ow pressure vacuum carburizing has expanded to encompass the latest demands of the aerospace, automotive and industrial markets, particularly in the areas of new material development. Carburizing techniques have been developed for such advanced materials as:

- Aubert & Duval X13 VDW and XD15NW
- Carpenter Technology Corporation Pyrowear 53 and 675
- Bohler Uddeholm N360 Iso Extra, N695, R250, and R350
- Timken CSS-42L, Lescalloy BG42VIM-VAR, CSB-50NIL and CBS-600
- Questek Innovations Ferrium C61, CS62, C69, M60S, and S53

In order to achieve exacting performance requirements, these materials often require custom designed cycles to obtain deep case depths in the range of 0.60 in. - 0.250 in. (1.50 – 6.35 mm). Reduced processing times can be achieved by using high temperature carburizing. Quenching in oil and gas, including gas mixtures, is being used with success.

Establishing and controlling critical process parameters are essential, and extensive development work has been done at Midwest Thermal-Vac (MTV) to establish achievable case depths and required temperature uniformity, to create surface carbon control techniques for the avoidance of carbide networks and necklace formation, and to understand thermal characteristics during both heating and cooling when working with parts sensitive to distortion.

**Why Vacuum Carburizing Is in Demand**

Only low pressure vacuum carburizing allows the end user to “dial in” settings for case depth, carbon profiles, surface/core hardness, and case/core microstructure, and predict distortion results to achieve required properties at the lowest unit cost. Conventional materials such as 8620, 8822, 9310, and parts that are traditionally atmosphere carburized benefit from these techniques. Documented savings in post-machining operations and material stock allowances make the use of vacuum carburizing practical.

An extensive material and process database has been developed by MTV from over 13,000 runs, or an average of 10 carburizing cycles a day using an ECM vacuum carburizing system. Over 1,000 different recipes have been cus-
One of the most demanding product applications is gears. Gears under load are subject to gradient stresses both along the pitch line and at the root fillet (Fig. 1). Properly selected materials and heat treatments will produce strength gradients that are adequate to compensate for these stress gradients with an acceptable margin of safety.

In all gears the choice of material must be made only after careful consideration of the performance demanded by the application. A balance must be struck between overall cost and service life. Key design considerations include an analysis of the type of applied load (whether gradual or instantaneous) and the desired mechanical properties (such as bending fatigue strength or wear resistance), which will define core strength and heat treating requirements. Manufacturing economics plays an important role as well.

Different service demands are required of each region of the gear tooth profile. For example, in the root area good surface hardness and high residual compressive stress are desired to improve endurance, or bending fatigue life. At the pitch diameter, a combination of high hardness and adequate subsurface strength is necessary to handle contract stress and wear and to prevent spalling. However, only so much can be achieved using conventional materials (see Table 1).

### Advanced Materials

A new generation of materials (Table 2) is emerging to meet today’s service and performance needs. They are designed specifically for high temperature applications, retaining their hardness and mechanical properties well into a service range of 600°F - 950°F (315°C - 510°C) and higher. Many of these materials are similar in chemistry to that of stainless and tool steels to take advantage of better corrosion and wear resistance with better core microstructures and surface hardness as good as 440C.

These new materials demand better control of hardness and carbon distribution, optimized microstructures, and control of grain size, retained austenite, and carbide size.

Extensive work with aerospace and automotive partners to control material and microstructure variation in vacuum carburizing has resulted in avoidance of many common problems. For example, the inherent high chromium content (1 – 17 percent) in these materials makes controlling carbide formation and avoiding carbide networks or necklaces (Fig. 3) a critical issue.

Vacuum carburizing (Fig. 4a) means we don’t have to settle for an inferior atmosphere carburized microstructure. Also, no preoxidation or pre-treatment steps are necessary as in atmosphere carburizing due to proprietary surface activation methods.

### Process Parameter Control

Today, MTV runs vacuum carburizing loads using temperatures between 1450°F - 2200°F (785°C - 1205°C). Temperature uniformity, especially in the low temperature ranges, is critical. A maximum spread of 10°F is required to maintain tight case depth control throughout the load. This is equally important for vacuum carbonitriding cycles, which can go as low as 1425°F (775°C).

