principles of Acoustic Dark-field Imaging.

Fig. 36. Dark-field Images of Same Notches Shown in Fig. 33.

Fig. 37. Schematic Showing the Use of a Diverging Lens to Prevent Sound Focusing Within the Tube Wall.

Fig. 38. Acoustic Amplitude Micrograph (Top) and Interferogram of Tube SRI, Showing the Characteristics of a Sound Field Propagated through an Aluminum Lens with a 10-mm Radius of Curvature.

Fig. 39. Acoustic Amplitude Micrograph (Top) and Interferogram of Tube SRI, Showing Typical Image Characteristics Obtained by Through-wall Plane-Wave Insonification of a Tube Segment.

Fig. 40. Acoustic Amplitude Micrograph (Top) and Interferogram of Same Tube Section Shown in Fig. 39, Obtained by Through-wall Insonification with an Aluminum Lens. Note the increased aperture size and straightening of the fringes compared with Fig. 39.

Fig. 41. Schematic Showing External Axial Insonification.

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Fig. 42. Acoustic Amplitude Micrograph (Top) and Interferogram of "Clean Zone" in Tube SRI, Obtained with External Axial Insonification.

AFT3 24-25

Fig. 43. Acoustic Amplitude Micrograph (Top) and Interferogram of Buried Inclusion (Circled) in Tube SRI, Obtained with External Axial Insonification.

Fig. 44. Acoustic Amplitude Micrographs of the Two Axial Outer-surface Notches Shown in Fig. 33, Obtained with External Axial Insonification.

Fig. 45. Schematic Showing External Circumferential Insonification of a Tube.

Fig. 46. Ray-tracing Diagram Showing Propagation of Shear Waves in a Tube Undergoing External Circumferential Insonification.

Fig. 47. Ray-tracing Diagram Showing Propagation of Longitudinal Waves in a Tube Undergoing External Circumferential Insonification.

Fig. 48. Schematic Showing the Approximate Locations of the Three Sound Fields Created by External Circumferential Insonification.

AFT2 28

Fig. 49. Acoustic Amplitude Micrograph (Top) and Interferogram of Tube SRI with External Circumferential Insonification. Image of EDM notch is circled. Numbers on micrographs refer to sound fields defined in Fig. 48.

Fig. 50. Interferogram Produced by External Circumferential Insonification. Numbers refer to sound fields defined in Fig. 48.

Fig. 51. Acoustic Amplitude Micrograph Produced with External Circumferential Insonification, Showing Longitudinal EDM Notch (Circled).

Fig. 52. Schematic of Tube Scanner Operating in Reflection Mode.

(a)

(b)

Fig. 53. Conceptual Design for Through-transmission Acoustic Microscopy of Long SiC Tubes. (a) Isometric view; (b) schematic of overall system; (c) details of regions A, B, C, D of (b).

(c)

Fig. 53. (continued)

tubes is necessary to compensate for thermal expansion and contraction. The characteristic flow of the glass adhesive at high temperature allows for this relative motion.

A. Comparison of Ultrasonic, RT, and PT Methods for Testing a Butt Joint

Previous reports^{13,15} in this series discussed the detection, by holographic interferometry, of a subsurface crack-like flaw in a 150- μ m-wide butt joint of an NC430 SiC tube (J6). Figure 3 shows a micrograph of a ceramic joint (arrow) in a similar tube. The small grain size of the joint relative to the tube wall is evident. Tube J6 was examined by PT, RT, and ultrasonic techniques to compare the effectiveness of these methods with that of holographic interferometry.

In the first test, the outer surface of tube J6 was exposed to a fluorescent dye penetrant. The results were somewhat ambiguous because of the irregular surface. A linear indication was seen in the outer surface of the joint in the region where the interferometry suggested an inner-surface crack, but the dye washed out very easily, suggesting that the indication was due to a slight step or mismatch in the joining of the tubes.

The tube was then radiographed, and again the results were ambiguous. No "crack-like" indication was seen; however, the entire joint appeared to have a lower density than the tube wall.

