HAYNES® N-86 is a nickel-based alloy with significant additions of chromium and molybdenum. The full composition can be seen below:

<table>
<thead>
<tr>
<th>wt%</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>Mg</th>
<th>Ce</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05</td>
<td>25.0</td>
<td>10.0</td>
<td>0.015</td>
<td>0.03</td>
<td>Rem.</td>
</tr>
</tbody>
</table>

This alloy occasionally fails to meet mechanical property specifications. The goal of this project is to mitigate this issue by defining the relationship between processing parameters and microstructural and mechanical properties.

HAYNES® N-86 sheet is produced as follows:

- **Forging**
- **Remelting**
- **Annealing**
- **Hot Rolling**
- **Pickling**
- **Cold Rolling**
- **Annealing**

This research studied the cold rolling and continuous annealing processes (boxed above) to produce the final sheet thickness and the resulting mechanical properties of HAYNES® N-86.

### Experimental Procedures

Haynes provided the team with HAYNES® N-86 samples in the pre-cold worked state. To determine the effects of cold work and annealing temperature on hardness and tensile properties, a 12-condition experimental matrix was developed. The anneal time was 2 min for all conditions.

### Annealing Temperature-Cold Work Study

#### Hardness Testing:
A decrease in hardness was observed after annealing. In addition, hardness post annealing is not a clear function of prior cold work. Samples annealed at 1120°C did not decrease in hardness as much as 1170°C and 1220°C, possibly indicating those samples underwent incomplete annealing.

#### Metallography:
The grains were more equiaxed in the annealed conditions than the as-cold worked condition, with large equiaxed grains appearing in the higher anneal temperature samples. The 1120°C anneal resulted in incomplete recrystallization. A significant difference in grain size across different regions of the sample was not apparent.

#### Grain size measurement confirmed the trends that could be seen visibly in the optical micrographs. The significantly lower grain size in the 1120°C samples is further evidence of incomplete recrystallization.

### Conclusions and Recommendations

Annealing at 1170°C for 2 minutes was sufficient for acceptable microstructures and properties to be developed. Lowering the anneal temperature should not be considered due to incomplete recrystallization observed at 1120°C. Changes in tensile properties with %CW indicated that a single cold work-anneal cycle should not exceed 45%CW. The annealing time study indicated that annealing time could be lowered due to the recrystallization seen in just 1 min of annealing time. Tensile testing for shorter-time anneals would need to be done to validate this proposal.

Further tensile testing, especially at elevated temperature, needs to be done to properly draw conclusions about the processing effects on mechanical properties. Other variables from earlier in the process (i.e., before cold work) could be investigated for their effects on the final annealed microstructure and properties.

### Acknowledgements and References

In addition to our faculty advisor, Prof. Kevin Trumble, and our primary Haynes contact, Kyle Stubbs, who provided insightful suggestions and encouragement throughout the project, we also would like to thank Eric Dill and Kristin Groome from Haynes International for their help with metallography and tensile testing, respectively.

**References:**