n today’s competitive business climate, more manufacturers are focusing on using raw materials that provide the lowest life-cycle cost rather than lowest initial cost. This shift created a strong worldwide demand for materials that not only have high strength and toughness properties, but also are relatively easy to fabricate, reliable, and provide long-term service, even in corrosive environments. Carpenter Technology’s premium, double vacuum-melted, martensitic age-hardenable stainless steel (Custom 465, UNS S46500) meets these requirements. Figure 1 shows several vacuum arc remelt (VAR) furnaces. Despite its higher initial cost than competing stainless and alloy steels such as 15-5PH, 13-8, Type 4340, and 300M, Custom 465 is used increasingly by the aerospace industry and other end-use markets including the medical, oil and natural gas, consumer, and sporting-equipment industries.

The patented alloy (nominal composition: 11-12.5% Cr, 10.8-11.3% Ni, 0.8-1.2% Mo, 1.5-1.8% Ti, bal Fe) is used as a corrosion resistant upgrade to high-strength alloy steels. Unlike standard alloy steels, which can require chrome, nickel, or cadmium plating to provide corrosion resistance, parts made of Custom 465 are not susceptible to cracking or loss of plating that could result in subsequent corrosion attack.

Materials that require coatings for corrosion protection also require periodic inspection to ensure the integrity of the coating. This can add significantly to the life-cycle cost of a component due to both the cost of the inspection and the downtime of the equipment being serviced. In addition, environmental issues related to the electroplating process and the disposal of the process waste solutions could pose an even larger problem. The U.S. Environmental Protection Agency is increasing its regulatory scrutiny of such effluents. Also, the European Union implemented the REACH Regulation in 2007, a phased initiative to ban certain hazardous chemicals including cadmium from select products. Even if cadmium is not entirely banned from all products, future restrictions and regulations could make the cost of disposing of used plating baths prohibitive.

Properties and microstructural characteristics

The final microstructure of Custom 465 is influenced by the double vacuum melting, subsequent hot working, and final thermal treatment. Strengthening and toughening mechanisms consist of martensitic phase transformation, followed by precipitation of hexagonal W-phase needles and orthorhombic Ni$_3$(Ti, Mo) plates. Maximum strengthening occurs before precipitates become visible in a light optical microscope. Increasing the aging temperature increases toughness, but lowers strength. Austenite reversion occurs during aging, which plays a significant role in the ductility of the alloy.

Solution annealing (Condition A) is carried out by heating to 980°C (1800°F), holding for one hour and cooling rapidly. Solution annealing is followed by refrigerating to -73°C (-100°F), hold-
ing for eight hours, and warming to room temperature. Sub-
zero cooling should be performed within 24 hours of solu-
tion annealing.

For conditions H 900, H950, H1000, H1050, H1100 and
H1150, the alloy is given a single age hardening step con-
sisting of heating to a temperature between 480 and 620°C
(900 and 1150°F), holding for four hours, and air cooling
or liquid quenching (preferred for section sizes greater
than 3 in., or 76 mm). The aging temperature used depends
on the desired combination of strength, ductility, tough
ness, and stress corrosion resistance. Figure 2 shows a typ-
ical microstructure of the alloy.

**Comparison of properties**

The tensile strength of Custom 465 stainless ranges
between 1034 to more than 1724 MPa (150 to 250 ksi)
depending on the aging treatment. Cold working prior
to aging can result in tensile strength values exceeding
1931 MPa (280 ksi). Aging between 510 and 565°C (950
and 1050°F) is used to achieve the desired balance of
strength, toughness, and stress corrosion cracking (SCC)
resistance. Typical applications require an H950 or
H1000 condition.

