Ultrasonic Characterization of Blisk and Disk Gradient Microstructures to Improve Fatigue Life and Creep Resistance

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Final Report

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**Title and Subtitle**

ULTRASONIC CHARACTERIZATION OF BLISK AND DISK GRADIENT MICROSTRUCTURES TO IMPROVE FATIGUE LIFE AND CREEP RESISTANCE

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**Abstract**

Nickel-based superalloys intended for advanced disk applications require high creep resistance and crack growth resistance in the rim region to withstand operating temperatures exceeding 650°C. However, they also require high strength and fatigue resistance in the bore and web regions, which operate at temperatures of 500°C or lower. A disk of uniform coarse-grain microstructure compromises strength-dependent properties at intermediate temperatures in the bore and web. Conversely, a disk of uniform fine-grain microstructure compromises creep resistance and dwell crack growth resistance in the rim region. Therefore, an optimal disk would have a dual microstructure, consisting of fine grains (~ 5 µm) in the bore and web and coarse grains (~ 60 µm) in the rim to alleviate the predominant failure mechanism in those specific regions. Several heat treatment methods exist to create these dual microstructures for optimized reliability. However, to qualify these disks for flight, a nondestructive evaluation measurement of grain size is needed.

A measurement tool was created for this project that calculates grain size from ultrasonic backscattering measurements. The tool unifies the entire process, including controlling the ultrasonic scanner, data acquisition, experimental backscattering calculation, theoretical backscattering prediction, numerical optimization between experiment and theory to obtain grain size, and data visualization. The tool was tested on nickel superalloys, including IN718, Waspaloy, Rene 88, and an alloy 10 disk with grain sizes ranging from ~10 microns to ~30 microns from the bore to the rim. We calculated the grain size and elastic moduli across the disk and in the other nickel alloy samples. The ultrasonic metallography tool compares favorably with traditional metallography measurements of grain size. This measurement tool has applicability far beyond nickel alloys and we are working on automating many of the steps.
ACKNOWLEDGEMENTS

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXECUTIVE SUMMARY</td>
<td>ix</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. LABORATORY MEASUREMENTS</td>
<td>1</td>
</tr>
<tr>
<td>2.1 Attenuation and Speed of Sound Measurements</td>
<td>2</td>
</tr>
<tr>
<td>2.2 Backscattering Measurements</td>
<td>7</td>
</tr>
<tr>
<td>3. BACKSCATTERING THEORY</td>
<td>10</td>
</tr>
<tr>
<td>4. ULTRASONIC GRAIN SIZE MEASUREMENT (EXPERIMENT AND THEORY)</td>
<td>13</td>
</tr>
<tr>
<td>5. SUMMARY AND CONCLUSIONS</td>
<td>19</td>
</tr>
<tr>
<td>6. REFERENCES</td>
<td>20</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>An Ultrasonic Signal From a Material, Showing the Reflection for the Front Surface and First and Second Reflections From the Back Surface</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Immersion Samples on Leveling Platform With Five Leveling Screws and Transducer Mounted on Goniometer and Acquisition Portion of Attenuation Workspace During Acquisition Showing the RF Waveform of Sample Scan Data</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Post-Processing Portion of the Attenuation Workspace: A-Scan Display With Sliders to Select Scan Location, Average Attenuation Obtained Using FS and BS1 Signals From the Test Sample, Attenuation Obtained Using BS1 Signals From the Test and Reference Samples for Each Scan Location, Average Attenuation Obtained Using BS1 Signals From the Test and Reference Samples, and Difference Between Average Attenuation Obtained by the Two Methods</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Comparison Between the Current System and Benchmark Attenuation Data for Radial Propagation in the Ti-64 High Noise 1 Sample From the CBS</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>The RF Backscattering Signal in the GE Nickel Alloy Specimen From the Workspace During Data Acquisition</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>The Inspection Portion of Workspace Following Backscattering Scan of the Ni Sample From GE: The A-scan, B-scans, and C-scan</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>Inconel 718 Sample From NASA-GRC in Immersion Tank and RF Signal From the Workspace During the Acquisition of the Backscattered Signal</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>Inspection Portion of Workspace Following Backscattering Scan of Inconel 718 Sample From NASA Glenn Research Center: The A-scan, B-scans, and C-scan</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>The Two-Point Correlation Relationship to the Microstructure</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>The Backscattering as a Function of Frequency for Three Different Grain Sizes and the Difference Between the Backscattering and the Frequency Response of the Transducer Used for Backscattering Measurements</td>
<td>12</td>
</tr>
<tr>
<td>11</td>
<td>Potential Backscattering Profiles Across the Gradient Microstructure Disk</td>
<td>12</td>
</tr>
<tr>
<td>12</td>
<td>Microstructure of the Nickel Forging Specimen and the Amplitude of the Backscattering Over a 2&quot; x 2&quot; Region</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>The Experimental Backscattering and Theoretical Predictions Using Grain Size From Metallography; The Frequency Ranges Used for the Least Squares Method Are Shown</td>
<td>13</td>
</tr>
</tbody>
</table>
The Experimental Measurement of the Backscattering and Theoretical Predictions of Using the Grain Sizes Determined From the Least Squares Minimization Process

