Nickel alloys provide levels of corrosion resistance not possible with other alloys. This is part one of a three-part series about corrosion-resistant nickel alloys.

Nickel is an ideal base for corrosion-resistant alloys. Not only is it inherently resistant to certain chemicals, but also it can be highly alloyed with elements known to enhance corrosion performance, such as chromium, copper, and molybdenum, while retaining its ductile face-centered cubic structure. Iron is not as accommodating; thus high levels of such elements are not possible in the stainless steels without structural instability.

In addition to commercially pure nickel, three binary alloy systems also provide exceptional corrosion resistance. These include nickel-chromium (Ni-Cr), nickel-copper (Ni-Cu), and nickel-molybdenum (Ni-Mo). Chromium enhances the resistance of nickel to oxidizing acids by encouraging the formation of passive films. Copper is very helpful in seawater, brackish water, and reducing acids, in particular hydrofluoric. Molybdenum is extremely beneficial in all reducing acids.

This article focuses on commercially pure nickel and the three binary alloy systems. Future articles will cover ternary systems and the effects on various nickel alloys of industrially important acids, bases, and salts.

### Commercially pure nickel

Several materials are sold under the guise of commercially pure nickel. Most contain in excess of 99% nickel, and most contain small, elemental additions to control specific properties. Many were designed for electronics, where the electrical and magnetic properties of pure nickel are crucial.

From a corrosion standpoint, the commercially pure nickels are important for two reasons:

- **Resistance to the caustic alkalies**: They provide outstanding resistance to caustic soda and caustic potash over wide ranges of concentration and temperature.
- **Formability**: They are easy to form into complex shapes and have inherent resistance to mild corrosives; thus they are suitable for food processing equipment.

The nominal compositions of several commercially pure nickels are given in Table 1. Wrought Nickel 200 is by far the most widely used. However, for applications above approximately 300°C (570°F), Nickel 201 is preferred, because it has a lower carbon content and is thus resistant to graphitization. It also has higher creep resistance than Nickel 200.

Another important commercially pure nickel is Duranickel alloy 301, which can be strengthened by heat treatment. It was designed as an alternate to Nickel 200, for applications requiring

### Table 1 — Commercially pure nickel alloys

<table>
<thead>
<tr>
<th>UNS No.</th>
<th>Form</th>
<th>Composition</th>
<th>Ni</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Si</th>
<th>C</th>
<th>Al</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>N02200</td>
<td>Wrought</td>
<td>99.5</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>201</td>
<td>N02201</td>
<td>Wrought</td>
<td>99.5</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>301</td>
<td>N03301</td>
<td>Wrought</td>
<td>96.5</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
<td>0.2</td>
<td>4.4</td>
<td>0.6</td>
</tr>
<tr>
<td>CZ-100</td>
<td>N02100</td>
<td>Cast</td>
<td>95**</td>
<td>1.25*</td>
<td>1.5*</td>
<td>2*</td>
<td>1*</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Values denoted with * are maxima, and ** are minima.
The primary attribute of the nickel-copper Monel alloys is resistance to seawater and brackish water.

Monel alloy K-500, which can be strengthened by age-hardening, is the second most important Ni-Cu alloy. The hardening precipitate is again γ', and this is induced by additions of aluminum and titanium. In its hardened state, the alloy offers corrosion characteristics similar to alloy 400, in a material with three times the yield strength. Several cast Ni-Cu alloys are also available, notably M-35-1, which can function in the as-cast condition.

Nickel-molybdenum

The nickel-molybdenum, or Hastelloy B-type alloys, have a long history of service within the chemical process industries. Their chief benefit is high resistance to pure hydrochloric and sulfuric acids, over large ranges of concentration and temperature. They also resist pure hydrobromic acid, hydrofluoric acid, food-grade phosphoric acid, acid chlorides, and other non-oxidizing halide salt solutions.

