This article is the Introduction to The Nickel Advantage, a 50-page publication replete with useful information about the physical and mechanical properties, weldability, and corrosion resistance of nickel-containing stainless steels.

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Chromium is the key alloying element that makes stainless steels “stainless.” Steel must include more than 10.5% chromium to allow formation of the protective chromium oxide film that provides corrosion resistance and the bright, silvery appearance. In general, the more chromium, the greater the corrosion resistance. That discovery was made about a century ago, yet even some of the early stainless steels also contained nickel. Today about two-thirds of the tonnage of stainless steel produced each year contains nickel, even though nickel may be seen as a relatively high-cost alloying addition.

What is the role of nickel, and why is it used so extensively? This article answers that question in terms of strength, toughness, corrosion resistance, weldability, and formability.

Austenite structure
The primary function of nickel is to stabilize the austenitic structure of the steel at room temperature and below. This austenitic (i.e., face-centered cubic crystal) structure is particularly tough and ductile. Those and other properties are responsible for the versatility of these grades of stainless steel. Aluminum, copper, and nickel itself are good examples of metals with the austenitic structure.

The minimum amount of nickel that can stabilize the austenitic structure at room temperature is around 8%, and so that is the percentage present in the most widely used grade of stainless steel, namely Type 304. It contains 18% chromium and 8% nickel (often referred to as 18/8). That composition was one of the first to be developed in the history of stainless steel, in the early twentieth century. It was used for chemical plants and to clad the iconic Chrysler Building in New York City, which was completed in 1929.

Manganese was first added to stainless steel in the 1930s. The 200-series of low-nickel, austenitic

The Air Force Memorial consists of three stainless steel spires reaching 64 meters into the air. Each spire has a 19-millimeter-thick skin of S31600 stainless steel (which contains 11% nickel) covering a core of reinforced concrete. Engineers chose S31600 to prevent corrosion and allow the structure’s appearance to be retained over decades without the need for manual cleaning. Though Washington is not coastal, the memorial is surrounded by three highways treated occasionally with de-icing salt that could threaten a lesser material. S31600 also provides structural integrity to help withstand the tendency for the spires to sway in windy conditions. Photo: Catherine Houska for Nickel Institute.
grades was developed further in the 1950s, when nickel was scarce. More recent improvements in melting practices have allowed the controlled addition of increased amounts of nitrogen, a potent austenite former. This might suggest that all the nickel can be replaced, with the structure remaining austenitic. However, it is not as simple as that, and all the high-manganese austenitic grades commercially available today still contain some deliberate additions of nickel. Many also have a somewhat reduced chromium content, to maintain the austenitic structure. As noted below, this side effect reduces the corrosion resistance of these alloys compared with the standard 300-series nickel grades.

- **Duplex:** As the total content of austenite formers is reduced, the structure of the stainless steel changes from 100% austenite to a mixture of austenite and ferrite (body-centered cubic) known as duplex stainless steels. In these grades, nickel continues to stabilize the structure of the austenite phase. All the commercially important duplex grades, even the “lean duplexes,” contain about 1% or more nickel as a deliberate addition. Most duplex stainless steels have a higher chromium content than the standard austenitic grades: the higher the mean chromium level, the higher the minimum nickel content must be. This is similar to the case for the 200-series noted above.

The two-phase structure of the duplex grades makes them inherently stronger than common austenitic grades. Their slightly higher chromium content also gives them slightly higher corrosion resistance compared to standard grades. Although other characteristics must be considered, the duplex grades have found some valuable niche applications.

- **Ferritic:** Reduction of the nickel content further – even to zero – results in grades with no austenite at all. These have a completely ferritic structure. Iron and mild steels also have a ferritic structure at ambient temperatures. However, not all the ferritic grades are completely nickel-free. Nickel is known to lower the ductile-to-brittle transition temperature (DBTT), that is, the temperature below which the alloy becomes brittle. The DBTT is also a function of other factors such as grain size and other alloying additions. Nevertheless, some of the highly alloyed super-ferritic grades contain an intentional addition of nickel to improve the DBTT, especially of welds.

- **Martensitic:** Unlike the austenitic grades, the martensitic grades are hardenable by heat treatment. However, some do contain nickel, which not only improves toughness but also enables the steel to have a higher chromium content, and this in turn provides increased corrosion resistance. The hardening heat treatment involves heating to a certain temperature and then quenching the material, followed by a tempering operation.

- **Precipitation hardening:** Finally, the precipitation-hardening (PH) grades can also develop high strength by heat treatment. The group has various families of PH grades, but all contain nickel. The heat treatment does not involve a quenching step, unlike the case with the martensitic family.

**Formability characteristics**

The characteristics of the austenitic structure give nickel stainless steels good tensile ductility and good formability, as reflected in comparative forming limit diagrams. The common 18% chromium/8% nickel grade shows particularly good stretch forming characteristics, but has a somewhat lower limiting

