Ultrasonic Backscattering Measurements of Grain Size in Aircraft Engine Alloys

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Outline

- Motivation
- Materials
- Experimental measurements – from literature
- Theoretical calculations – forward problem
- **Grain size determination from backscattered noise – inverse problem**
- Summary and future work
Motivation

Motivation:

- The rim and bore of rotating disks experience different operating conditions and failure mechanisms.
  - Fatigue failure at the bore
  - Creep failure at the rim

- Aircraft engine manufacturers have developed heat treatment methods to tailor grain size at the bore and rim.

Need:

- An NDE method to measure grain size is needed to qualify engines for flight.

Fatigue Failure  
\(~500^\circ F\)  
Creep Failure  
\(~1300^\circ F\)

Dual Microstructure Heat Treatment (DMHT) disks

Transition Region

Figure 1.—Schematic of dual microstructure heat treatment (DMHT) assembly used for solution heat treatment of disk, with location of grain size transition zone indicated.

Target grain sizes: 5µm – 8µm

Cycles to fatigue failure: 14661

Reference: Fatigue resistance of the Grain size Transition Zone in a dual Microstructure Superalloy Disk, T. P. Gabb et al., NASA/TM-2010-216369
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Ultrasonic C-scan of Alloy-10 dual grain disk

Ultrasonic Scattering for Materials Characterization

- In the **time domain** contributions to measurements are a **mathematical convolution**
- Cables, Pulser receiver, Transducer, scattering
- In the **frequency domain** these contributions **multiply**

<table>
<thead>
<tr>
<th>Time domain</th>
<th>Fourier Transform</th>
<th>Frequency domain</th>
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<tbody>
<tr>
<td>$\tilde{V}<em>R(t) = \int</em>{-\infty}^{+\infty} \tilde{s}(\tau) \tilde{t}_A(t-\tau) d\tau$</td>
<td>$V_R(f) = s(f) t_A(f)$</td>
<td></td>
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</table>

$\tilde{s}(t)$ = Electrical and ultrasonic-to-electrical elements (pulser receiver, cables, transducer) – Every transducer is different!

$\tilde{t}_A(t)$ = elastic wave propagation and scattering processes in fluids and solids – The parameters we are looking for

To quantify material properties **independent of the measurement system** it is far easier work in the frequency domain
Attenuation Measurements Using Multiple Echoes

Contributions to measurement
- Diffraction (Eliminate with theory)
- Transducer Efficiency (Eliminate with reference signal – front surface echo)
- Scattering (Grain size)
- Absorption (Dislocations…)

\[
\Gamma(f) = \text{the Fourier amplitude}
\]
\[
\beta(f) = \text{transducer efficiency}
\]
\[
T, R = \text{Transmission, Reflection coefficients}
\]
\[
D(f) = \text{Diffraction correction}
\]

**Contributions to measurement**

- **Diffraction (Eliminate with theory)**
- **Transducer Efficiency (Eliminate with reference signal – front surface echo)**
- **Scattering (Grain size)**
- **Absorption (Dislocations…)**

\[
\Gamma_{FS}(f) = |\beta(f) R_{01} D_{FS}(f)|
\]

\[
\Gamma_{BS1}(f) = |\beta(f) T_{01} R_{10} T_{10} D_{BS1}(f)| e^{-2\alpha z}
\]

\[
\alpha(f) = -\frac{1}{2t} \ln \left[ \frac{|\Gamma_{BS1}(f)| \cdot |R_{01} D_{FS}(f)|}{|\Gamma_{FS}(f)| \cdot |T_{01} R_{10} T_{10} D_{BS1}(f)|} \right]
\]