The primary limitation of the Ni-Mo alloys is that they cannot tolerate either oxidizing acids, such as nitric, or acids that contain oxidizing species. Such species include oxygen, hydrogen peroxide, chlorine, bromine, ferric ions, and cupric ions.

Monel alloy K-500, which can be strengthened by age-hardening, is the second most important Ni-Cu alloy. The hardening precipitate is again γ', and this is induced by additions of aluminum and titanium. In its hardened state, the alloy offers corrosion characteristics similar to alloy 400, in a material with three times the yield strength. Several cast Ni-Cu alloys are also available, notably M-35-1, which can function in the as-cast condition.

Nickel-copper

Nickel and copper, neighbors in the Periodic Table, share the same atomic structure, face-centered cubic (fcc). Moreover, this structure is retained in all mixtures of the two elements, at all temperatures in the solid range. This is the basis for several commercially important nickel-copper and copper-nickel alloys.

This article is concerned with the nickel-copper alloys that contain approximately 30 to 45 wt% copper. These are closely associated with Special Metals Corp. Monel trademark. At the other end of the spectrum, copper alloys containing approximately 30 wt% nickel have been commercially successful, albeit under less aggressive conditions. In fact, these copper-nickel alloys have the best general resistance to aqueous corrosion of all the commercially important copper alloys, especially in hydrofluoric acid.

The primary attribute of the nickel-copper Monel alloys is resistance to seawater and brackish water. They are known for their resistance to biofouling in such environments. They also possess excellent resistance to hydrofluoric acid and moderate resistance to other non-oxidizing acids. They withstand cavitation erosion and are therefore ideally suited to applications in flowing water, such as propellers and pumps.

The nominal compositions of two wrought Ni-Cu alloys are given in Table 2. Monel alloy 400 was one of the first nickel alloys developed (in 1905) and is still one of the most widely used.

Monel alloy K-500, which can be strengthened by age-hardening, is the second most important Ni-Cu alloy. The hardening precipitate is again γ', and this is induced by additions of aluminum and titanium. In its hardened state, the alloy offers corrosion characteristics similar to alloy 400, in a material with three times the yield strength. Several cast Ni-Cu alloys are also available, notably M-35-1, which can function in the as-cast condition.

Nickel-molybdenum

The nickel-molybdenum, or Hastelloy B-type alloys, have a long history of service within the chemical process industries. Their chief benefit is high resistance to pure hydrochloric and sulfuric acids, over large ranges of concentration and temperature. They also resist pure hydrobromic acid, hydrofluoric acid, food-grade phosphoric acid, acid chlorides, and other non-oxidizing halide salt solutions.

The primary limitation of the Ni-Mo alloys is that they cannot tolerate either oxidizing acids, such as nitric, or acids that contain oxidizing species. Such species include oxygen, hydrogen peroxide, chlorine, bromine, ferric ions, and cupric ions.

The nominal compositions of several wrought and cast Ni-Mo alloys are given in Table 3. All contain about 30 wt% molybdenum and few additional elements. The original Hastelloy B alloy was introduced in the late 1920's as a casting material.

Wrought products became available in the 1950's, notably with a lower maximum carbon content. Post-weld annealing was necessary with Hastelloy B, because significant levels of carbon and silicon (known to cause problems in weld heat-affected zones) could not be avoided at that time.

In the 1960's, a new melting technique known as argon-oxygen decarburization (AOD), was introduced. This technology enabled the manufacture of corrosion-resistant nickel alloys with much lower carbon and silicon contents, which allowed...
them to be safely used in the as-welded condition. Application of this melting technology led to the introduction of wrought B-2 alloy in the 1970’s, then the more stable B-3 alloy in the 1990’s.

- **Cast Ni-Mo alloys** include only one significant development, and that is the introduction of Chlorimet 2 (more generally known as N-7M). This has a lower carbon limit than the original cast Hastelloy B alloy (the composition of which is still made under the designation N-12MV), to minimize the precipitation of grain boundary carbides. It has a higher molybdenum content for enhanced corrosion resistance.