The H950 condition (510°C) provides a good combi-
nation of high strength, toughness, and notch tensile
strength; tensile strength in excess of 1724 MPa is possi-
ble. This strength is greater than that of any other precip-
ation hardening (PH) stainless steel long product. The
H1000 condition (540°C, or 1000°F) provides increased
toughness at slightly lower strength. This condition pro-
vides a good combination of strength, toughness, ease of
fabrication, and stress corrosion cracking resistance
compared with other high-strength PH stainless alloys
such as Custom 455 stainless (UNS S45500) and Carpen-
ter 13-8 stainless (UNS S13800).

Table 1 and Figure 3 show typical properties of PH
stainless steels in different heat treated conditions. Figure
4 shows the relationship between yield strength and frac-
ture toughness of commonly used PH stainless steels in dif-
ferent heat treated conditions.

**Corrosion resistance**

The general corrosion resistance of Custom 465 stain-
less approaches that of Type 304 stainless. In both the
H950 and H1000 conditions, exposure to 5% neutral salt
spray at 35°C (95°F) per ASTM B117 results in no corro-

**TABLE 1 — TYPICAL PROPERTIES OF CARPENTER PH STAINLESS STEELS**

<table>
<thead>
<tr>
<th></th>
<th>Custom 630 (17-4)</th>
<th>Custom 450</th>
<th>Carpenter 13-8</th>
<th>Custom 455</th>
<th>Custom 465</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>H950</td>
<td>H900</td>
<td>H1000</td>
<td>H950</td>
<td>H1150</td>
</tr>
<tr>
<td>YS, MPa (ksi)</td>
<td>1069 (155)</td>
<td>1296 (188)</td>
<td>1413 (205)</td>
<td>1551 (225)</td>
<td>1648 (239)</td>
</tr>
<tr>
<td>UTS, MPa (ksi)</td>
<td>1172 (170)</td>
<td>1351 (196)</td>
<td>1482 (215)</td>
<td>1620 (235)</td>
<td>1751 (254)</td>
</tr>
<tr>
<td>Elong., %</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>RA, %</td>
<td>50</td>
<td>56</td>
<td>55</td>
<td>50</td>
<td>63</td>
</tr>
<tr>
<td>K_Ic, MPa √m (ksi √in.)</td>
<td>110 (100)</td>
<td>78 (71)</td>
<td>127 (115)</td>
<td>77 (70)</td>
<td>98 (89)</td>
</tr>
<tr>
<td>CVN, J (ft-lb)</td>
<td>34 (25)</td>
<td>54 (40)</td>
<td>54 (40)</td>
<td>19 (14)</td>
<td>27 (20)</td>
</tr>
</tbody>
</table>

**Fig. 2** — Typical microstructure of Custom 465 in the H950 condition.

**Fig. 3** — Relative strength and toughness of PH stainless steels.
Stress corrosion cracking (SCC) resistance is also good. Data obtained using the rising step load (RSL) test method on samples in the H950 condition tested in 3.5% NaCl solution, natural pH, and open circuit potential, show the alloy maintains a $K_{isc}$ value that is 75% of the fracture toughness ($K_{lc}$) value measured in air testing.

Furthermore, stress corrosion resistance improves with increasing aging temperature. Samples in H1000 condition tested using the same RSL test parameters retain 90% of original $K_{lc}$ values under $K_{isc}$ conditions. Custom 465 stainless has comparable SCC resistance to Carpenter 13-8 and Custom 455 stainless at the same aging temperatures, but with significantly higher strength. Also, stress corrosion resistance of Custom 465 stainless is superior to both alloys when over-aged to the same strength level. Figure 5 illustrates the relative strength, general corrosion resistance, and stress corrosion cracking resistance of traditional PH stainless steels.

**First developed for aerospace applications**

Custom 465 was originally designed to help meet the demand from the aerospace industry for materials that could enable aircraft to keep flying 30 years or more with minimal maintenance. As part of the aerospace alloy development process, which tends to have a longer timeline than that for non-aerospace materials, Carpenter partnered with several aerospace companies to determine and refine their requirements for a new material. Airframe producers were seeking to maximize corrosion resistance, fatigue resistance, and mechanical strength in one alloy. After seven years of testing, the alloy received AMS 5936 and ASTM A564 aerospace specifications, was included in MMPDS, and was qualified for use by major aircraft manufacturers.

