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MEASUREMENTS OF ULTRASONIC SCATTERING FROM BULK FLAWS OF COMPLEX SHAPE

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Rockwell International Science Center
Thousand Oaks, CA 91360

ABSTRACT

The report summarizes the design and early results of scattering experiments on flaws of complex shape. In close collaboration with the various theoretical groups representing different inversion algorithms, a unique set of diffusion bonded samples have been designed. These samples contain a variety of irregular and multiple flaws whose scattering characteristics will be obtained in order to guide and evaluate developments of theoretical approaches and test specific theoretical predictions. The majority of these samples have been received and the measurements have begun. Results on selected samples are presented and compared with scattering from ellipsoidal voids. The measurements will include angular, frequency and time domain variations of the scattered signals made possible with a new ultrasonic data acquisition system.

INTRODUCTION

The objective of this task is to predict the fatigue life of a metallic component containing a defect in its interior, by ultrasonic non-destructive evaluation. We report on progress on data acquisition for testing inversion algorithms, the preparations of new diffusion bonded samples, and the characteristics of spherical voids with small perturbations.

DESIGN AND PREPARATION OF NEW TRAILER-HITCH SAMPLES

Earlier phases of this program were concerned with the development of methods for producing flaws of known size, shape and location for use as ultrasonic reference standards. A range of defect sizes and shapes for which theoretical solutions for the scattering of incident ultrasonic energy are available have been produced. In addition, a number of defect geometries such as fatigue cracks and crack-like defects in diffusion bonded samples were also prepared. Previous work has emphasized rather simple internal voids and inclusions such as spherical defects and prolate or oblate spheriods. The new effort places more emphasis on modifications of these basis defect types and on rather more realistic flaws such as actual fatigue cracks, multiple defects and regular defects such as prolate spheriods, but with controlled surface roughness such as might be found in a realistic flaw.

New samples produced during the current year's program are listed in the Sample Inventory in Table 1. Only those samples produced under the new program have been listed in Table 1. Samples prior to Serial No. 69 are described in previous reports under this program. Drawings for samples 69-74 and 95-100 are contained in Figs. 1-9. The sample code in Table 1 gives only a general description of the defect type, and a precise description must be derived from the appropriate figure. The figures typically show three views, a three-dimensional view of the lower half of the trailer hitch, a more detailed view of the defect with design dimensions, and a micrograph of the actual defect after machining, but before bonding. Sample No. 69 is a simple circular 3 mm-diameter crack-like defect produced by inserting a thin layer of yttria in the bonding plane before the bonding operation. This sample and all other samples through Serial No. 74 are machined to a spherical shape as was done previously in order to permit acoustic scattering experiments over a wide range of angles in three dimensions. Sample No. 70 contains two overlapping spheres, the purpose...
of this geometry being to test the applicability of summation procedures in the theoretical work. Sample No. 71 contains a single 400 μm radius void surrounded by a 200 μm wide simulated yttria crack in the form of a "Saturn" ring. This geometry simulates a crack initiating out of an internal void and is probably as close to a realistic defect causing a crack in an actual material as can be produced by the sample preparation procedures used in this study. Sample No. 72 is a simulated elliptical crack in the interior of a spherical sample, while sample No. 73 contains an overlapping sphere and a modified prolate spheroid of the form shown in the drawing. Sample No. 74 contains a rough oblate spheroid to simulate a void with a realistic internal roughness to study the interaction of this rough surface with ultrasound of various frequencies. The surface of the oblate spheroid was roughened mechanically prior to the bonding operation. Samples 75-87
Sample No. 74 is a 2 1/4-inch diameter, 3 11/16-inch high sample, again with spherical external geometry, and contains two separated spheres, both with 400µ between centers. Sample No. 96 also contains two spheres, on a 400µ radius, the other a 600µ radius with a center-to-center separation of 1400µ. Sample No. 97 contains a 6.35 mm sphere with pronounced machining grooves, sample No. 99 is a spare, while sample No. 98 is a 4-inch diameter, 1-inch high specimen with a simulated fatigue crack 3 mm diameter produced internally by a spark erosion method. The manner in which this simulated fatigue crack surface was produced is worth describing in detail since it is somewhat complex. A
fatigue fracture surface produced by a fatigue crack growth at high $\Delta K$ in a pure titanium specimen was used as a model fatigue crack surface. A 3 mm diameter disc was then cut from the Ti specimen and placed into a suitably cut recess in one of the specimen halves. The opposite face was left smooth and the two specimens bonded together to form an internal fatigue crack-like surface.