The ultrasonic testing did indicate an anomaly in the region where a flaw had been detected with holography. Figure 54 shows the experimental arrangement and results. Two 20-MHz contact transducers were employed in a pitch-catch configuration; the transducer pair was moved around the tube and the amplitude of the received signal was monitored. A weak signal indicates that something has interrupted the beam or the material attenuation has changed. The flaw seen by holographic interferometry appeared in the 0° position of region A, and indeed, the received ultrasonic signal (Fig. 54, lower right) was ~ 6 dB lower in the 0° position than in any other area of the joint, and more than 6 dB lower than in regions B and C (the tube walls). The data in Fig. 54 show that the attenuation in the tube joint was less than that in the tube wall, although the radiographic results suggested that the joint had a relatively low density, which would be expected to cause increased attenuation. Characterizing the flaw by this method is, of course, very difficult.

The SiC tube was also interrogated by a single transducer, in a configuration similar to that of Fig. 54. Here, an echo from a defect would appear among other geometrical reflector signals. Figure 55 shows signals obtained at the 0° and 45° positions of the joint. At the 0° position, there is indeed an unidentified ultrasonic reflector. The echoes on both sides of the flaw signal are the result of the roughness and irregular geometry of this particular sample. At 45° and other positions around the tube, no flaw signals were observed. These results suggest that ultrasonic testing is a viable technique for examining butt joints in SiC tubes but that because of the irregular geometry, holographic interferometry may be more effective in characterizing the flaws. Future work will include ultrasonic testing from the bore side, as well as more extensive efforts employing acoustic microscopy and holography.

B. Holographic Interferometry for Ceramic Joint Assessment

The detection of cracks and other imperfections in ceramic materials by means of holographic interferometry has been illustrated previously.¹⁵ Surface imperfections as small as 100 μm in depth have been detected as distortions in the regular fringe pattern of an interferogram. This technique should be particularly applicable to the assessment of ceramic joint integrity because (1) the technique is less sensitive than other NDE techniques to geometrical distortions that may be present after a joint is made, (2) holographic interferometry may be capable of detecting undesirable strains at the joint when the sample is under thermal or mechanical loading, and (3) the application would be simpler than a general inspection, since it is limited to a small and well-defined region of the tube. Advances that simplify the use of holographic interferometry have been made in the present program. The progress can be divided into three areas:

- (1) Improvements in flaw (i.e., crack) detection methods.
- (2) Improvements in the technology.
- (3) Improvement in the general procedure.

1. Improvements in Flaw Detection Methods.

The detection of flaws using holographic interferometry was discussed previously.^{15,16} In these publications, the fundamentals of crack detection were analyzed and particular emphasis was given to the detection of small (100- μm) flaws. The authors concluded that in order to observe small flaws, holographic interferometry microscopy was necessary.

The resolution of this technique can be improved by adding a system of carrier fringes to the hologram. In the present work, fringes corresponding to a fictitious component displacement are introduced by changing the angle of the reference beam. Changes in the straightness of the fringes are utilized to detect the presence of small flaws. This technique can be supplemented by detection of the difference between the fringe systems produced by unloaded and loaded specimens. This can in principle be achieved by introducing a 180° phase difference between the unloaded and loaded images. Identical regions cancel out; regions that are different are not cancelled and will appear in the resulting image. The principle of the technique is illustrated in Fig. 56.

The detection of anomalies in joints of ceramic materials presents a different problem from the general detection of small flaws. For flaw detection in joints, one wants to observe general regions where discontinuities may appear in the holographic fringes or where the fringes concentrate. Owing to rigid-body motions, concentration of fringes may not be sufficiently noticeable for quick detection of flaws. This problem can be solved in several ways. One involves using the holographic moiré¹⁶ to view relative displacements. In this case, the regions where the defects are concentrated will be characterized by a change in the pitch of the moiré fringes (isotactic lines). Another alternative for flaw detection is to enhance the difference between flawed and unflawed region. This can be achieved by observing the gradients (changes of fringe density) of the holographic patterns. Sciammarella and Chawla¹⁶ have shown that the gradients of the patterns corresponding to each of the illumination beams can be obtained by pattern shifting, if carrier

