Extreme Condition Mechanical Testing of AM Materials Using Complementary Methods

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Supported Students

Students:
The project currently supports three graduate students at Wichita State University:

- PhD: Changlong Cui, since August 2017.
- PhD: Pavan Bhavsar, since August 2017.
Publications


- Two abstracts have been submitted to the Society for Experimental Mechanics (SEM) to be presented on June 2019 in Greenville, SC. The abstracts will be accompanied with papers to be published at the conference proceedings:
Project Goals and Presentation Outline

The scientific goals are to:

(i) Study the mechanical properties of additively manufactured (AM) materials over a wide range of strain rates and temperature, using strain rate and temperature fields measured in highly instrumented Kolsky compression and machining tests.

(ii) Investigate the correlation between the two in the range of overlapping strain rates,

(iii) Develop constitutive model parameters to fit the data.

(iv) Explore high speed constrained machining as a novel test to also impose high hydrostatic pressure.

• Report constitutive models for additive manufacturing Inconel 625 (AM IN 625) and cast-wrought Inconel 625 (CW IN 625) from Kolsky compression testing under strain rates \( \sim 10^3/s \).

• Introduce experimental techniques for measurement of the strain rate field during machining tests.

• Report results from strain rate measurements from machining tests.

• Report results from microstructure analysis (shear banding) from machining tests.

• Introduce steps currently under way to avoid shear banding during machining.
Research Scope

From Kolsky compression testing and machining:

\[ \sigma = (A + B\varepsilon^n)[1 + Cln(\dot{\varepsilon}/\dot{\varepsilon}_0)](1 - T^n_{h}) \]

- Strains (\(\varepsilon\))
- Flow Stress (\(\sigma\))
- Temperatures (\(T^m_h\))
- Strain Rates (\(\dot{\varepsilon}\))
- Coefficients (\(A, B, C, n, m\))
## Machining vs. other common high strain rate testing methods

<table>
<thead>
<tr>
<th>Testing method</th>
<th>Loading Mode</th>
<th>Characteristic time (s)</th>
<th>Effective Strain</th>
<th>Effective Strain Rate (1/s)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hopkinson bar impact</td>
<td>Tension, compression, torsion</td>
<td>$10^{-4} - 10^{-6}$</td>
<td>Up to 50%</td>
<td>$10^2 - 10^4$</td>
<td>Plane stress. Inertia forces limit max strain rate.</td>
</tr>
<tr>
<td>Plate impact</td>
<td>Compression, Shear</td>
<td>$10^{-6} - 10^{-8}$</td>
<td>Up to 25%</td>
<td>$10^5 - 10^7$</td>
<td>Shock wave propagation. Inertial confinement. Specimen is very thin. Material should have fine grain to maintain polycrystalline behavior.</td>
</tr>
<tr>
<td>Machining</td>
<td>Combined</td>
<td>Several seconds</td>
<td>50% – 400%</td>
<td>$10^2 - 10^6$</td>
<td>Plane strain. Non-uniform stress, strain rate, and temperature fields.</td>
</tr>
</tbody>
</table>
Kolsky Compression Testing

Pulses Travel at the Speed of Sound in Steel (~ 5000 m/s)

Source: Direct correspondence with Steven Mates, NIST
Comparison of AM and cast-wrought materials

<table>
<thead>
<tr>
<th>JC Parameter</th>
<th>AM IN 625</th>
<th>CW IN 625</th>
</tr>
</thead>
<tbody>
<tr>
<td>A [MPa]</td>
<td>709</td>
<td>158</td>
</tr>
<tr>
<td>B [MPa]</td>
<td>2366</td>
<td>2337</td>
</tr>
<tr>
<td>n</td>
<td>0.726</td>
<td>0.461</td>
</tr>
<tr>
<td>C</td>
<td>0.000209*</td>
<td>0.000209*</td>
</tr>
<tr>
<td>$\dot{\varepsilon}_o$ [1/s]</td>
<td>1670*</td>
<td>1670*</td>
</tr>
<tr>
<td>m</td>
<td>1.56</td>
<td>1.65</td>
</tr>
<tr>
<td>Test strain rate [1/s]</td>
<td>2500</td>
<td>3250</td>
</tr>
</tbody>
</table>

Fig. 1: Flow stress vs. strain during adiabatic deformation at shear strain rate of $3 \times 10^4$ 1/s


Machining Setup: Strain Rate Measurements

Fig. 2. a) Schematic of the ultra-high speed visible imaging system for digital image correlation (DIC). b) Timing diagram indicating camera exposure and laser pulses.

