The advantages of ion nitriding in many low-alloy steels and titanium alloy gears used in high-performance applications include resisting wear and fatigue.

Thermochemical surface engineering is effective in improving the performance of various gears made of ferrous alloys [1-5]. The cost of machining typical gears during the manufacturing process often exceeds 55 percent of total cost, especially when there is significant grinding after carburizing the gears [5]. Therefore, improvements in the manufacturing of gears that can lead to a reduction in machining are valuable.

Nitriding produces high hardness and compressive stresses in many low-alloy steels used for gears. It is a nearly distortion-free process, which allows for the treating of finished components, thus minimizing costs. The complex nature of the stresses at the contact area of rotating gears leads to contact fatigue and sliding friction. Nitriding is superior to other surface engineering techniques in resisting wear at gear flanks. When a high-strength alloy steel suitable for nitriding is used, a nitrided surface layer withstands high contact Herztian stress (contact stress) at gear flanks better than a deeper carburized layer in many instances [4]. Also, the maximum operating temperature for nitrided gears is higher than for carburized gears, typically 455°C versus 150°C [6]. Rolling contact fatigue (RCF) and tooth root-bending
fatigue are primary gear failure modes [7, 8]. With the proper microstructure, certain alloy steels enable achieving a sufficiently thick, hard nitrided layer that resists high contact stresses (2068-2413 MPa, or 300-350 ksi), such as those generated in jet-engine main-shaft applications [9, 10].

In addition, most of the distress in aero-engine bearings is brought on by surface conditions, not by the so-called classical subsurface fatigue initiation [11]. A similar situation may also be considered in gear applications. Contact fatigue and negative effects of intergranular nitrides (IGN) present in the nitrided microstructure can lead to premature failure. This may also increase the spall propagation rate over that normally experienced in materials that are not nitrided [10, 11]. For high-performance, high-speed gears used in power-generation applications, nitriding enhances long-term resistance to pitting and tooth flexure [12]. These applications require a deep (>1 mm) nitrided layer that’s free of IGN.

Ion nitriding is also applied to high-performance titanium alloy gears used in the aerospace industry.

**NITRIDING PROCESS**

The process of ion nitriding is carried out in a glow discharge with the workpiece as the cathode and the vessel wall is the anode [2]. The atmosphere is typically a mixture of nitrogen and hydrogen, occasionally enriched with argon or methane. Treated parts can be observed through a porthole (as shown in Figure 1).

High-quality nitriding requires that the nitriding temperature is at least 28°C (50°F). The process involves the introduction of nitrogen into the workpiece, leading to a layer of nitrides that enhance the wear and corrosion resistance of the material.

**Table 1: Recommended case depths for small modulus (high diametral pitch) alloy steel gears**

<table>
<thead>
<tr>
<th>Diametral pitch</th>
<th>Case depth, mm</th>
<th>Case depth, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.013-0.025</td>
<td>0.0005-0.001</td>
</tr>
<tr>
<td>70</td>
<td>0.025-0.051</td>
<td>0.001-0.002</td>
</tr>
<tr>
<td>50</td>
<td>0.051-0.102</td>
<td>0.002-0.004</td>
</tr>
<tr>
<td>30</td>
<td>0.051-0.102</td>
<td>0.002-0.004</td>
</tr>
<tr>
<td>25</td>
<td>0.051-0.010</td>
<td>0.002-0.004</td>
</tr>
</tbody>
</table>

Figure 3a: Cross section of the gear teeth shown in Figure 2, etched using Marble reagent

Figure 3b: Cross section of the gear teeth shown in Figure 2 at 500x, etched using nital

Figure 3c: Cross section of the gear teeth shown in Figure 2 at 50x, etched using nital

Figure 4: Microindentation hardness profile in the nitrided layer of the gear shown in Figure 2
Nitriding gears do not require a case as deep as that required in carburized gears. Table 1 lists recommended case depth for different high diametral pitch (DP) [13].

LOW-MODULE (FINE-PITCH) GEARS
Several unique characteristics of ion/plasma nitriding enable applying it to a variety of ferrous and nonferrous alloys [2]. Nitriding high-alloy steels, including stainless steels, are carried out at a temperature between 350°C and 600°C. Stainless steels are used in aerospace applications requiring maximum mechanical strength and durability. Many components are ion nitrided in a finished condition. Because nitriding is carried out at a temperature far lower than the phase transformation temperature, properly nitrided gears exhibit no distortion. An advantage of ion nitriding in these applications is the ease of protecting selective areas from hardening using mechanical masking [2].

Uniformity of the nitrided layer around the fine-pitch tooth profile is excellent when the process is carried out using proper control (as shown in Figures 2, 3, and 4). The hardness of the nitrided layer formed in precipitation hardenable stainless steels, such as 15-5 PH, is high across the entire layer (see Figure 4). While control of the nitrided layer structure in high-alloy steels is difficult, it is achieved by proper adjustment of gas composition, pressure, plasma density, and frequency and pulsation (duty cycle).