Micrographs of the Two Nickel Alloy Specimens From Different Regions in a Billet

Experimental Backscattering and Theoretical Predictions Using Grain Size From Metallography; The Frequency Ranges Used for the Least Squares Method Are Shown

Experimental Backscattering Data and Theoretical Predictions Using the Grain Sizes Determined From the Least Squares Minimization Process

Comparison of the Grain Size Determined From the Backscattering Method vs. Metallography

Photographs of Typical Rotating Engine Disk in a Sonic Shape and an Experimental Disk Used for This Study

The Ultrasonic Metallography Tool Showing the Grain Size Determination in Two Different Regions of an Alloy 10 Dual Microstructure Disk: Backscattered Grain Noise at 15 MHz Over a Region of the Dual Heat Treat Disk and Experimental and Theoretical Grain Noise and the Grain Size in Microns From the Fitting Procedure

Grain Size From the Ultrasonic Metallography Tool vs. Grain Size From Traditional Sectioning and Metallography for Several Nickel Alloys
**LIST OF SYMBOLS AND ACRONYMS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>BS</td>
<td>Back surface</td>
</tr>
<tr>
<td>FQ</td>
<td>Fused quartz</td>
</tr>
<tr>
<td>FS</td>
<td>Front surface</td>
</tr>
<tr>
<td>GE</td>
<td>General Electric</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>NASA-GRC</td>
<td>National Aeronautics and Space Administration Glenn Research Center</td>
</tr>
<tr>
<td>NDE</td>
<td>Nondestructive evaluation</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>WP</td>
<td>Water path</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

Nickel-based superalloys intended for advanced disk applications require high creep resistance and crack growth resistance in the rim region to withstand operating temperatures exceeding 650°C. However, they also require high strength and fatigue resistance in the bore and web regions, which operate at temperatures of 500°C or lower. Disks of uniform coarse-grain microstructure compromise strength-dependent properties at intermediate temperatures in the bore and web. Conversely, disks of uniform fine-grain microstructure compromise creep resistance and dwell crack growth resistance in the rim region. Therefore, an optimal disk would have to have a dual microstructure, consisting of fine grains (~ 5 µm) in the bore and web and coarse grains (~ 60 µm) in the rim to alleviate the predominant failure mechanism in those specific regions. Several heat treatment methods exist to create these dual microstructures for optimized reliability. However, to qualify these disks for flight, a nondestructive evaluation (NDE) measurement of grain size is needed.

The team developed novel ultrasonic scattering methods and software tools to measure the grain size in these dual microstructure disks and other nickel alloys, as well as creating a first-of-a-kind ultrasonic metallography tool to measure the backscattering from metal alloys, predict the backscattering from existing theoretical formulations, and calculate the grain size. Furthermore, the team integrated the scanning tank control, data acquisition, calculation of the measured ultrasonic attenuation and backscattered grain noise, the theoretical prediction of the backscattered grain noise, and the optimization to calculate the grain size in a single software platform. Using the InspectionWare software package from Utex Scientific Instruments, disparate pieces of code written in different programming languages by various people were also successfully eliminated. InspectionWare was chosen in part because the major engine manufacturers, including General Electric Aviation, Rolls-Royce® plc, and Pratt & Whitney, use this product, thereby allowing rapid transfer of the technology when it is developed. Prior to this project, no effective NDE technology existed to measure grain size in a form that could be used by engineers and nondestructive testing practitioners in the aircraft industry. The unification is a first-of-a-kind measurement and calculation tool to directly measure the grain size using ultrasonic scattering.
1. INTRODUCTION.

