High Modulus Reinforcement Alloys
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Pure Ni remains ductile and tough at fracture at cryogenic temperatures.

Chromium has solubility up to 20 wt% in nickel.

Cobalt has very large solubility in nickel, although itself has a hexagonal crystallographic structure.

Molybdenum has the solubility slightly higher than 10 wt% in nickel room temperature and below,

Melting Point for Ni-Al system.
# COMPARISON OF YOUNG MODULUS OF SELECTED NICKLE ALLOYS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ni-Cr</th>
<th>Ni-Mo</th>
<th>Ni-Co</th>
<th>Ni-Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni*</td>
<td>Inconel718**</td>
<td>Haynes242***</td>
<td>Elgiloy* ***</td>
<td>MP35N* ****</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Room Temperature</th>
<th>210</th>
<th>200</th>
<th>221</th>
<th>216</th>
<th>226</th>
</tr>
</thead>
<tbody>
<tr>
<td>77 K</td>
<td>224</td>
<td>208</td>
<td>237</td>
<td>229</td>
<td>238</td>
</tr>
<tr>
<td>4 K</td>
<td>&gt;226</td>
<td>-</td>
<td>238</td>
<td>-</td>
<td>239</td>
</tr>
</tbody>
</table>

***Tensile properties measured from plate
****Tensile properties measured from sheet metals
*****Dynamic modulus measured from rod
Comparison of 4K strain hardening of SS316LN and H242

At 4K, H242 has higher yield strength, higher strain hardening rates, and higher tensile strength than SS316LN—this relates to high densities of nano-sized domains.

At 4K, the amplitude of the discontinuous-yielding increases with the increase of plastic deformation strain and stresses. H242 has lower amplitude of discontinuous-yielding than SS316LN.
Transmission electron microscopy bright field image showing the nano-sized domains in Ni-Mo based alloy (Haynes 242) aged at high temperature. The formation of nano-sized domains enhances Young's modulus. In order to form high density of nano-sized domains, $\geq 2$ hours is required for aging. To reduce the initial hardening time, a new alloy is made.
The new alloy needs significantly shorter time for age-hardening.

The new alloy has higher modulus than Haynes 242.

Similar to Haynes 242, Co-Ni alloy (MP35N) is also strengthened by nanosized particles with certain orientation. This produces high strength and modulus, but also anisotropy.
Co-Ni based reinforcement alloy (MP35N) has been used as a structural reinforcement component for high field pulsed magnets operating at 77 K.

- USA MagLab has also pursued the application of MP35N below 77 K, such as either reinforcement or substrates for high-temperature superconducting (HTS) magnets operating at 4.2 K.
- One of the driver to pursue Co-Ni based reinforcement alloy is its high elastic modulus.

# Comparison of Young Modulus of MP35N

<table>
<thead>
<tr>
<th>Test Orientation</th>
<th>Temperature (K)</th>
<th>Young's Modulus (GPa)</th>
<th>Stdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG-LD</td>
<td>77</td>
<td>224</td>
<td>19</td>
</tr>
<tr>
<td>AG-TD</td>
<td>77</td>
<td>263</td>
<td>19</td>
</tr>
<tr>
<td>AG-LD</td>
<td>4</td>
<td>236</td>
<td>32</td>
</tr>
<tr>
<td>AG-TD</td>
<td>4</td>
<td>264</td>
<td>15</td>
</tr>
</tbody>
</table>
Summary

- Nickel-chromium based alloys (e.g. Inconelxxx) have higher modulus than stainless steels.
- The alloys based on nickel-molybdenum-chromium (e.g. Haynes242) have higher modulus than other candidates for cryogenic and magnet applications.
- Nickel-cobalt-molybdenum alloys (e.g. MP35N) have high modulus and mechanical strength.
- Deformation and aging further enhances the Young’s modulus in these high modulus alloys.
- The high modulus is partially introduced by prolonged aging reaction.
- A new alloy is introduced with significant shorter aging time than conventional Ni-alloys.
- Cold-deformation induces texture and anisotropy in Young’s modulus.
ACKNOWLEDGMENT

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