fringes are introduced (e.g., two identical interferograms are superimposed and shifted relative to each other to generate a moire pattern). If one measures the displacement u along the x -axis of reference (Fig. 57), one can show that by shifting each of the two identical patterns corresponding to the two illumination beams (only one shown in Fig. 57), one obtains fringes of arguments

$$\phi_x = \frac{2\pi}{\lambda} \left| (1 + \cos \theta) \frac{\partial w}{\partial x} + \sin \theta \frac{\partial u}{\partial x} \right| \Delta x , \quad (1)$$

$$\phi'_x = \frac{2\pi}{\lambda} \left| (1 + \cos \theta) \frac{\partial w}{\partial x} - \sin \theta \frac{\partial u}{\partial x} \right| \Delta x , \quad (2)$$

where ϕ_x and ϕ'_x are the phases of the gradient fringes for the first and second beam, respectively, θ is the angle that the illumination beam makes with the normal to the surface, w is the displacement along the z -axis, assumed to be normal to the surface, Δx is the shift between the patterns produced by the two beams, and λ is the wavelength of the light. Depending on the signs of the displacements corresponding to each of the illumination beams, the slope $\partial w / \partial x$ will be added to the strain $\epsilon_x = \partial u / \partial x$ for one direction of illumination and subtracted from the other. Owing to Poisson's effect, regions with large deformations will also show large changes of slope; consequently, regions with defects will be regions with a high density of gradient fringes.

2. Improvements in the Technology

(a) Fringe Contrast

The moire fringes corresponding to the in-plane displacements are given by an equation of the form¹⁷

$$I = I_0 [1 + \cos \phi \cos \psi] , \quad (3)$$

where

$$\cos \phi = \frac{2\pi}{\lambda} 2u \sin \theta \quad (4)$$

and

$$\psi = \frac{2\pi}{\lambda} 2w (1 + \cos \theta) + \beta ; \quad (5)$$

u , w , θ have the same meaning as before, and β is the phase angle introduced (by rotation of the plate or reference beam) to generate the carrier fringes. The term $\cos \phi$ corresponds to the moire fringes, and the visibility of the moire depends on the contrast of the carrier fringes. The carrier fringes are also important in other flaw-detection methods.

The pattern formed by the superposition of the holographic fringes and the carrier fringes can be expressed by the following equation¹⁷ (which describes the contrast in the resultant fringe pattern):

$$\langle I(P) \rangle = \langle I \rangle [1 + v \cos \psi_R] , \quad (6)$$

where P is a point on the pattern, $\langle I \rangle$ is the resultant average intensity, the symbol $\langle \rangle$ indicates the mean value over the ensemble, ψ_R is the difference of phase due to the change of optical path caused by the applied load added to the phase angle β , and v is the fringe visibility;

$$v = \frac{\langle I_{\max} \rangle - \langle I_{\min} \rangle}{\langle I_{\max} \rangle + \langle I_{\min} \rangle}$$

$$= \frac{2 \sqrt{\langle I_1 \rangle \langle I_2 \rangle}}{\langle I_1 \rangle + \langle I_2 \rangle} |\Gamma| \quad (7)$$

where $\langle I_1 \rangle$ and $\langle I_2 \rangle$ are the intensities corresponding to the two interfering wave fronts and $|\Gamma|$ is the degree of coherence between them.

One can show that

$$|\Gamma| = |\Gamma_1| \cdot |\Gamma_2| \quad (8)$$

The factor $|\Gamma|$ takes into consideration that at the pupil plane of the observation system (Fig. 58), the two interfering wave fronts Σ_1 and Σ_2 have a relative displacement. Because of this displacement, certain portions of the wavefronts that were within the aperture before specimen loading are no longer within it after loading, and vice versa. The factor $|\Gamma_2|$ takes into consideration the loss of visibility due to the relative displacement of identical points on the two wavefronts at the image plane. It can be shown¹⁶ that for a circular aperture,

$$|\Gamma| = \frac{2J_1 \left| \frac{1.22 \pi |\tilde{T}'|}{\rho} \right|}{\frac{1.22 \pi |\tilde{T}'|}{\rho}} \left| 1 - \frac{2 |\tilde{T}|}{\pi a} \right| \quad (9)$$

where J_1 is a Bessel function of the first kind, T' (as shown in Fig. 58) is the displacement vector in the observation plane, $|\tilde{T}|$ is the displacement vector in the pupil plane, a is the aperture diameter, and ρ is the speckle diameter. The effect of $|\tilde{T}'|$ is more important than that of $|\tilde{T}|$ and when $|\tilde{T}'| = \rho$ the visibility falls to zero.