Currently, Custom 465 is used by major airframe manufacturers worldwide for such structural applications as torque tubes, pneumatic cylinders, braces, struts, fuse pins, and other leading and trailing edge structural elements. The most recent inroads have been made in gimbals, seat tracks, slat tracks, and flap tracks.

It could be used as a corrosion resistant replacement for 300M, AISI 4340, and similar grades of steels that must be plated or otherwise surface coated to provide corrosion resistance. It also can be considered as a higher strength replacement for 15-5, 17-4 and 13-8 stainless steels, which, while having acceptable corrosion resistance, have lower than desired strength and toughness.

**Various other applications**

The aerospace industry has taken advantage of Custom 465 properties to design improved components either by allowing a switch to a stainless from a non-stainless steel without mechanical property degradation, or by improving the strength of an existing stainless steel part. Since its original use in the aerospace industry, the material has been selected for use in a variety of other applications including medical, energy, automotive, sporting equipment, hand-tool, and oil and natural gas industries.

**Medical**

The evolution of new surgical techniques requires higher performance medical instruments that will not break, distort, or otherwise fail during surgery. Materials...
used in the fabrication of today’s minimally invasive instruments must withstand higher operational torque loads and multiple autoclaving cycles.

Custom 465’s combination of high strength and toughness enables designing longer components having smaller cross sections, such as endoscopic instruments used for minimally invasive surgeries. The instruments allow smaller incisions. For parts having smaller than 20 mm (0.75 in.) diameter, cold-worked and aged material can achieve a tensile strength approaching 300 ksi (2070 MPa), and is used for surgical and dental instruments and needle wire. Other uses include scrapers, cutters, and suture needles. Some devices include a coating such as titanium nitride or aluminum nitride to provide a sharper cutting edge.

Energy

Premature equipment failures in deep-hole drilling operations can result in the loss of expensive tools and valuable production time. Driveshafts used for downhole drilling tools are typically made of EN30B or 4330V. Newly designed driveshafts and mud motors made of Custom 465 provide ten times the service life of previous alloys, lasting up to 1500 hours before replacement is required. This dramatically reduces total replacement costs and costs associated with lost drill rig production time.

In H1000-H1050 condition, Custom 465 provides nearly twice the ultimate tensile strength of the alloy steels replaced, along with excellent notch tensile strength and fracture toughness. It also is more resistant to general corrosion and stress corrosion cracking. Applications include pumps, valves, and related parts.

Automotive

Automotive applications for Custom 465 include suspension coil springs, engine valve springs, torsion bars, and instrumented wheel sensors to prevent corrosion related failures, improve vehicle performance, save weight, and make the components stronger. It could also be considered to replace 17-4 and other PH stainless steels in certain high-end automotive parts, especially high-performance and racing applications.

Hand tools

High-performance hand tools made of Custom 465 offer a combination of attributes that are useful to the medical, biomedical, biotech, pharmaceutical, food, nuclear, marine, and other industries concerned with clean room sterility and/or exposure to corrosive environments. Examples are conventional screwdrivers, L- and T-pattern hex keys, and ball-end, L-pattern hex keys. In this application, the alloy combines high strength, hardness, and toughness, as well as the torque capability of carbon steel counterparts, but with better resistance to both general corrosion and stress corrosion cracking. The tools can be treated in an autoclave and they are resistant to surface oxidation in a steam environment.

Sporting goods and equipment

Custom 465 is used in a wide variety of sporting goods and equipment including golf club faceplates. Its higher strength compared with other PH stainless steels used in the application allows using a thinner face plate and redistributing the saved weight for optimum balance.

The alloy also is used for the wire face shields on such protective equipment as lacrosse helmets, and for big-bore firearms cylinders such as the Ruger Super Redhawk .454 Casull revolver.

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