Experimental backscattered grain noise measurement

15 MHz transducer
Planar, focused
½” diameter

Reference signal
Backscattering Measurement Model

\[
\sqrt{\eta} = \frac{\left| \Gamma_{rms}(f) \right| R_{02} a^2 \rho_0 v_0 D_{ref} k_1}{\Gamma_{ref}(f) 2 T_0^2 \rho_1 v_1 e^{2\alpha_0 t}} \left[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |C(f)|^4 P(z_1) e^{-4\alpha_1 z_1} dx_1 dy_1 dz_1 \right]^{1/2}
\]

\eta = \text{backscattering coefficient}

\[k_1 = 2\pi \frac{f}{v_1}\]

\(a = \text{transducer radius}\)

\(C(f) = \text{From Transducer Beam Model}\)

\[P(z_1) = 1, \quad \frac{t_a v_1}{2} \leq z_1 \leq \frac{t_b v_1}{2} \quad \text{Gated Region}\]

\[P(z_1) = 0, \quad \text{Outside of Gated Region}\]

Microstructures of In 718 forging

13 µm
High Noise
15 MHz transducer
FL ~ 4 inches
½” diameter

4.7 µm
Low Noise

~2 inches on a side


P.D. Panetta measured the grain size
Experimental backscattered grain noise

Experimental Data from:
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Backscattering coefficient

\[ \eta(\omega) = \left( \frac{\omega^2}{4\pi \rho V^4} \right)^2 \int d^3 (\vec{r} - \vec{r}') \left\langle \delta C_{3333} (\vec{r}) \delta C_{3333} (\vec{r}') \right\rangle e^{2ik(\vec{r} - \vec{r}') \cdot \hat{k}} \]

Microstructure

- Single scattering
- Texture free
- \(<…> = ensemble average
- Single phase

Density = 8.91 g/cm³

Single crystal elastic constants for nickel

- \( C_{11} = 248.1 \text{ GPa} \)
- \( C_{12} = 154.9 \text{ GPa} \)
- \( C_{44} = 124.2 \text{ GPa} \)

Mathematical description of microstructure

\[
\langle \delta C_{IJ}(r) \delta C_{KL}(r') \rangle = \langle \Delta_{IJ} \Delta_{KL} \rangle P(|\vec{r} - \vec{r}'|) \]

Two point correlation of elastic constant perturbations

\[
\Delta_{IJ}(r) = C_{IJ}^0 - C_{IJ}(r)
\]

Amplitude

\[
A_{IJKL} = \langle \Delta_{IJ} \Delta_{KL} \rangle
\]

Decay rate

\[
P(r - r') = e^{-a_g |r - r'|}
\]

Grain Size

\[
|r - r'|
\]
Theoretical prediction: grain size from metallography

Grain sizes from metallography
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Fitting regions for theory inversion

Least square optimization with grain size as adjustable parameter

Grain sizes from metallography

- Experiment Ni High Noise (13 um)
- Experiment Ni Low Noise (4.7 um)
- Theory (13 um)
- Theory (4.7 um)
Theoretical prediction: grain size from inversion

- Experiment Ni High Noise (13 um)
- Theory (14.6 um)
- Experiment Ni Low Noise (4.7 um)
- Theory (6.9 um)

Grain size from inversion
Grain size from backscattering vs. grain size from metallography
Micrographs for In-718 GFM-A Billet


Fitting regions for theory inversion

Experimental Data from:
Theoretical prediction: grain size from inversion

Predicted Grain Size
17.8 µm and 31.5 µm
Grain size from Backscattering vs. grain size from metallography for In 718

- Good agreement from backscattering inversion
Summary and future work

- Theory closely matches experimental measurements of backscatter grain noise in equaixed In 718 forging and billet material
- Inversion algorithm accurately determines grain size
- Single crystal elastic constants and multiple scattering may cause overestimate/underestimate of grain sizes and differences in frequency response.

Future work

- Collect experimental data on nickel alloys with larger grain size
- Calculate grain size from physics based theory
- Develop inspection procedure for automated grain size measurements on dual microstructure disks using backscattering
Acknowledgments

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