The displacements of the observed plane (Fig. 59) are characterized by the six components $T_x, T_y, T_z, R_x, R_y, R_z$ (where T indicates translation and R rotation). The translation vector has components

$$\underline{T}_T = \underline{T}_R + \underline{T}_D + \underline{T}_F \quad (10)$$

where $\underline{T}_R$ is the rigid-body translation, $\underline{T}_D$ is the translation produced by the deformation of the body, and $\underline{T}_F$ is the fictitious translation to generate the auxiliary fringes. The rotation vector has analogous components,

$$\tilde{R} = \tilde{R}_R + \tilde{R}_D + \tilde{R}_F \quad . \quad (11)$$

One can show¹⁷ that for point 0 of Fig. 59,

$$\tilde{T} = \tilde{F}_1(\tilde{R}) + \tilde{F}_2(\tilde{T}) \quad , \quad (12)$$

$$\tilde{T}' = \tilde{T}_{x\tilde{i}} + \tilde{T}_{y\tilde{j}} \quad , \quad (13)$$

where $\tilde{F}_1$ and $\tilde{F}_2$ are linear matrix functions. An examination of Eqs. (9), (12), and (13) leads to two conclusions. For the fringes to exhibit optimal visibility, $\tilde{T}'$ must be reduced to a minimum. To achieve this, $\tilde{T}_R$ and $\tilde{T}_F$ must be zero. Further analysis of the problem shows that the fringe orientation and density also depend on R_z . This implies that one must minimize the rigid-body motion to maximize fringe contrast.

(b) Generation of Auxiliary Fringes

Previously, the auxiliary fringes were generated by a rotation of the holographic plate. In Ref. 18, the rotation of the plate is shown to be equivalent to an infinitesimal rotation of the body. This result is obtained by a first-order theory; the actual rotation of the plate produces displacements perpendicular to the axis of rotation. These displacements contribute to the term $\tilde{T}_F$ of Eq. (10) and hence to the drop in visibility. This component can be eliminated by utilizing the setup illustrated in Fig. 60. If θ_R indicates the angle of incidence of the reference beam, a rotation $\Delta\theta_R$ of the mirror introduces in the reconstructed wave front an angular change,

$$\Delta\theta = 2 \cos \theta_R \Delta\theta_R \quad . \quad (14)$$

The total amplitude corresponding to the object and the reconstructed wave fronts is

$$\tilde{E}(x) = E(1 + e^{i2\pi x \frac{\Delta\theta}{\lambda}}) \quad , \quad (15)$$

where $\tilde{E}(x)$ is the resulting amplitude in the x direction (Fig. 60) and E is the amplitude of each of the two superimposed wavefronts (which are assumed to have the same amplitude). We can see that the object image is modulated by a system of sinusoidal fringes. This result is locally valid and therefore fringes smaller than the speckle size can be generated.

The mirror can be mounted in a system capable of producing rotations about any axis that lies on a diameter of the mirror. In this way it is possible to orient the carrier fringes in the most convenient way.