The last sample produced in the current series is illustrated in Fig. 10 and consists of a specimen bonded together such that an internal defect introduced at its center line was used to initiate a fatigue crack laterally out from the diffusion bond. By producing specimens in this manner, the bond line was not in a fatigue crack plane and therefore would not interrupt or perturb the crack propagation process. This sample is to be used in some experiments to simultaneously study fatigue crack growth while examining the crack using ultrasonic methods of various kinds from the exposed specimen surface. The grips used to load the specimen enable access to both top and bottom faces of the specimen, thus allowing the study of both transmitted and reflected waves during fatigue cycling of the sample. The design of this sample is described in detail in a later section.

![Fig. 10. Sample No. 98.](image)

In summary, as a necessary part of calibrating and evaluating new NDE procedures and test equipment, standard samples containing defects of known size, shape and location, some of which simulate real defects found in service, have been designed and fabricated under this portion of the program. Rather than using the conventional flat-bottom hole, internal defects of accurately controlled geometry have been produced by a diffusion bonding method, since in general, scattering from internal defects is more completely understood than scattering from surface defects. In the current year, an attempt has been made to produce realistic defects of the type that might appear in service, and fatigue cracks growing from internal voids is a good example of this type of defect. Most of the samples have been produced from Ti-6Al-4V by methods which have been described in detail in previous reports.

### Table 1

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**DESIGN OF A CENTRAL CRACK FATIGUE SPECIMEN**

We have designed a dumbbell shaped specimen which will be used to monitor ultrasonically the growth of a central fatigue crack. Two Ti-6-4 plates, each with a 1/8 inch radius thumbnail EDM notch have been diffusion bonded together such that the two semicircular notches will form a circular starter notch (1/4 inch diameter). With suitable grips, the specimen can be installed into a 200,000 lbs electrohydraulic fatigue frame. The grips have been designed in such a way that the two end faces are accessible for placement of transducers. Growth of the central crack under fatigue conditions will be monitored in the pulse-echo mode. It is also intended to perform tests in which the signal scattered in the plane of the crack will be interrogated. For this purpose, a receiver transducer will be mounted to the cylindrical surface of the specimen.

In the tension-tension fatigue loading the cyclic stress intensity range for this specimen is given by (1)

$$\Delta K = 1.95 \Delta \sigma \sqrt{a / Q}$$

where $\Delta \sigma = \sigma_{max} - \sigma_{min}$, $a$ is the instantaneous radius of the central crack and $Q = 0.5$ for an aspect ratio of 0.5 (circular crack). For Ti-6-4 the yield strength, $\sigma_y$, of the material is $\sigma_y = 130$ KSI. Using full load capacity of the fatigue frame the specimen can be cycled at $\sigma_{max} = 200,000$ lbs/3.14 (inches)$^2 = 0.5 \sigma_y$. A load ratio
R>σ_{max}/σ_{min} = 0.08 will yield da = 26.5 Ks/τ\text{m}
will be achieved. For this stress intensity range
a fatigue crack growth rate da/dn of about
20\text{inches}/cycle is deduced from published data.
The growth of a fatigue crack will be continuously
monitored in the pulse-echo mode. For verification
of the growth, "marker cycles" will be ap­plied periodically. For AK > 20 Ks/τ\text{m} the growth
should occur according to the Paris equation (5)

\[
\frac{da}{db} = A(\Delta K)^m
\]

with A = 7.2 x 10^{-4} and m = 3.15. Combining Eqs.
(1) and (2) and integration over the total growth
regime yields the remaining cycles to failure

\[
\Delta N = \frac{2}{(m - 2)A(1.95\sigma_{max}^{1/2}a_c)^m} \left[ 1 - \frac{1}{a(m - 2)/2} \right]
\]

where \( K_c \) is the fracture toughness of the material
\( (K_c = 45-50 \text{Ksi} ≤ (\text{in}) \). Since the \( K_c \) is not that
accurately known, we will actually determine \( K_c \)
from the critical flaw size

\[
a_c = \left( \frac{\sigma_{max}}{1.95\sigma_{max}} \right)^{2} \]

for our particular material and geometry.
Equation (4) is a consequence of Eq. (3) for \( \Delta B = 0 \).