The temperatures in the high-pressure turbine section of today’s aircraft engines range from 500°F at the bore to 1300°F at the rim, creating different failure mechanisms in these regions of disks and blisks. At the bore, failure usually occurs due to fatigue damage while, at the rim, failure is usually caused by creep damage. Traditionally, components are fabricated from Ni-based superalloys with uniform microstructures to satisfy a wide range of temperatures and loading conditions. Unfortunately, a uniform microstructure is not optimal for preventing either fatigue or creep damage and thus leaves the disks susceptible to failure. Ideally, the microstructure in each area should be tailored to protect against the damage specific to that area. Specifically, in the low-temperature bore region, where fatigue is the dominant failure mechanism, it is best to have a fine-grain (<10 microns), high-strength, fatigue-resistant microstructure to impede the movement of dislocations and slow the growth of cracks [1 and 2]. In contrast, in the high-temperature rim region, it is best to have a creep-resistant microstructure with relatively coarse grains (>40 microns) [3]. As described in a patent by General Electric (GE) [4] and reports by Rolls-Royce® plc and others [5-7], these competing requirements led to the development of dual heat-treated disks possessing fine-grain bore and coarse-grain rim microstructures. The objective of this project was to develop ultrasonic scattering techniques and analysis tools to measure the grain size in disks and blisks to ensure that target grain sizes are achieved to help extend the life of aircraft engines. Ultrasound is traditionally used to detect cracks, corrosion, and other defects in aircraft engine alloys and other materials. In addition to being useful in detecting these flaws, ultrasonic measurements can also be used to characterize the material properties of alloys and composites. Specifically, when ultrasound traverses a metal alloy, it scatters at grain boundaries because of the mismatch of crystallographic orientation across the interface. The scattering produces two effects: first, it reduces the energy transmitted in the propagating wave, attenuating the signal amplitude, second, a portion of the scattered signals return directly to the transmitting transducer, overshadowing flaws. These incoherent backscattered signals look like electronic noise on the oscilloscope screen and are often called backscattered noise or backscattered grain noise. Both the ultrasonic attenuation and backscattering are directly related to the size and shape of grains and can be used to determine the average grain size.

Using the attenuation and backscattering to determine the grain size requires accurate and precise measurements that follow precise experimental procedures and use knowledge of the effects of the measurement system on the measured amplitudes, speed of sound in the material, and an accurate model to deconvolve the frequency-dependent attenuation and backscattering from the measured amplitude. Using published data, the grain size was determined from backscattering measurements in certain nickel alloys to within 2 microns. The experimental measurements and theoretical processes are described in this report, followed by a summary and discussion of future work.

2. LABORATORY MEASUREMENTS.

During this project, the measurement methods and accompanying software were developed to measure the ultrasonic attenuation, speed of sound, and backscattering needed to determine the grain size.
2.1 ATTENUATION AND SPEED OF SOUND MEASUREMENTS.

As a simple example, the amplitude of a signal seen on an oscilloscope screen reflected from the front surface (FS) of a material is related to the material properties and the measurement system based on equation 1 where:

- \( FS \) identifies variables related to the FS reflection
- \( \tau = \) the integration variable
- \( \Gamma_{FS}(t) = \) the measured amplitude of the reflection from the FS in the time domain
- \( \beta(\tau) = \) transducer efficiency
- \( R = \) Reflection coefficient, with 0 representing water, and 1 representing the sample
- \( \alpha_{water}(\tau) = \) Attenuation of the sound in water
- \( D_{FS}(t) = \) Diffraction correction for the sound wave reflecting from the FS
- \( d_{water} = \) water path (WP) (distance from the transducer to the sample)
- \( t = \) time

\[
\Gamma_{FS}(t) = \int_{-\infty}^{\infty} R_0 \beta(\tau) D_{FS}(t-\tau) e^{-2d_{water}\alpha_{water}(\tau)} d\tau \tag{1}
\]

A schematic of the signals is shown in figure 1 [8 and 9].

![Figure 1. An Ultrasonic Signal From a Material, Showing the Reflection for the Front Surface (FS) and First and Second Reflections From the Back Surface (labeled back surface1 (BS1) and back surface2 (BS2), respectively)](image)

Equations for these variables, including the diffraction correction and reflection coefficient, can be found in standard ultrasonic texts or in the references [9 and 10].

