Ductile iron (DI) is a form of cast iron containing spherical graphite nodules, which enhance mechanical properties, serve as crack arrestors, and improve toughness and fatigue properties [1]. Austempering is a heat treatment process that entails: 

- Austenitizing — form an entirely gamma matrix; then
- Quenching — to above the martensite start temperature; then
- Single Step Austempering — hold at this temperature to nucleate and grow ferrite, which rejects carbon into the austenite making it a metastable phase [2],
- Dual Step Austempering — second austempering temperature slightly higher than first step; finer ferrite from first step, second step enhances carbon diffusion to stabilize austenite [2].

Two key microstructural features of ADI are theorized to 

- greater wear resistance
- nodules, which enhance mechanical properties, serve as crack arrestors, and improve toughness and fatigue properties [1].

Heat Treatment

- Austempering in a second box furnace per experiment matrix
- Austenitizing
- Heat map of phase evolution during austempering [5]
- Austempered ductile iron (ADI) is being considered as an alternative for these high-wear components. This project explores how variations in heat treatment influence the microstructure, mechanical properties, wear resistance, and suitability of ADI for pellet mill components.

Experimental Procedures

**Slurry Wear Testing**

- Coupon DI samples prepared to ASTM G75 dimension standards
- Austenitized in box furnace at 950°C for 2 hours
- Quenched in nitrate salt bath at 250°C for 10 minutes
- Austempering in a second box furnace per experiment matrix
- Four heat treatment parameters had duplicate samples prepared to be sent out for external wear testing. These are designated by a colored box in experiment matrix and are assigned alphabetic nomenclature to be used throughout study

**Nanoscratch Testing**

- Austenitized and mounted in bakelite, polished to 1 µm finish
- Etched with 2% nital for 5-10 seconds
- Rockwell C hardness (5 indentors per sample)

**Nanoindentation**

- PullTec XRD to obtain integrated intensity of 0°26 and 0°28 peaks
- Calculate retained austenite using ASTM E975-13
- Heat treatment parameters should be closely monitored to reduce quenching rate
- Phase evolution during austempering [5]
- Phase map during austempering [5]
- Phase map during austempering [5]

**Slurry Wear Testing**

- ASTM G75 slurry wear testing
- Samples A, B, C, D, and a reference quench and tempered DI

**Metallography and Hardness**

- Specimen Nomenclature

- **Austempering Experiment Matrix**

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>1 1 1</td>
</tr>
<tr>
<td>260</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>280</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>300</td>
<td>1 1 1 1</td>
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<tr>
<td>320</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>340</td>
<td>- - - 2</td>
</tr>
</tbody>
</table>

**Specimen Nomenclature**

- A = 250°C, 30 min
- B = 280°C, 120 min
- C = 310°C, 30 min
- D = 340°C, 120 min

**Results**

- Records scratch position, load, and surface profile before, during, and after the scratch
- Data was cleaned to zero the surface profile at beginning of scratch (30 µm into the test)

| Top | Profile traces and scratch load as functions of scratch position | Representative of one scratch on one sample |
| Bottom | Average scratch plastic deformation profile (fit-relast) as functions of load | Greater absolute plastic deformation indicates poorer wear resistance | Deformation energy measured from curve integration |

**Slurry Wear Testing**

- Top: Mass loss (mg) of samples at 2-hour intervals
- Greater mass loss signifies poorer wear resistance

<table>
<thead>
<tr>
<th>Linear Reg Slope</th>
<th>Linear Coefficient</th>
<th></th>
<th>P.E. Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.830</td>
<td>248</td>
<td>181</td>
</tr>
<tr>
<td>B</td>
<td>0.934</td>
<td>163</td>
<td>163</td>
</tr>
<tr>
<td>C</td>
<td>0.771</td>
<td>285</td>
<td>154</td>
</tr>
<tr>
<td>D</td>
<td>0.730</td>
<td>246</td>
<td>147</td>
</tr>
</tbody>
</table>

**Discussion**

- Heat map of regression R² values between experimental variables. The table is color-coded, so that cells with a greater hue have higher correlation (R² values), and cells with a redder hue have lower correlation.

- This work is sponsored by CPM, 1114 E Wabash Ave, Crawfordsville, IN 47933

**Conclusions**

- Nanoscratch does not sufficiently correlate with G75 to be a substitute
- Further investigation should focus on potential non-linearity of wear behavior
- Slowing down and tempering are a large determinant in microstructural development - transport time between steps and quenching parameters should be closely monitored
- Reasons in deterrence of wear performance between sample A & D and after the scratch

**References**

[5] This work is sponsored by CPM, 1114 E Wabash Ave, Crawfordsville, IN 47933.