Effective case depth ranges for vacuum carburized parts routinely vary from 0.010 in. - 0.250 in. (0.25mm - 6.35mm). A maximum case variation
within a load can be held to within 0.005 in. (0.125 mm) and is routinely done so for aerospace and most automotive applications. In one vacuum carbonitriding application the specification called for an extremely shallow case, 0.0005 in. - 0.0025 in., the final part variation achieved was 0.0018 in. - 0.0022 in.

Surface carbon is controlled in the range of 0.60 - 0.80 percent for most conventional materials, and between 0.45 - 0.75 percent for many of the advanced materials. Controlling retained austenite levels is also important.

Cycle time reduction can be significant using vacuum carburizing techniques in combination with proper material selection and pretreatment methods. About 60 hours is required to develop a 0.045 in. (1.15 mm) effective case depth with certain stainless grades. Significantly less time is required as the alloy system is properly enhanced and the resultant microstructures (Fig. 4) meet application requirements.

The relationship between carburizing pressure and gas flow (carrier and hydrocarbon) as a function of load surface area has been worked out to avoid carbide necklaces and to optimize carbide formation. Pressure ranges must be allowed to vary between 3.75 - 15 torr (5 - 20 mbar) and gas flow, a function of the load surface area, typically is controlled between 0.05 - 0.20 cfh (1500 - 6000 ml/hr). Carbon flux is a function of the type of hydrocarbon gas used.

No preoxidation or pre-treatment steps are necessary, as they are in atmosphere carburizing due to proprietary surface activation methods. It has been found that if a temperature variation exists within a load during a preoxidation step, the resultant variation in layer thickness been found to cause results in non-uniformity of case depth.

Finally, oil quenching, and certain combinations of gas type, gas pressure, fan speed, and flow pattern have been found to produce an optimum microstructure of finely dispersed carbides in a matrix of tempered martensite (surface to core). Cross sectional area is an important variable, as is loading configuration.

Table 2 — Advanced Material Grades Routinely Processed at Midwest Thermal-Vac

<table>
<thead>
<tr>
<th>Material</th>
<th>%C</th>
<th>%Mn</th>
<th>%Cr</th>
<th>%Ni</th>
<th>%Mo</th>
<th>%Si</th>
<th>%V</th>
<th>%Co</th>
<th>%Cb</th>
<th>%Al</th>
<th>%Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>XD15NW[a]</td>
<td>0.37</td>
<td>—</td>
<td>15.5</td>
<td>0.20</td>
<td>1.80</td>
<td>—</td>
<td>0.30</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>X13VDW[a]</td>
<td>0.12</td>
<td>—</td>
<td>11.5</td>
<td>2.50</td>
<td>1.60</td>
<td>—</td>
<td>0.03</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>N360 Iso Extra[b]</td>
<td>0.33</td>
<td>0.50</td>
<td>15.0</td>
<td>0.40</td>
<td>1.00</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>N695[b]</td>
<td>1.05</td>
<td>0.20</td>
<td>17.0</td>
<td>—</td>
<td>0.50</td>
<td>0.50</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>R250[b]</td>
<td>0.83</td>
<td>0.70</td>
<td>4.00</td>
<td>—</td>
<td>4.30</td>
<td>0.20</td>
<td>1.10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>R350[b]</td>
<td>0.14</td>
<td>0.30</td>
<td>4.25</td>
<td>3.50</td>
<td>4.30</td>
<td>0.18</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CBS-600[c]</td>
<td>0.19</td>
<td>0.60</td>
<td>1.45</td>
<td>—</td>
<td>1.00</td>
<td>1.10</td>
<td>0.06</td>
<td>—</td>
<td>—</td>
<td>0.06</td>
<td>—</td>
</tr>
<tr>
<td>Pyrowear 53[c]</td>
<td>0.10</td>
<td>0.35</td>
<td>1.00</td>
<td>2.00</td>
<td>3.25</td>
<td>1.00</td>
<td>0.10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.0</td>
</tr>
<tr>
<td>Pyrowear 675[c]</td>
<td>0.07</td>
<td>0.65</td>
<td>13.0</td>
<td>2.60</td>
<td>1.80</td>
<td>0.40</td>
<td>0.60</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Lescalloy BG42VIM-VAR[d]</td>
<td>1.15</td>
<td>0.50</td>
<td>14.5</td>
<td>—</td>
<td>4.00</td>
<td>0.30</td>
<td>1.20</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CSB-50NIL[d]</td>
<td>0.13</td>
<td>0.25</td>
<td>4.20</td>
<td>3.40</td>
<td>4.25</td>
<td>0.20</td>
<td>1.20</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CSS-42L[d]</td>
<td>0.12</td>
<td>—</td>
<td>14.0</td>
<td>2.00</td>
<td>4.75</td>
<td>—</td>
<td>0.60</td>
<td>12.5</td>
<td>0.02</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ferrium C61[e]</td>
<td>0.15</td>
<td>0.15</td>
<td>3.50</td>
<td>9.50</td>
<td>1.10</td>
<td>—</td>
<td>0.09</td>
<td>18.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Notes: [a] Aubert & Duval Alloys; [b] Bohler Uddeholm Alloys; [c] Carpenter Technology Corporation Alloys; [d] The Timken Company Alloys; [e] Questek Innovations Alloys (Proprietary Compositions)