To measure a property as simple as the reflection coefficient, \( R \), the other factors in equation 1 must be removed from the measured amplitude. Removing the other factors requires a
deconvolution in the time domain. This mathematical complexity can be avoided by transforming the received signal to the frequency domain through a Fourier transform as shown in equations 2 and 3:

\[ \Gamma(f) = \frac{1}{\sqrt{2\pi}} \int_\infty^{-\infty} \Gamma(t) e^{-2\pi i ft} dt \] (2)

\[ |\Gamma_{FS}(f)| = \|\beta(f) R_{01} D_{FS}(f)\| e^{-2d_{\text{water-water}}(f)} \] (3)

Here, \( f \) is the frequency. This process makes the measurement system effects multiplicative, rather than mathematically, convoluted, thus allowing for simple division to extract the parameter of interest. This process will be described below specifically for the attenuation and backscattering where the measurement system parameters are known, can be measured, or can be eliminated with appropriate reference signals.

Both the attenuation and speed of sound are needed to measure the backscattering. The paragraphs that follow describe the methods and software developed to date to provide these measurement capabilities.

A workspace was created to measure the speed of sound and the average ultrasonic attenuation of a test sample, over a scanned area, using two methods first developed by Bob Gilmore from GE and then modified by Frank Margetan from Iowa State University’s Center for Nondestructive Evaluation [10].

The first method uses an ultrasonic reflection from the FS of the sample as a reference signal to eliminate the transducer efficiency and the first back surface (BS) echo from the test sample to calculate the attenuation. The following equations describe these signals in the frequency domain:

\[ |\Gamma_{FS}(f)| = \|\beta(f) R_{01} D_{FS}(f)\| e^{-2d_{\text{water-water}}(f)} \] (4)

\[ |\Gamma_{BS1}(f)| = \|\beta(f) T_{01} R_{10} T_{10} D_{BS1}(f)\| e^{-2d_{\text{water-water}}(f)} e^{-2d_{\text{Sample-sample}}(f)} \] (5)

\[ \alpha_{\text{Sample}}(f) = -\frac{1}{2d_{\text{Sample}}} \ln \left( \frac{|\Gamma_{BS1}(f)|}{|\Gamma_{FS}(f)|} \frac{|R_{01} D_{FS}(f)|}{|T_{01} R_{10} T_{10} D_{BS1}(f)|} \right) \] (6)

For this case, the diffraction correction needs to be calculated from the Thompson-Gray measurement models based on the transducer diameter, frequency, and focal properties. Refer to references 9 and 10 for the exact form of the diffraction correction.

The second method uses a reflection from the BS of fused quartz (FQ) as the reference signal to eliminate the transducer efficiency and the diffraction correction. Equations governing these signals are:
\[
|\Gamma_{\text{FQ}}(f)| = |\beta(f)T_{01}^{\text{FQ}}R_{01}^{\text{FQ}} F_{10}| F_{\text{FQ}}(f) e^{-2d_{\text{FQ}}^w(f)} e^{-2d_{\text{FQ}}^w(f)} \\
|\Gamma_{\text{BSI}}(f)| = |\beta(f)T_{01}^{\text{BSI}}R_{01}^{\text{BSI}} F_{10}| F_{\text{BSI}}(f) e^{-2d_{\text{BSI}}^w(f)} e^{-2d_{\text{BSI}}^w(f)} \\
\alpha_{\text{Ni}}(f) = -\frac{1}{2d_{\text{Ni}}} \ln \left[ \frac{\Gamma_{\text{BSI}}(f)}{\Gamma_{\text{FQ}}(f)} \right] \left[ T_{01}^{\text{FQ}} R_{01}^{\text{FQ}} F_{10} \right] \cdot F_{\text{FQ}}(f) e^{-2(d_{\text{BSI}}^w - d_{\text{Ni}}^w) u_{\text{BSI}}(f)} \right] 
\]

For the diffraction corrections to cancel out of the attenuation calculation, the WPs for both the reference signal and the data from the sample need to be adjusted so that the total travel paths are identical. The total travel paths are given by the following equations:

Total travel path for the sample = \( WP_s + \frac{V_s}{V_w} d_s \)  

\( \text{Total travel path for the sample} = WP_{\text{FQ}} + \frac{V_{\text{FQ}}}{V_{\text{FQ}}} d_{\text{FQ}} \)

Where:

Ni = nickel  
FQ = fused quartz  
WP = water path  
\( V \) = speed of sound  
\( d \) = thickness of the material  
subscript \( w \) = water  
subscript \( s \) = sample