**Typical physical properties of stainless steel families**

<table>
<thead>
<tr>
<th>Family</th>
<th>Grade</th>
<th>Density, g/cm³ (lb/in.³)</th>
<th>Thermal conductivity at 100°C, W/m·K (Btu/ft·°F)</th>
<th>Electrical resistivity, nΩm</th>
<th>Specific heat, J K⁻¹ (Btu/lb·°F)</th>
<th>Thermal expansion, 0-100°C</th>
<th>Magnetic permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferritic</td>
<td>430</td>
<td>7.8 (0.28)</td>
<td>26.1 (15.1)</td>
<td>600</td>
<td>460 (0.11)</td>
<td>10.4 (5.8)</td>
<td>600-1000</td>
</tr>
<tr>
<td>Martensitic</td>
<td>410</td>
<td>7.8 (0.28)</td>
<td>24.9 (14.4)</td>
<td>570</td>
<td>460 (0.11)</td>
<td>9.9 (5.5)</td>
<td>700-1000</td>
</tr>
<tr>
<td>Austenitic</td>
<td>304</td>
<td>8.0 (0.29)</td>
<td>16.2 (9.4)</td>
<td>720</td>
<td>500 (0.12)</td>
<td>17.2 (9.6)</td>
<td>1.02</td>
</tr>
<tr>
<td>Austenitic (high Mn)</td>
<td>201</td>
<td>7.8 (0.28)</td>
<td>16.2 (9.4)</td>
<td>690</td>
<td>500 (0.12)</td>
<td>15.7 (8.7)</td>
<td>1.02</td>
</tr>
<tr>
<td>Superaustenitic</td>
<td>S31254</td>
<td>8.0 (0.29)</td>
<td>14 (8.1)</td>
<td>850</td>
<td>500 (0.12)</td>
<td>16.5 (9.2)</td>
<td>c.1</td>
</tr>
<tr>
<td>Duplex</td>
<td>2205</td>
<td>7.8 (0.28)</td>
<td>16 (9.3)</td>
<td>800</td>
<td>500 (0.12)</td>
<td>13.0 (7.2)</td>
<td>&gt;&gt;1</td>
</tr>
<tr>
<td>PH</td>
<td>17-4PH</td>
<td>7.8 (0.28)</td>
<td>18.3 (10.6)</td>
<td>800</td>
<td>460 (0.11)</td>
<td>10.8 (6.0)</td>
<td>95</td>
</tr>
</tbody>
</table>

Stress-strain curves of four different types of stainless steel.
drawing ratio than some ferritic grades. Slightly higher nickel contents increase the stability of the austenite further, and reduce the work hardening tendency, thereby increasing suitability for deep drawing. Unlike traditional low-nickel, high-manganese grades, these are not susceptible to delayed cold cracking. This good formability has led to the widespread use of 300-series austenitic grades for items that demand good formability, such as kitchen sinks, pots, and pans.

Weldability

Many components have to be fabricated by welding. In general, the nickel austenitic grades have better weldability than other grades, and Types 304 and 316 are the most widely fabricated stainless steels in the world. They are not susceptible to embrittlement as a result of high-temperature grain growth, and the welds have good bend and impact properties. They are also more weldable in sections thicker than about 2 mm.

The duplex grades are far more weldable than the ferritic grades for equivalent alloy content, but even the standard and more highly alloyed superduplex alloys require more attention to the details of the welding procedure than the equivalent austenitic grades. The 200-series alloys have welding characteristics similar to the 300 series.

High-temperature properties

The addition of nickel gives the austenitic grades significantly better high-temperature strength than other grades, particularly the ability to resist creep. These grades are also much less susceptible to the formation of deleterious intermetallic phases as a result of exposure at intermediate and high temperatures. Nickel also promotes the stability of the protective oxide film, and reduces spalling during thermal cycling. Consequently, the austenitic grades are used for high-temperature applications and where fire resistance is needed.

It is worth noting that there is a continuum in composition between the austenitic stainless steels and the nickel-based superalloys that serve in the most demanding high-temperature applications such as gas turbines.

Corrosion resistance

As noted, it is the formation of the chromium-
rich oxide layer that accounts chiefly for the corrosion resistance of stainless steels. However, this layer is susceptible to damage, particularly in the presence of chlorides, and such damage can lead to the onset of localized corrosion such as pitting and crevice corrosion. Both molybdenum and nitrogen increase resistance to pit initiation in the presence of chlorides. Nickel does not influence the initiation phase, but is important in reducing the rate at which both pitting and crevice corrosion propagate. This is critical in determining how serious corrosion will be.

Nickel also influences the resistance of stainless steels to another form of localized corrosion, namely chloride stress corrosion cracking. In such cases, however, there is a minimum in resistance at nickel contents of around 8%. Stress corrosion cracking resistance increases markedly at nickel levels that are both lower and higher than this.

In general, increasing the nickel content in stainless steels, including ferritic grades, also increases their resistance to reducing acids such as sulfuric acid. Other elements such as molybdenum and particularly copper, also have a strong influence in this regard. However, the presence of nickel in the ferritic grades has potential drawbacks related to stress corrosion cracking resistance and the formation of intermetallic phases.

Sustainability
Taking into account the Brundtland Report’s definition of sustainable development — “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” — it is clear that stainless steels in general, and the nickel-containing steels in particular, have a major role to play in the areas of environmental protection and economic growth, and social equality.

To appreciate the contribution a material makes toward sustainability, it is important to look at that material’s whole life cycle, from extraction to recycling or disposal at the end of the product’s life. Most nickel-containing alloys are fully recyclable, and their high value encourages this. Recycling lessens the environmental impact by reducing both the need for virgin raw materials and the use of energy.

For example, the amount of stainless steel scrap recycled today reduces the energy required for the manufacture of stainless steel to about 33% less than if 100% virgin materials were used. Nearly half of that reduction comes from end-of-life scrap. Only lack of availability of more scrap, because of the long useful life and considerable growth in stainless steel products, prevents a greater reduction.

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