3. Improvements in the General Procedure

(a) Real-time Observations

The possibility of using holographic moire patterns in real time greatly broadens the scope of the method. The setup, shown in Fig. 61, differs from that used in double-exposure interferometry only by the addition of an immersion tank (not shown) which is mounted on a universal stage and contains the holographic plate. The events that take place when the specimen is loaded

can be viewed directly on a TV monitor and the fringe patterns can be simultaneously recorded on videotape. A single exposure is made of the object before loading. The plate is processed either outside or inside the tank. The tank movement controls allow the observer to obtain a reconstruction image free from residual fringes. The carrier fringes are then generated by rotating the collimated reference beam. Once the body is loaded, the holographic fringes may fade away unless, as explained in the preceding section, the translation T' is compensated. The use of real time confers a distinct advantage in this part of the operation: One can, by trial and error, obtain optimum visibility of the fringes while keeping the camera lens fully open. Localizing the fringes in the object or its neighborhood is a sufficient condition for the elimination or reduction of T' . Good visibility of the carrier fringes on the object surface suggests satisfactory implementation of the method, while poor visibility evidences an error in correction. Finally, one may obtain supplementary information by successively observing the individual images produced by each of the illuminating beams.

(b) The TV System

The resolution of a standard TV camera is dictated by the frequency of operation. With carriers of 4 MHz, the total number of picture elements is

$$N_T \cong 426 \times 338 = 144,000 \quad , \quad (16)$$

where 426 and 338 correspond to the number of picture elements in the horizontal and vertical direction, respectively. The actual resolution that can be observed in a standard monitor is less than that:

$$N_{TM} = 400 \times 300 = 120,000 \quad . \quad (17)$$

If we consider the 4:3 aspect ratio of the standard system, the horizontal and vertical resolutions per unit length become equal. Utilizing sinusoidal patterns, we have determined that effective resolution can be obtained with 300 picture elements, which result in 150 lines. The format of the vidicon tube picture area is also a rectangle with an l/w ratio of 4:3. If we call w_o the width of the object that we want to view, and w_v the width of the vidicon window, the required magnification is

$$m_v = \frac{w_v}{w_o} \quad . \quad (18)$$

According to geometric optics,

$$m_v = \frac{f}{x_o} \quad , \quad (19)$$

where x_o is the distance of the object from the first focal plane and f is the focal length of the lens. If the distance between the lens and the object is designated L ,

$$m_v = \frac{f}{L-f} \quad . \quad (20)$$

Taking Eq. (19) into consideration,

$$\frac{w_v}{w_o} = \frac{f}{L-f} \quad . \quad (21)$$

Equation (21) can be utilized to select the necessary parameters for observing the region of interest. The fringe spacing that can be observed on the object is equal to the object width divided by the number of lines:

$$\delta_t = \frac{w_o}{150} \quad , \quad (22)$$

which is independent of the size of the vidicon tube, the intermediate optics, and the size of the monitor. If we call w_d the monitor width, the magnification ratio between the vidicon and the monitor is

$$m_m = \frac{w_d}{w_v} \quad . \quad (23)$$

This magnification does not change the resolution.

4. Applications

(a) Detection of Small Flaws

The application of microscopy to holographic interferometry allows the use of the method for direct observation of very small flaws. Figure 62 shows a surface crack 200 μm long and $\sim 100 \mu\text{m}$ in depth on a 5.95 x 2.95-mm bar, introduced by a Knoop indenter. The bar has been loaded in pure bending and an initial system of fringes has been introduced. The presence of the crack is revealed by the change in fringe spacing in the region of the crack tip. With this type of pattern, it is feasible to apply the previously suggested technique of subtracting loaded and unloaded patterns.

(b) Inspection of Joints in Ceramic Heat-exchanger Tubes

Two 200-mm-long SiC tubes of 25.4 mm nominal diameter and 3.18 mm wall thickness, with butt joints in the central plane, have been tested. Three different loadings were utilized; heating alone, mechanical loading, and a combination of both. The heating was performed by introducing a linear heating element along the axis of the tube. The tubes were mechanically loaded in three-point bending, with the concentrated load applied to the plane of the joint. The tension side of each tube was inspected with the holographic technique previously described. Observations were then made covering 360°, and the patterns were recorded on videotape. The examples described below are pictures taken from the TV monitor after replaying the tapes.