DATA ACQUISITION TECHNIQUES FOR
TESTING INVERSION ALGORITHMS

Data has been collected on two samples, one
containing an 800\text{μm} diameter spherical void
and another containing 800\text{μm} x 400\text{μm} oblate spheriod
(0.01) in accordance with the requirements for the
POFFIS algorithm used by N. Bleistein and J. Cohen
of Denver Applied Analytics. The data set in­cludes explicit timing information defining the
velocity in the trailer-hitch for several dif­ferent
angles and the absolute arrival times of the flaw
echos for the determination of absolute
flaw position. Data has also been collected and
sent to J. Rose of the University of Michigan,
comprising waveforms along the longitude and
equator of trailer hitches containing a thin el­liptic disk and an oblate spheroid. New require­ments on transducer placement have been received
from A. Mucciardi of Adaptronics so that both
pitch-catch and pulse-echo waveforms may be col­lected
in a new window format to be used for in­version. The data were collected on a trailer­
hitch with an oblate spheroid and sent to
Adaptronics. Data obtained in the recent past on
a variety of trailer-hitch defects have been transmitted to J. Gubernatis at Los Alamos.

In order to provide scattering data for use
with the POFFIS algorithm, it is necessary to
record pulse echo waveforms of the flaw as viewed
from a variety of angles including the absolute
position of the flaw echo in each waveform. Given
a knowledge of the velocity of the sound in the
host material, absolute position can be determined
from absolute arrival times of the flaw echos. In
conventional ultrasonic NDE, arrival time is used
as an approximate measure of flaw location. In
that case it is not necessary to know the arrival
time (position) more accurately than about one
diameter of the flaw. However, in the POFFIS
algorithm, the position information directly
affects the reconstructed shape and size of the
flaw. It is therefore necessary to know arrival
time (position) to a small fraction of the
diameter of the flaw.

In order to obtain absolute position infor­
mation for echos from the flaws in the spherical
("trailer hitch") specimens, the following data
were collected:

1. The known shape of the surface of the specimen
   (in this case a sphere).
2. The velocity of sound in the measurement
   directions in the specimen.
3. The arrival time of the flaw waveform
   with respect to the instant when the peak
   of the incident sound pulse passed from the
   transducer into the specimen. For normal
   incidence immersion measurements, this
   instant can be measured directly
   from the received waveform, but for angle
   beam or (as in our case) contact measure­
   ments, it must be separately determined.

The procedures used to obtain the absolute
arrival time and sound velocity measurements
are described below:

Arrival Time - Received ultrasonic waveforms are
usually timed with respect to a trigger pulse
which is approximately coincident with the genera­
tion of the transmitted sound pulse. In our appa­
ratus, which consists of a Parametrics 5052P
Pulser/Receiver and a Biomation 8100 Transient
Recorder, time is measured with respect to an in­stant,
50 sample intervals before the trigger
pulse from the Parametrics crosses the trigger
threshold of the Biomation. In order to be able
time the ultrasonic echos precisely, it is neces­
sary to determine when the peak (or some other
feature) of the ultrasonic pulse emerges from the
face of the transducer. The peak is used because
it is the time at which most of the frequency
components of the pulse are in phase and is therefore
a high signal-to-noise feature which can be ident­
ified in either the time or frequency domains.

Because the transducer cannot be used as a
receiver while it is transmitting, the pulse peak
time is measured by placing the transducer in
contact with a 1 inch thick layer of aluminum and
measuring the first round trip time. Then the pulse
peak time is calculated using the thickness
and velocity of sound of the aluminum block. The
velocity of sound is in turn determined by sepa­rating
the transducer from the block by a water
buffer and measuring the front surface and first
round trip times and the thickness of the block.

The resulting pulse peak time is then used as
the reference of time for flaw waveform measure­ments.
It will vary if any of the components of the
apparatus (transducer, pulser, transient rec­order) are changed or even readjusted (for
example, pulser damping or Biomation trigger
Sound Velocity - In order to convert the absolute arrival times measured above into absolute positions, it is necessary to know the sound velocity of the specimen. For anisotropic materials, such as Ti-6Al-4V, this requires measurements in several directions. We have made sound velocity measurements in the trailer hitch specimens by through transmission measurements along various diameters of the hitches. The technique used is to divide the thickness of the hitch (including end caps) by the time when the peak of the pulse reaches the receiving transducer minus the time when the peak emerges from the transmitting transducer. This requires a 2-transducer reference measurement analogous to the single transducer reference measurement described above, consisting of measuring and transmission arrival time through the 1 inch aluminum reference block and subtracting the known propagation time through the block.

