Case Study:

Residual Stress Measurement
Residual stresses have numerous origins that are highly variable. Residual stresses relax at service temperatures.
Load stress (LS) versus residual stress (RS)

external loads (L)

<table>
<thead>
<tr>
<th>stress measurement</th>
<th>relationship</th>
<th>selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct</td>
<td>$M \approx \bar{t} \cdot A = \iint T^{LS} , dA$</td>
<td>excellent</td>
</tr>
<tr>
<td>semi-direct</td>
<td>$M \approx M_0 (1 + \varepsilon)$</td>
<td>high</td>
</tr>
<tr>
<td>indirect</td>
<td>$M \approx M_0 (1 + \eta \varepsilon + \ldots)$</td>
<td>low</td>
</tr>
</tbody>
</table>

$$\lim_{\Delta A \to 0} \frac{\Delta F_i}{\Delta A} = T_i$$

$$T_i = \tau_{ij} n_j$$

$$\tau_{ij} = C_{ijkl} \varepsilon_{kl}$$

$$\iint T^{LS} \, dA = \sum A$$

$$\iint T^{RS} \, dA = 0$$
Potential NDE Techniques

**direct**
- stiffness
- vibration analysis
- etc.

**semi-direct**
- hole drilling
- contour mapping
- x-ray or neutron diffraction
- etc.

**indirect**
- magnetic
- ultrasonic
- eddy current
- thermoelectric
- etc.

\[
T = \tau A
\]

\[
v \approx \sqrt{\frac{\tau}{D}}
\]

stress relief hole  strain rosette

Time

Amplitude

H

B noise

\[ T = \text{Time} \]

\[ H \]

\[ B \text{ noise} \]
Sources of Residual Stress

**material-related**
- multi-phase microstructure
- composites
- inclusions
- etc.

**processing-related**
- casting
- quenching
- cold working
- cutting
- joining
- case hardening
- surface treatments
- etc.

**service-related**
- mechanical
- thermal
- chemical
- etc.
Surface-Enhancement Techniques

Shot Peening (SP)

Laser Shock Peening (LSP)

Low-Plasticity Burnishing (LPB)

Residual Stress [MPa]

Depth [mm]

Cold Work [%]

Depth [mm]
X-ray Bragg Diffraction

\[ 2D \sin \theta_B = n\lambda \]

\[ D(hkl) = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \quad \text{(cubic)} \]

\[ a \approx 2 - 10 \text{Å}, \quad \lambda \approx 0.5 - 5 \text{Å} \]

\[ \varepsilon = \frac{\Delta D}{D} \approx 10^{-3} - 10^{-4} \]

Main Challenge:
low penetration depth (≈1-10 µm)
XRD Measurements on Shot-Peened Waspaloy Specimens

before (solid circles) and after full stress relaxation (empty circles) at 900 °C, 24 hrs
Synchrotron Radiation and Neutron Diffraction

Main Advantage and Disadvantage:
- good penetration depth (≈1-5 cm)
- availability of source

incident beam

diffracted beam

\[ \theta_B \approx 0.5 \text{ mm} \]

Distance from Surface [mm]

Residual Stress [MPa]

<table>
<thead>
<tr>
<th>Distance from Surface [mm]</th>
<th>Residual Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
</tr>
</tbody>
</table>

shot-peened turbine alloy (Ezeilo et al., 1992)

x and y directions

z direction

synchrotron (Univ. Dortmund)

isotope reactor (ORNL)
Indirect NDE Methods for Near-Surface Residual Stress Assessment

- Ultrasonic: SAW
- Eddy Current: probe coil, magnetic field, eddy currents
- Thermoelectric: heat, thermoelectric current, nozzles, flaggate
Nonlinear Acoustoelastic Effect

Potential Energy [a. u.]

Normalized Lattice Distance

Potential well

Elastic Stiffness [a. u.]

Normalized Lattice Distance (Strain)

parabolic potential function

unstrained

typical

Relative Velocity Change [%]

Uniaxial Strain [%]

parallel polarization

normal polarization

AI-2024 T351

0.9 0.95 1 1.05 1.1

-0.3 -0.2 -0.1 0 0.1 0.2 0.3

-0.2 -0.1 0 0.1 0.2 0.3

0.9 0.95 1 1.05 1.1

-0.2 -0.1 0 0.1 0.2 0.3
Surface Acoustic Wave Dispersion

Surface wave →

Normalized SAW Velocity

Normalized Frequency

stiff coating layer
compliant coating layer
uncoated

$\lambda \approx \lambda$

$d << \lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

$\lambda$

Relative Velocity Change [%]

Frequency [MHz]

Al 2024 Almen 8A

Al 2024 Almen 6A

Relative Velocity Change [%]

Frequency [MHz]

300 °C

250 °C

225 °C

200 °C

150 °C

intact

300 °C

250 °C

225 °C

200 °C

150 °C

intact
Indirect NDE Methods for Near-Surface Residual Stress Assessment

- **Ultrasonic**
  - SAW
  - Transducer
  - Interferometer
  - Laser

- **Eddy Current**
  - Probe coil
  - Magnetic field
  - Eddy currents

- **Thermoelectric**
  - Heat
  - Thermoelectric current
  - Magnetometer
Piezoresistive Measurements in Different Metals

- **Ti-6Al-4V**
- **Al 2024**
- **Al 7075**
- **Waspaloy**
- **IN718**
- **Copper**
The excess apparent conductivity gradually vanishes during thermal relaxation!
Inversion of Measured AECC in Low-Plasticity Burnished Waspaloy

- AECC Change [%] vs. Frequency [MHz]
- Cold Work [%] vs. Depth [mm]
- Residual Stress [MPa] vs. Depth [mm]
Indirect NDE Methods for Near-Surface Residual Stress Assessment

**ultrasonic**

**eddy current**

**thermoelectric**
Magnetic Signatures Produced by Semi-Spherical Inclusions and Cavities

C11000 copper, $\nabla T \approx 0.6 \, ^\circ C/cm$, 2 mm lift-off distance, $3'' \times 3''$

0.25"-diameter tin inclusion, 33 nT_p

0.375"-diameter tin inclusion, 104 nT_p

0.375"-diameter cavity, 18 nT_p

before annealing

after annealing
Noncontacting Thermoelectric Inspection in Shot-Peened C11000 Copper

- 2nd relaxation at 315 °C
- 3rd relaxation at 460 °C
- Recrystallization at 600 °C

Graphs showing fluxgate gradiometer data before stress release and after partial stress release (30 min, 315 °C) for Almen 4A, 8A, and 12A.
Conclusion

Essentially the same destructive method works in every material.

Very different nondestructive methods are needed in different materials.