Fig. 3 — Left, Optimized vacuum carburized Pyrowear 675 microstructure. (Mid-Case, 0.090 in. ECD). Right, Non-Optimized atmosphere carburized Pyrowear 675 microstructure (Mid-Case, 0.065 in. ECD).

Fig. 5 — Left, Ferrium 69 Gear microstructure (0.040 in. ECD @ 53 HRC). Right, Ferrium 69 Camshaft microstructure (0.100 in. ECD @ 55 HRC).
Application Examples

Whether the need is to deliver greater horsepower in smaller transmission packages, survive harsh environments, stand up to the rigors of modern warfare or any one of a number of performance demands, customers are looking to the new generation of advanced materials for the solution. Some typical applications include:

Aerospace Sector — The aerospace industry includes rotorcraft, aircraft, rocketry, space vehicles and shuttles, landers and probes. All are looking to the next generation of materials in the design of such items as propulsion systems, landing systems, control and actuator systems, stabilizers, exhaust nozzles, wing sweep actuators, and the like. Many aerospace clients are working with us and their steel suppliers to optimize their designs, manufacturing methods, and heat treatment processes. One such application is in the commercial airline industry (Fig. 5A) where advanced materials are used in actuator systems (Fig 5B).

Automotive Sector — Both passenger car/truck manufacturers and racing teams rely heavily on vacuum carburized components for their engine fuel system, powertrain/transmission, braking, and steering components. Most of the major automotive manufacturers are working to improve performance by vacuum heat treatment. One such application is transmission components, such as those used by the racing industry. Phenomenal race results (Table 3) have been achieved using vacuum carburized components due to increased rear wheel horsepower with equivalent or reduced rotating mass.

Industrial Sector — Industrial applications include heavy duty military components such as transmission gears (Fig. 7), hydraulic cams, valves, seats and bushings, as well as tools, tool holders, punches, linear motion machinery, and many others. These components are typically made from more conventional materials.

Unique Application — Vacuum carburizing has found its way into

Table 3 — 2004 Nextel/Nascar, Busch Series Racing Results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nextel Cup (36 races)</td>
<td>22</td>
<td>11</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>Busch Series (36 races)</td>
<td>2</td>
<td>17</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>Craftsman Truck Series (24 races)</td>
<td>7</td>
<td>6</td>
<td>81</td>
<td></td>
</tr>
</tbody>
</table>
other challenging applications such as in medical devices, where carburizing is performed on implant screws (Fig. 8). The addition of carbon produces a high strength, high hardness surface with excellent wear and abrasion resistance. Residual compressive stresses at the roots of the threads are important to help achieve the best fatigue properties.

The Future

Aerospace and automotive specifications need to be reviewed in light of rapid developments underway with these new materials. Serious consideration must be given to the use of elevated temperature above 1900°F (1040°C) carburizing and direct quench to minimize cycle times and reduce carbon absorption without adversely affecting microstructure (Fig. 9, 10). Preoxidation treatments have been found to be unnecessary, and rules for the use of high gas pressure quenching need to be better established. Once this is accomplished, vacuum carburizing technology offers almost limitless possibilities.

Fig. 8 — Vacuum carburizing of N360 medical fasteners for implantable devices. (0.10 oz./piece carburized to 0.0015 in.)

Fig. 9 — 1600°F (900°C) Atmosphere carburized Aubert & Duval X13VDM

Fig. 10 — 1950°F (1065°C) Vacuum carburized Pyrowear 675

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