By equating the total travel path, the WP for the FQ can be calculated by the following equation:

\[
WP_{\text{FQ}} = WP_s + \frac{V_s}{V_w} d_s - \frac{V_{\text{FQ}}}{V_{\text{FQ}}} d_{\text{FQ}} 
\]

In addition to ensuring that precise reference signals are collected, it is necessary to orient the specimen and transducer so that the surface of the sample is parallel to the scan plane and the acoustic beam is perpendicular to the surface. This was achieved by leveling the sample using a custom leveling platform and normalizing the transducer to the surface of the sample using a goniometer. Figure 2 shows these items, along with a screen shot of the radio frequency (RF) waveform.
Figure 2. Immersion Samples on Leveling Platform With Five Leveling Screws and Transducer Mounted on Goniometer (left) and Acquisition Portion of Attenuation Workspace During Acquisition Showing the RF Waveform of Sample Scan Data (right)

Figure 3 shows the analysis portion of the attenuation workspace. A-scan results are shown in (a). Attenuation is calculated for each scan location using the FS and first BS signals in (b). Attenuation calculated for each scan location using BS1 signals from the test and FQ reference samples are provided in the display indicated as (c) and the average is displayed in (d). These two methods produced essentially the same attenuation values as shown by their difference (e).

To validate that the values are accurate, the measured attenuation on the current system was benchmarked against a Ti-64 sample from the contaminated billet study. Figure 4 shows the comparison. For these data, we propagated along the radial direction of the high noise 1 sample. Agreement between the measurements is very good, especially considering the previous data were collected with a 1/4" diameter, 10 megahertz (MHz) transducer, while the current data were collected with a 1/2" diameter, 15 MHz transducer.
Figure 3. Post-Processing Portion of the Attenuation Workspace: (a) A-Scan Display With Sliders to Select Scan Location, (b) Average Attenuation Obtained Using FS and BS1 Signals From the Test Sample, (c) Attenuation Obtained Using BS1 Signals From the Test and Reference Samples for Each Scan Location, (d) Average Attenuation Obtained Using BS1 Signals From the Test and Reference Samples, and (e) Difference Between Average Attenuation Obtained by the Two Methods

Figure 4. Comparison Between the Current System and Benchmark Attenuation Data for Radial Propagation in the Ti-64 High Noise 1 Sample [11]
2.2 BACKSCATTERING MEASUREMENTS.

A second InspectionWare workspace was developed to determine the backscattering based on the Thompson-Gray measurement model and the work of Margetan et al. [8 and 10]. Measuring the backscattering is more complex than the attenuation and requires knowledge of the attenuation and speed of sound of the material, as well as the physical parameters of the transducer. For backscattering, it is best to use a focused transducer to increase the measured signal well above the electronic noise. For this research, a 15 MHz, 1/2 diameter transducer with a nominal focal length of 3.80 in. was used. Figure 5 shows a screen shot from the software. The FS echo can be observed at about 57 µs and the BS echo can be observed at about 65.5 µs. These signals saturated because the gain needed to be increased to 70 dB to measure the backscattering between the FS and BS echoes. The backscattering is well above the electronic noise observed before the FS echo and increases in amplitude in the focal zone of the transducer near 63 µs.

![Figure 5. The RF Backscattering Signal in the GE Nickel Alloy Specimen From the Workspace During Data Acquisition](image)

The backscattering coefficient is calculated from the measured backscattered signals using equation 13:

\[
\sqrt{\eta} = \frac{\left| \Gamma_{\text{RMS}}(f) \right| R_{02} d^2 p_0 v_0 D_{\text{FOVref}}^k}{\left| \Gamma_{\text{FOVref}}(f') \right| 2 \eta_1^2 v_1 e^{2q_{\text{water}} d_{\text{water}}}} \left[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |C(f, x_1, y_1, z_1)|^4 P(z_1) e^{-4\sigma_{\text{air}} z_1} dx_1dy_1dz_1 \right]^{-1/2}
\]  

(13)
Where:

\[ \eta = \text{Backscattering coefficient} \]
\[ k_1 = 2\pi \frac{f}{v_i} \]
\[ a = \text{transducer radius} \]
\[ C(f) = \text{Beam Focal Properties} \]
\[ P(z_1) = 1, \quad \frac{f_\text{y}_1}{2} \leq z_1 \leq \frac{f_\text{y}_1}{2} \quad \text{Gated Region} \]
\[ P(z_1) = 0, \quad \text{Outside of Gated Region} \]

For the backscattering measurement, the reference signal is also a BS echo of a fused silica sample, but with the sound focused on the BS of the sample. The \( C(f, x_1, y_1, z_1) \) term compensates for the focusing properties of the transducer in the sample [10].