LARGE-MODULE GEARS
Large-module gears are often made of low-

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alloy steels containing chromium and molybdenum with medium carbon content, which are excellent for nitriding. For example, consider a 4340 alloy steel gear used in the power industry (see Figure 5). The nitrided layer consists of roughly a 10-µm-thick compound layer composed of iron nitrides (Fe₄N) and approximately a 0.4-mm-thick diffusion layer (see Figures 6 and 7). The hardness gradient has a smooth transition compared with the layer in 15-5 PH steel. Mechanical masking was applied to the gear to limit nitriding to the teeth section only.

Deep nitriding is often required to enhance admissible fatigue strength values of heavily loaded gears. Figure 8 shows the cross section of such a gear after plasma nitriding. A very long nitriding cycle (>200 h) is required to achieve a 1-mm-thick case depth [14]. Despite long nitriding process times, avoiding excessive compound (white) layer thicknesses in the nitride layer structure is easily achieved because of the nature of the process — low partial pressure of nitrogen and sputtering [15]. A side effect of the sputtering in long nitriding cycles is the deposit of nitrides. This is from the dusty plasma visible on top of the gear tip, as you can see in Figure 8 [2]. The deposit is easily removed by light mechanical cleaning.

**GAS NITRIDING**

Gas nitriding of gears enables forming layers with the same depth and structure as in plasma nitriding. However, this requires good process control to avoid formation of an excessively thick compound layer containing porosity in long cycles. Also, selective treatment in gas nitriding is difficult because it requires copper plating for local protection from nitriding.

**ION NITRIDING TITANIUM GEARS**

Titanium alloys have specific properties, such as a high strength-to-weight ratio, as well as low magnetic susceptibility and low thermal and electrical conductivities [16]. Ion-nitrided titanium alloys also have excellent tribological and corrosion-resistant properties [17]. Therefore, nitriding is used for parts used in the most demanding applications. The process is carried out at a temperature between 680°C – 900°C, typically in pure nitrogen or a mixture of nitrogen with argon. Gear shafts in the as-nitrided condition used in aerospace applications are shown in Figure 9. It is not possible to do selective hardening of titanium products as is done with ferrous alloys due to the high chemical reactivity of titanium toward nitrogen [2]. Nitriding a titanium part imparts a gold or yellow color attributed to the presence of a thin (meaning few microns) titanium nitride (TiN) film, which is very hard. The layer underneath, composed of Ti₂N and Ti-Al-V nitrides, is about 10 µm thick (see Figure 10). The diffusion layer below the nitride layer cannot be etched easily due to its high corrosion resistance, but its thickness is determined from a microindentation hardness profile (see Figure 11). Hardness in the diffusion layer diminishes relatively quickly even though total nitrogen penetration reaches 30-40 µm in a typical nitriding cycle.

**CONCLUSIONS**

Ion nitriding is applied to various ferrous and titanium alloy gears. The main benefit to steel gears is the formation of a nitrided layer with a well-controlled structure at relatively low temperatures. This
enables the process as a final operation, thus reducing manufacturing costs. Another benefit is the ability to apply mechanical masking for selective hardening of the product. Ion-nitrided titanium alloys also have excellent tribological and corrosion-resistant properties.

REFERENCES


ABOUT THE AUTHORS: Dr. Edward Rolinski received his M.S. in manufacturing technology in 1970 at the Warsaw University of Technology in Warsaw, Poland. Upon receiving his doctorate for his research on phenomenon in the ion nitriding process in 1978, Rolinski continued his academic career, teaching physical metallurgy and surface engineering, and received his ScD (habilitation) for studying plasma nitriding of titanium in 1989. He has also worked on the plasma nitriding process at MIT with Professor Nick J. Grant and with Professor Ken H. Jack at the University of Newcastle upon Tyne. In 1989, he moved to the United States and eventually joined the staff at Advanced Heat Treat Corp. where he is the vice president of technology, solving technical problems and developing technologies. He has published numerous articles and co-authored two books. Tekin Damirgi received his B.S. in engineering technology in production and metallurgy. From 1980 to 1995, he was a research engineer at Specialized Institute for Engineering Industries at Bagdad, Iraq. From 1997 to 2001, Damirgi worked at Mentor Automotive Inc./Heritage of Rockwell Technology, Fairfield, Iowa, as a material conformance engineer. Since 2001 to present, he has been working at Advanced Heat Treat Corp. in Waterloo, Iowa, as a chief metallurgist, developing new process instructions and recipes for nitriding ferrous alloys and titanium alloys for different applications and developing new nitriding specifications through custom design engineering. Mikel S. Woods has been the senior VP of sales and marketing at Advanced Heat Treat Corp (AHT) for the last three years, after assuming the director of sales and marketing position for seven years. Prior to AHT, Woods was program manager at HUSCO International (Waukesha, Wisconsin) and senior/staff auditor at PricewaterhouseCoopers in Milwaukee. He has an Executive M.B.A. from the University of Wisconsin-Milwaukee and a B.B.A. in accounting from the University of Iowa. At AHT, Woods has co-authored publications on ion nitriding, gas nitriding, and ferritic nitrocarburizing, and he has played an active role in obtaining several grants associated with plasma nitriding.