The atomic structure of the B-type alloys is predominantly face-centered cubic (fcc). The alloys are supplied in the solution-annealed and water-quenched condition. The purpose of the anneal is to dissolve the majority of second phases in the microstructure, and the purpose of the quench is to “lock-in” the high temperature fcc structure. The solution annealing temperature is approximately 1065°C (1950°F).

Second phases develop quickly when the B-type alloys are exposed to moderately high temperatures, especially in the range 650°C to 800°C (1200°F to 1470°F). Such phases reduce ductility and render the alloys susceptible to mechanical fracture (under the action of residual stress) and stress-corrosion cracking. The second phases of most concern are Ni$_3$Mo (which forms very quickly); Ni$_3$Mo (which requires more diffusion of molybdenum, and is therefore slower to form); M$_6$C, and M$_{12}$C. The latter two are tied to the carbon contents of the alloys. They are particularly damaging because they tend to form in the alloy grain boundaries.

### Nickel-Chromium

Early experiments involving the addition of chromium to nickel not only resulted in materials resistant to oxidizing acids, but also paved the way for the development of a wide range of oxidation-resistant high-temperature alloys. Indeed, some of the first Ni-Cr materials were, and still are, used for heating elements in domestic appliances.

The most common wrought corrosion-resistant Ni-Cr materials are Inconel alloy 600 and Inconel alloy 625. The primary corrosion-related attributes of alloy 600 include excellent resistance to sodium hydroxide and good resistance to stress corrosion cracking (SCC), relative to many stain-

Table 4 — Nickel-chromium alloys

<table>
<thead>
<tr>
<th>Ni-Cr alloy</th>
<th>UNS No.</th>
<th>Form</th>
<th>Ni</th>
<th>Cu</th>
<th>Mo</th>
<th>Cr</th>
<th>Fe</th>
<th>W</th>
<th>Mn</th>
<th>Si</th>
<th>C</th>
<th>Al</th>
<th>Ti</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>N06600</td>
<td>Wrought</td>
<td>76</td>
<td>0.2</td>
<td>—</td>
<td>15.5</td>
<td>8</td>
<td>0.5</td>
<td>0.2</td>
<td>0.08</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>625</td>
<td>N06625</td>
<td>Wrought</td>
<td>61</td>
<td>—</td>
<td>9</td>
<td>21.5</td>
<td>2.5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.05</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>Nb + Ta 3.6</td>
</tr>
<tr>
<td>690</td>
<td>N06690</td>
<td>Wrought</td>
<td>58**</td>
<td>0.5*</td>
<td>—</td>
<td>29</td>
<td>9</td>
<td>0.5*</td>
<td>0.5*</td>
<td>0.05*</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>725</td>
<td>N07725</td>
<td>Wrought</td>
<td>57</td>
<td>—</td>
<td>8</td>
<td>21</td>
<td>7.5</td>
<td>0.35*</td>
<td>0.2*</td>
<td>0.03*</td>
<td>0.35*</td>
<td>1.5</td>
<td>Nb 3.5</td>
<td></td>
</tr>
<tr>
<td>G-35</td>
<td>N06035</td>
<td>Wrought</td>
<td>58</td>
<td>0.3*</td>
<td>—</td>
<td>8.1</td>
<td>33.2</td>
<td>2*</td>
<td>0.6*</td>
<td>0.5*</td>
<td>0.6*</td>
<td>0.05*</td>
<td>0.4*</td>
<td>—</td>
</tr>
<tr>
<td>Allcorr</td>
<td>N06110</td>
<td>Wrought</td>
<td>Bal.</td>
<td>—</td>
<td>10</td>
<td>31</td>
<td>—</td>
<td>2</td>
<td>—</td>
<td>0.02</td>
<td>0.25</td>
<td>0.25</td>
<td>Nb 0.4</td>
<td></td>
</tr>
</tbody>
</table>

Values denoted with * are maxima, and ** are minima.