The thermal load utilized did not allow visual detection of the defect. However, the mechanical load revealed the presence of the defect at about 55% of the computed failure load. At 68%, the defect became fully visible. Figure 63 shows a closeup of the fringes in the region of the defect. The defect can be seen as a sharp discontinuity of the fringes. The white dots in the picture, $\sim 13 \text{ mm}$ apart, are markings placed on the surface to locate the defect. The flaw-free appearance of the surface and the sharpness of the discontinuity indicate that the defect is beneath the surface and is made

visible by the orientation of deformations. Figure 64 shows the same region as Fig. 63, but viewed with double illumination. The fuzzy region is a moire fringe that passes through the joint. The sharp gradient due to the defect is also visible. Figure 65 is a double-beam picture in which two moire fringes surround the joint. The discontinuity appears as a straight vertical fringe. Figure 66 shows moire fringes (gray areas) obtained for the same tube under simultaneous mechanical and thermal loading. Figure 67 is a closeup of another picture obtained with dual loading, here with an increased mechanical load. The carrier fringes are horizontal. The moire fringes become closer in the region of the joint, revealing a larger deformation. Figure 68 shows a plot of the displacements along the tube, and Fig. 69 gives the corresponding strains. The strain is maximum at the joint. The results given in Fig. 69 show that the strains may provide an excellent means of detecting defects.

5. Future Developments

The introduction of a vidicon camera and the use of image-processing techniques provide many new possibilities for flaw detection, including a completely automated system. We have indicated the feasibility of detecting small flaws by introducing a 180° phase shift between the patterns for the specimen with and without loading. This process can be achieved in real time through video image-processing techniques that utilize existing hardware. The frame corresponding to the unloaded condition is stored in the memory of a processor; the pattern for the loaded condition is recorded and the processor calculates the difference between the contents of the memory and the incoming video frame. This difference can be displayed on a monitor and a hard copy simultaneously printed. The display will show only flawed regions.

If a more quantitative result is desired, the strains can be directly determined from the information contained in the holograms corresponding to the illuminating beams in holographic moire interferometry. By means of Eqs. (1) and (2), one can determine $\partial u / \partial x = \epsilon_x$ from the difference between the phases ϕ_x and ϕ'_x . This method was developed and optically implemented in Ref. 16. The same result can be achieved in real time by using a computer, which can also obtain and plot the strains. Here, monitors will provide the information concerning the location and severity of the defects.

C. IR Scanning of an Overlap Joint

The results of previous work employing IR scanning techniques for assessment of SiC tubing¹⁵ indicated that these techniques would not be advantageous for flaw detection. However, recent work with overlap joints of SiC tubing suggests that in assessment of joints for bond integrity, IR techniques may be capable of detecting anomalies not evident by other NDE methods. The specimens, provided by Solar Turbines International, consisted of NC430 SiC tubes joined with various glass adhesives. Figure 70 shows a schematic of the IR scanning arrangement used. One end of the specimen is heated, and the heat is transmitted across the glass adhesive joint to the other end. Any defect in the adhesive could result in anomalous heat transfer across the bond, resulting in a hot or cold region of the upper tube which could, in principle, be detected by an IR camera. The camera used is an AGA 750 capable of resolving temperature differences of 0.2°C .

Figure 71 shows a photograph of a specimen joined with Corning #0080 glass adhesive. This particular specimen had been fired at too low a temperature and was expected to have a poor bond. Black and white reproductions of color photographs of IR scans of this tube are shown in Fig. 72. The different shades represent temperature differences of about 0.5°C (with the exception of the tube edge). In this particular example, the tube was painted black to assure uniform emissivity, and the free end of the larger tube was heated, so that heat flowed through the glass adhesive to the smaller tube. The area indicated by the dark spot in Fig. 72a is $\sim 0.5^{\circ}\text{C}$ cooler than the surrounding area. Another anomalous region is indicated in Fig. 72b, while the other side of the tube (Fig. 72c) exhibits a generally smooth change in temperature from top to bottom. Attempts to characterize these anomalous regions by radiography or through-transmission and pulse-echo ultrasonic techniques were not successful.