We are currently developing a multistep analysis process for the backscattering. We collected preliminary backscattering data on two nickel alloy samples, one from GE and a second from National Aeronautics and Space Administration Glenn Research Center (NASA-GRC). For the GE sample, the focal zone of the transducer can be seen at about 63 µs in the A-scan (figure 6). The backscattering is well above the electronic noise, which can be observed at times before the FS echo.

Figure 6 shows a view of the backscattering scan data from InspectionWare with the A-scan in the top left corner, the B-Scans in the top right and bottom left corners, and the amplitude C-scan in the bottom right corner. The backscattering is relatively uniform over the scan region of 20 mm x 20 mm.
Figure 6. The Inspection Portion of Workspace Following Backscattering Scan of the Ni Sample From GE: The A-Scan (top left), B-Scans (top right and bottom left), and C-Scan (bottom right)

Data were also collected on an Inconel 718 sample from NASA-GRC, shown in the tank in figure 7 (along with the A-scan of the backscattering signal). Figure 8 shows the results from the scan. The backscattering in that sample varies across the scan region, indicating there may be some variations in grain size in the sample.

Figure 7. Inconel 718 Sample From NASA-GRC in Immersion Tank (side view, left) and RF Signal From the Workspace During the Acquisition of the Backscattered Signal (right)
3. BACKSCATTERING THEORY.

The theory describing the ultrasonic backscattering as a function of frequency from equiaxed grains in the absence of texture was developed by Jim Rose [12]. The backscattering coefficient \( \eta(\omega) \) is described by the equation below:

\[
\eta(\omega) = \left( \frac{\omega^2}{4\pi \rho V^4} \right)^2 \int d^3 \left( \tilde{r} - \tilde{r}^i \right) \left\langle \delta C_{3333} \left( \tilde{r} \right) \delta C_{3333} \left( \tilde{r}^i \right) \right\rangle e^{2i\alpha \left( \tilde{r} - \tilde{r}^i \right) \cdot \mathbf{k}} \tag{14}
\]

In this theory, the microstructure is described by the two-point correlation of elastic constant perturbations in the brackets \( \langle \ldots \rangle \) given by the equations below. It mathematically describes the variations of the elastic constants from point-to-point over an ensemble of grains. The \( \langle \Delta_{ij} \Delta_{kl} \rangle \) term describes the elastic anisotropy and the \( P(|\tilde{r} - \tilde{r}^i|) \) describes the spatial variation of the two-point correlation. For most materials, \( P \) can be approximated as an exponentially decaying function of the spatial distance with an inverse decay rate equal to the grain radius, \( a \). Figure 9 shows a schematic of this mathematical description:

\[
\left\langle \delta C_{ij}(r) \delta C_{kl}(r^i) \right\rangle = \langle \Delta_{ij} \Delta_{kl} \rangle P(|\tilde{r} - \tilde{r}^i|) \tag{15}
\]
Figure 9. The Two-Point Correlation Relationship to the Microstructure

The theory was used to answer two distinct questions: (1) What frequency is optimum to differentiate between the grains expected for these dual gradient microstructures? and (2) What can we expect to measure for spatial variations of the backscattering for the grain sizes expected? To answer the first question, the backscattering was calculated as a function of frequency for grains with diameters ranging from 40 µm to 70 µm as expected in these disks (figure 10). For these calculations elastic constants of pure nickel were assumed. While not exact, using single crystal, elastic constants has proven to be a reasonable approximation [10 and 11]. To determine the optimum frequency for distinguishing the grains, the difference between the backscattering from the grain sizes was calculated. The results are shown in figure 10 (middle plot). The peak in the difference ranges from 12 MHz to 16 MHz with the center of the range occurring at 14 MHz for these predictions. These results were used to choose the optimum frequency for the transducer, resulting in a 15 MHz transducer that spans the expected range. The frequency spectrum from the manufacturer, Olympus® NDT (Panametrics™), shows a bandwidth that spans the range of interest and reaches a maximum at 13.26 MHz, very close to the maximum backscattering difference frequency.