The results of the sound velocity measurements (for those angles where physical access allowed a through transmission measurement to be made) are given below. They show a consistent anisotropy as well as a systematic variation between the two samples.

<table>
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<tr>
<th>Angle from</th>
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<th>Sample 39</th>
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<td>(mm/μs)</td>
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</table>

ELASTIC WAVE SCATTERING BY BUBBLE DEFECT

Next, we turn to study a non-spherical defect shown in Fig. 2. The defect is a spherical cavity of diameter 80D, to which a hemisphere cavity of diameter 40D has been added. The hemisphere will be referred to as the "bubble"; it represents a deviation of size b from a simple shaped smooth cavity of characteristic size a. The questions addressed were the following:

(1) At what frequencies (e.g., values of ka) is the bubble observable?

(2) At what angles of incidence and scattering is its effects most pronounced?

To answer these questions preliminary experiments were first carried out to compare the backscattering by the large sphere to that of the non-spherical defect. Figures (11a, b, c) show the backscattered amplitude vs frequency for (a) an 80D sphere without the bubble defect (b) a side view of the defect normal to the axis-of-symmetry, and (c) a frontal view of the bubble defect. The differences appear above about 4 MHz (ka = 1.5, kb = 0.75). The largest deviation is obtained for the case of Fig. 11c, i.e., when the bubble is directly illuminated.

The frequency spectra were experimentally obtained by Fourier analyzing and normalizing the observed backscatter waveforms. The spectra of Figs. 11b and 11c are modulated with about the same periodicity as that obtained for a sphere, Fig. 11a, but a modulation with longer periodicity (in k) is superimposed. While for the sphere the first three peaks are of approximately equal amplitude, with the bubble present, the amplitudes decrease in magnitude. These observations agree qualitatively well with the findings of Domany et al (6).

Turning now to the angular distribution of power, Fig. 12 shows the polar plot of power versus scattering angle for an incident direction along the normal to the axis of symmetry (side view) and a scattering angle of 0 = 135 from the forward scattering direction. This work is for ka = 2 and shows that the presence of the bubble has caused noticeable loss of the symmetry associated with a "true" spherical cavity. Also shown in the plot are results of calculations by Domany et al (6) and Opsol (7) in qualitative agreement with the experiment. Domany's calculations are based on the use of the Distorted Wave Born Approximation, while Opsol's results are based on the use of Vissher's matrix theory (8).

We plan to extend this work to the other defects described earlier and attempt to achieve a quantitative comparison.
Fig. 12 Polar plot of power scattered (dB) as a function of scattering angle in a pitch-catch experiment.

ACKNOWLEDGEMENT

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7. J.L. Opsal, this volume.

MEASUREMENTS OF ULTRASONIC SCATTERING FROM BULK FLAWS OF COMPLEX SHAPE

B. Tittmann

DISCUSSION

JIM ROSE: Jim Rose, University of Michigan.

I notice that in your experiments that you just showed, you have the deeper split. Is that possibly true for --

MR. TITTMANN: That's fine structure that I think we can get rid of by being a little more precise in our normalization.

MR. ROSE: You don't think it's physical?

MR. TITTMANN: I don't think so.

MR. HOLLER: When you showed your experiments with the sphere and the bubble, I didn't understand the designations on the axes.

MR. TITTMANN: This was a polar plot with the bubble oriented towards $\theta = 0$. The radial axis is calibrated in dB of relative power.
SUMMARY DISCUSSION  
(B. Tittmann)

Jim Rose (University of Michigan): I notice that in your experiments you just showed, you have the deeper split. Is that possibly true for --

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Jim Rose: You don't think it's physical?

Bernie Tittmann: I don't think so.

Paul Holler (Inst. fur Zerst. Pruf.): When you showed your experiments with the sphere and the bubble, where the abscissa is, the ordinate with decibels, I didn't understand what you were -- must be an angle.

Bernie Tittmann: This was a polar plot. If we wanted to assign a reference, make the bubble direction zero degrees and this is 90 and that's 180, and so looking into that direction, then, you're looking away from the bubble and the amplitudes are in terms of DB.

# #