The tube was sectioned at the level of the cool spot to determine the cause of the anomaly. Figure 73 shows the tube cross section. The bond is clearly better in the "cool" region (arrow) than elsewhere; thus, one might expect better heat transfer in this area, with a resultant anomaly in the IR image. This example illustrates how IR techniques can be employed to obtain information about the integrity or uniformity of a ceramic overlap joint that cannot be obtained as readily, if at all, by other techniques. While the present results indicate an area of good bonding in a poorly bonded specimen, one can expect reciprocal results for poor bonding in an otherwise properly bonded tube. Tests will continue on tubes with properly bonded overlap joints as they become available.

VI. SUMMARY AND CONCLUSIONS

Generally, experience with respect to failure of structural ceramic components is acquired from the field and is related to NDE data and procedures, i.e., a failure probability is determined empirically for a given set of flaw data. Ultimately, one would hope to be able to predict the probability of failure of a component, and make appropriate accept/reject decisions, directly from the NDE information. Because fracture-initiating defects in these components are relatively small, the ability to predict failure in a practical manner requires detailed information about the failure process, critical flaw size, and stress gradients (see Ref. 19 for a discussion of accept/reject decisions and failure prediction in structural ceramics).

The goals of the present program are not only to develop hardware and procedures for efficiently inspecting SiC heat-exchanger tubes in conventional ways, but also to develop advanced NDE techniques that will allow effective failure prediction. The effort carried out during the past year has supported the belief that the development of an adequate NDE procedure for SiC heat-exchanger tubes will require the application of several NDE techniques, as well as input from personnel involved in heat-exchanger design, material fabrication, and fracture mechanics.

The main objectives in FY 1980 have been to (a) develop a computer-interfaced ultrasonic bore-side probe for pre- and in-service inspection, (b) develop and assess techniques for inspection of SiC tubing by acoustic microscopy, and (c) carry out preliminary tests to compare ultrasonic, holo-

Fig. 54. (Top) Schematic of Arrangement Used for Ultrasonic Inspection of SiC Tube Joint, Using Two 20-MHz Transducers in a Pitch-catch Mode; (Bottom) Inspection Results. The reduced signal amplitude at A-0° indicates an anomaly in this region.

Fig. 55. "A-scan" Traces Obtained at 0° and 45° Positions of Region A (Joint) in Tube J6. An anomaly (arrow) is indicated in the 0° scan. No anomalies were detected at 45° or other circumferential positions within Region A. The present result agrees with those obtained^{13,15} by ultrasonic through-transmission and holographic techniques.

Fig. 56. Use of the Image-subtraction Method to Visualize Areas Containing Flaws by Holographic Interferometry. (Top) hologram of unstressed specimen; (middle) hologram of specimen under stress; (bottom) difference hologram.

Fig. 57. Schematic Representation of the Process of Observation of the Gradients Corresponding to Holographic Patterns.

Fig. 58. Decorrelated Areas at the Pupil Plane (Hatched Zones) Due to a Translation T .

Fig. 61. Schematic Representation of the Recording Configuration in Image-plane Real-time Holography.

Fig. 62. Surface Crack (200 μm Long, 100 μm Deep) in a SiC Bar as Observed with Holographic Interferometry Microscopy.

Fig. 63. Discontinuity in a Butt Joint of a SiC Heat-exchanger Tube under Mechanical Load. Vertical distance between dots (arrows) is ~ 13 mm.

Fig. 64. Same Tube Region Seen in Fig. 63, under Double-beam Illumination, with One Moiré Fringe Passing Through the Joint.

Fig. 65. Same Tube Region Seen in Fig. 63, under Double-beam Illumination, with Two Moire Fringes Surrounding the Joint.

Fig. 66. Holographic Moire Pattern Obtained for Same SiC Heat-exchanger Tube Shown in Fig. 63, under Both Mechanical and Thermal Load.

Fig. 67. Same as Fig. 66, with Additional Mechanical Load. Moiré fringes passing through the point are closer together than in Fig. 66.

Fig. 68. Displacements Plotted from the Pattern of Fig. 67.

Fig. 69. Strains Obtained from the Graph of Fig. 68.

Fig. 70. Experimental Arrangement for IR Scanning of Overlap Joints in SiC Tubes. Arrows indicate heat flow in tube wall.