To determine what may be expected from a scan along the disk, the backscattering was calculated as a function of grain size, assuming three different distributions: (1) a sharp step function, (2) a gradual transition, and (3) a linear transition. Figure 11 shows the expected backscattering for a simulated line scan from the bore to the rim. It is expected that the grain size will gradually change in this area within a transition region rather than an abrupt change. One of the goals is to use the backscattering to identify the transition region.
The theory for the ultrasonic backscattering as a function of frequency was also used to calculate the grain size from experimental backscattering measurements. Literature data for four different nickel alloy samples were compared with the theory [13 and 14]. The average grain size of the specimens was 4.7 µm, 13.7 µm, 16.2 µm, and 32.5 µm. Figure 12 shows micrographs of the specimens with average grain sizes of 4.7 µm and 13.7 µm. The experimental data and theoretical predictions of the backscattering, assuming the average grain sizes from metallography, are shown in figure 13. Good agreement between the theory and experiment can be observed between 6.6 MHz and 11.3 MHz for the sample with a 4.7 µm grain size and 6.2 and 12.9 MHz for the sample with a 13.7 µm grain size.

Figure 10. The Backscattering as a Function of Frequency for Three Different Grain Sizes (left) and the Difference Between the Backscattering (middle) and the Frequency Response of the Transducer Used for Backscattering Measurements (right)

Figure 11. Potential Backscattering Profiles Across the Gradient Microstructure Disk
4. ULTRASONIC GRAIN SIZE MEASUREMENT (EXPERIMENT AND THEORY).

To calculate the grain size, the difference between the experimental data and theoretical predictions of the backscattering was minimized in the specified frequency ranges using a least squares method with the grain size as the adjustable parameter. This inversion process predicted grain sizes of 6.9 µm and 14.6 µm low noise and high noise samples, respectively. Figure 14
shows the theoretical prediction of backscattering using these grain sizes with the experimental data. Agreement is very good up to approximately 15 MHz.

![Graph showing theoretical predictions vs. experimental data](image)

Figure 14. The Experimental Measurement of the Backscattering and Theoretical Predictions of Using the Grain Sizes Determined From the Least Squares Minimization Process

To further test the theory and inversion process for larger grains, the same process was performed for a nickel alloy with average grain sizes of 16.2 µm and 32.5 µm, with experimental data taken from the literature [14]. Photographs of the microstructure of the samples are shown in figure 15. For these samples, the difference between the experimental data and theoretical predictions were a minimized in the 5.7 to 10.7 MHz range and the 4.0 to 13.6 MHz range for the samples with grain size of 16.2 µm and 32.5 µm, respectively. Figure 16 shows these data and predictions assuming grain sizes from metallurgy. The theoretical inversion process predicted grain sizes of 18 µm and 32 µm, and figure 17 shows the theoretical predictions of the backscattering assuming these grain sizes, along with the experimental data.

Figure 18 shows the grain size from the theoretical inversion process versus the grain size for all of the samples. The agreement is quite good and is within 2 µm of the metallographic determination of the grain size. For the smaller grains, the backscattering inversion process overestimated the grain size; for the sample with the largest grains, the inversion underestimated the grain size. There are several reasons why this may have occurred, including the elastic constants used for the calculation, variation in the grain size across the sample, or multiple scattering. At this time, the contribution of each of these factors has not been determined and is not within the scope of this project. Even with these unknown variables, the agreement is more than adequate for this application.
Figure 15. Micrographs of the Two Nickel Alloy Specimens From Different Regions in a Billet [13]

Figure 16. Experimental Backscattering and Theoretical Predictions Using Grain Size From Metallography; The Frequency Ranges Used for the Least Squares Method Are Shown (shaded regions)
Figure 17. Experimental Backscattering Data and Theoretical Predictions Using the Grain Sizes Determined From the Least Squares Minimization Process

Figure 18. Comparison of the Grain Size Determined From the Backscattering Method vs. Metallography
A workspace was created to measure the backscattering from metal alloys, predict the backscattering from existing theoretical formulations, and calculate the grain size. The following were integrated: the scanning tank control, data acquisition, calculation of the measured ultrasonic attenuation and backscattered grain noise, the theoretical prediction of the backscattered grain noise, and the optimization to calculate the grain size in a single software platform. Using the InspectionWare software package from Utex Scientific Instruments, disparate pieces of code written in different programming languages by various people were also successfully eliminated. InspectionWare was chosen in part because the major engine manufacturers, including GE Aviation, Rolls-Royce plc, and Pratt & Whitney use this product, thereby allowing rapid transfer of the technology when it is developed. The unification is a first-of-a-kind measurement and calculation tool to directly measure the grain size using ultrasonic scattering.