Fig. 3. Linear machining setup for strain and strain rate measurements. a) The cutting arrangement. b) The ultra-high speed imaging system. c) Schematic of the setup.
Machining: Images

Conventional Machining
CW IN 625
Speed: 2 m/s
Feed: 155 µm

Conventional Machining
AM IN 625
Speed: 2 m/s
Feed: 155 µm

Tool
Workpiece
Crack
Strain rate fields and strain rate profile from Digital Image Correlation (DIC)

Fig. 4. Sequence of two images of the PSZ from the cutting of AM IN 625. Infeed 145µm, cutting speed = 2 m/s, rake angle = +5°, relief angle = 6°. The time between the two images is 35 µs.

Fig. 5. Typical maximum shear strain field. Material: AM IN 625. Cutting tool: Tungsten carbide with +5° rake angle, +6° flank angle and cutting edge radius ~7.5 µm. Cutting speed = 2 m/s and depth of cut (feed) = 145 µm.
Strain rate fields and strain rate profile from Digital Image Correlation (DIC)

Fig. 6. a) Typical effective strain field that develops during the machining of IN 625. b) Effective strain rate profiles through the PSZ. Material: AM IN 625. Cutting tool: Tungsten carbide with +5° rake angle, +6° flank angle and cutting edge radius ~7.5 µm. Cutting speed = 2 m/s and depth of cut (feed) = 145 µm.
# Maximum Strain Rate

Summary of strain rate and normalized force measurements

<table>
<thead>
<tr>
<th>Machining Velocity</th>
<th>Feed</th>
<th>Material</th>
<th>Effective Strain Rate</th>
<th>Normalized Cutting Force</th>
<th>Normalized Thrust Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m/s)</td>
<td>(μm)</td>
<td>(1/s)</td>
<td>(N/mm²)</td>
<td>(N/mm²)</td>
<td></td>
</tr>
<tr>
<td>155</td>
<td>CW</td>
<td>38,000</td>
<td>2,380</td>
<td>1,080</td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>AM</td>
<td>24,000</td>
<td>2,540</td>
<td>1,370</td>
<td></td>
</tr>
<tr>
<td>116</td>
<td>AM</td>
<td>30,000</td>
<td>2,510</td>
<td>1,370</td>
<td></td>
</tr>
<tr>
<td>155</td>
<td>AM</td>
<td>28,000</td>
<td>1,910</td>
<td>1,020</td>
<td></td>
</tr>
</tbody>
</table>
Chip Microstructure

Fig. 7. Lateral views of a) CW IN 625 chip, and b) AM IN 625 chip. Cutting speed = 2 m/s. Polished and etched using standard metallographic procedures. Imaged with an optical microscope.
High Positive Rake Angle

Fig. 8 Schematic of the high rake-angle cutting configuration.

Fig. 9. Low strain and low strain rate machining set up. The dual linear slide provides high stiffness.
Constrained Machining

Speed: 0.01 m/s
Feed: 200 µm

Fig. 10. Picture of constraint and cutting tool arrangement

Fig. 11. Picture of High-Speed Constrained Machining set up
Summary

1. Constitutive models for AM IN 625 and CW IN 625 have been developed from Kolsky compression testing under strains up to 25%, strain rates of the order of $10^3$/s and temperatures up to 1000 °C.
2. From Kolsky testing, AM IN 625 is generally of higher flow stress than CW IN 625, but the critical strain for the onset of shear banding for both materials is about the same.
3. During machining tests, under strain rates of the order of $10^4$/s, AM IN 625 experiences more sharply defined shear bands than CW IN 625. The shear band interspacing and morphology is very random for AM, and very uniform for CW.
4. To avoid shear banding during machining, and to enable determination of constitutive models from machining tests, positive rake angles and machining with a constrained shear zone are under development.

Immediate future work will center attention on:

1. Using high positive rake angles to avoid shear banding.
2. Constrain the shear zone using constrained machining.
3. Develop constitutive models from machining under strain rates of the order of $10^4$/s.
4. Study effects of microvoids or second phase particles in shear banding.