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Fig. 71. Photograph of SiC Tube with Glass Overlap Joint. Numbers show locations of "cool" spots detected by IR scanning.

Fig. 72. Infrared Photographs of Tube Shown in Fig. 5. Anomalous spots (arrows) near the top and middle of the tube are seen in (a) and (b), respectively. No discontinuities are evident on the opposite side of the tube (c). Various colors (reproduced here as different shades of gray) represent different temperatures of tube surface, according to scale at left. The full range of colors represents 5°C.

Fig. 73. Cross Section of Overlap Joint Showing Area (Arrow) with Better Bonding Than in the Rest of the Joint. An infrared scan¹² had previously shown better heat transfer in this region.

graphic and IR techniques with more conventional dye-penetrant and radiographic methods for inspection of butt joints in ceramic tubes.

The ultrasonic bore-side probe was shown to be sufficiently sensitive to detect 250- μm -long x 125- μm -deep circumferential EDM notches on the inner and outer surfaces of sintered and siliconized SiC tubes. The signal-to-noise ratios for the ultrasonic echoes were better than 10 to 1, which exceeded initial expectations for detection of small reflectors. This resulted from focusing of the beam in the tube wall. The ultrasonic bore-side probe was able to detect and record the location of a circumferential outer-surface notch in a SiC tube while scanning a SiC tube under microcomputer control. For detection of laminar-type defects, a normal-incidence longitudinal probe of frequency >25 MHz and a more highly damped transducer (or more sophisticated data analysis) will be necessary.

Acoustic micrographs have been presented which demonstrate the difference in images generated with two types of insonification geometries. Circumferential geometry produces straight interference lines; axial geometry produces curved lines. Both axial and circumferential EDM notches have been imaged using the more recently developed circumferential insonification geometry. A comparison was also made between siliconized and sintered materials, using four SiC tubes. The sintered material showed high attenuation but good beam coherence (i.e., weak signals but little distortion), while the siliconized material showed good transmission but poor coherence (i.e., strong signals but moderate distortion).

Detection of EDM notches as small as 250 μm long and 125 μm deep has been demonstrated with the acoustic microscope in the dark-field imaging mode. Detection of outer-surface notches has been demonstrated using reflection-mode imaging, with a transducer and laser-scanned coverslip on the outside of the tube. A conceptual design was presented for inspection of tubes up to 7 feet in length in both through-transmission and reflection modes.

Problems with reverberating sound fields will have to be solved before lenses can be employed in an effective manner with the acoustic microscope to eliminate sound-field focusing in the tube wall.

Destructive examination of an overlap joint previously scanned with an IR camera revealed better bonding in one region of the joint than elsewhere. This region corresponds to a cool spot identified in the IR scan. These results suggest that IR techniques may be employed successfully in characterizing ceramic overlap joints through observation of heat-flow patterns.

Results of previous efforts had led to the conclusion that holographic interferometry, although sensitive to surface flaws, would be difficult to use as a general inspection method for ceramic materials. This technique needs to be reassessed with respect to ceramic joints for two reasons. One is that the irregular geometry of many joints makes ultrasonic signal interpretation difficult, but leaves open the possibility of detecting flaws indirectly by looking for regions of high strain. The other reason for a new look at holography is that the introduction of a television camera and videotape system has made the production and evaluation of holographic interferograms much easier. The present report reviews the holographic technique and describes some new developments. An example is presented in which a subsurface

linear indication at a butt joint is revealed clearly by holographic interferometry when the tube is stressed under a three-point bending load. Future efforts will concentrate on quantifying the effectiveness of holographic interferometry relative to other methods, and using destructive analysis to obtain information on the size of the discontinuities detected by the present technique.

Efforts to examine a butt joint with dye-penetrant, radiographic, ultrasonic, and holographic-interferometry techniques revealed that while holography seemed to identify more clearly the presence of a crack-like inner-surface flaw, ultrasonic pulse-echo and pitch-catch techniques at 22 MHz also indicated the presence of an anomaly; the ultrasonic and holographic results agreed with regard to angular location of the flaw.

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