Figure 20 shows a screen shot of the software we call the ultrasonic metallography tool for an ultrasonic C-scan of the backscattering from the interior microstructure of an Alloy 10 dual microstructure disk. The high backscattering from large grains at the rim is indicated in red and orange and the low backscattering from the fine grains in the rest of the disk—including the bore
region—is indicated in blue. The experimentally measured backscattered grain noise and theoretical prediction of backscattering for a high scattering and a low scattering region are shown in the right-hand graphs along with the grain size from the optimization routine. For this particular disk, the grain sizes were predicted to be 11 and 30 microns for the low-scattering and high-scattering regions, respectively. This is in reasonable agreement with the expected range, based on the metallography of a similar disk of 5 to 8 microns in the bore region and 44 to 70 microns in the rim region.

These measurements have been applied to a range of alloys, including Inconel 718, Rene 88, Rene 104, Udimet®, and Waspaloy®. Figure 21 shows a graph of the ultrasonically determined grain size versus metallographic determination. While the predicted behavior of the backscattering for Inconel 718 and Rene 104 agrees with experiments, some alloys do not match the theoretical predictions, based on the chosen elastic moduli and the current assumptions in the theory, including spherical grains of uniform size without texture or isotropic properties.

Figure 20. The Ultrasonic Metallography Tool Showing the Grain Size Determination in Two Different Regions of an Alloy 10 Dual Microstructure Disk: Backscattered Grain Noise at 15 MHz Over a Region of the Dual Heat Treat Disk (with red representing high backscattering and blue representing low backscattering, left), and Experimental and Theoretical Grain Noise and the Grain Size in Microns From the Fitting Procedure (the coarse grain region at the rim has a grain size of 30 microns while the interior region has a grain size of 11 microns, right)
5. SUMMARY AND CONCLUSIONS.

In this project, novel ultrasonic scattering methods and software tools were developed to measure the grain size in dual microstructure disks and other nickel alloys. A first-of-a-kind ultrasonic metallography tool was created to measure the backscattering from metal alloys, predict the backscattering from existing theoretical formulations, and calculate the grain size. The following were integrated: the scanning tank control, data acquisition, calculation of the measured ultrasonic attenuation and backscattered grain noise, the theoretical prediction of the backscattered grain noise, and the optimization to calculate the grain size in a single software platform. Using the InspectionWare software package from Utex Scientific Instruments, disparate pieces of code written in different programming languages by various people were also successfully eliminated. InspectionWare was chosen in part because the major engine manufacturers, including GE Aviation, Rolls-Royce® plc, and Pratt & Whitney, use this product, thereby allowing rapid transfer of the technology when it is developed. Prior to this project, no effective NDE technology existed to measure grain size in a form that could be used by engineers and nondestructive testing practitioners in the aircraft industry. The unification is a first-of-a-kind measurement and calculation tool used to directly measure the grain size using ultrasonic scattering.

The methods created generate very precise data and use specific measurement models with reference signals to remove the effects of the measurement system. Currently microstructures with grains that vary by as little as 2 microns in diameter can be distinguished. The high precision and reference signal process is extremely important because the grain size from the ultrasonic metallography tool measures the same grain size on a given sample independent of the ultrasonic system used to collect the data. This independence will allow reproducible measurements and rapid transition to industry measurement systems.
Now that the ultrasonic metallography tool has been created, this technology needs to be validated and transferred to the engine manufacturers and material suppliers. The next steps should include a parametric study to determine the effects of the measurement method and sample properties on the accuracy and precision of the grain-size measurement, as well as a refinement of the graphical user interface so that aerospace engineers and technicians can effectively use the tool. To ensure that it is the best quality tool, it should also be beta-tested at the engine manufacturers’ sites and by the material suppliers. To facilitate acceptance into the aerospace community, we should incorporate these measurement methods and processes into a military specification. It will also be important to perform a series of blind tests with this tool on nickel alloys and expand the capability to measure the grain size in nonequaxed metals and those with duplex microstructure, including the titanium alloys, Ti-64 and Ti-17, used in various stages of the engines. Final implementation in the engine manufacturers’ site and material suppliers’ sites will be an important outcome in the development of the ultrasonic metallography tool.

6. REFERENCES.


