An Exploration of Cost-Effective Solutions for Gear Production
Kenneth Craymer, John Dalton, and Michael Lyrenmann
Case Western Reserve University
Department of Materials Science and Engineering

Introduction

Gears are vital behind-the-scenes components to many common machines in everyday life, requiring advanced materials that must meet specific requirements for mechanical properties. Current steel gear production relies heavily on alloying elements to increase the mechanical properties of steel. Typical metals alloyed into the steel include chromium, nickel, manganese, and molybdenum. Alloys are added to enhance specific material properties including strength, fracture toughness, surface durability and hardness, and wear resistance. Gears often operate under extreme loading and stress state environments, so it is critical to achieve very high mechanical properties in the above areas. Unfortunately, the material costs for many traditional alloying elements are high and have the tendency to fluctuate dramatically with the market. There are more cost effective ways to increase these mechanical properties in gear production, though they typically are limited in how much improvement can be made and cannot often improve multiple properties. Alternatives to expensive alloy steels are being sought that can provide similar mechanical properties at a much lower cost.

Current Techniques/Applications

There are several steel alloys currently in major use for gear applications. AISI alloys 4320, 5210, and 8620 are common steels with alloying agents of nickel, manganese, molybdenum and chromium. As a result of the favorable enhancements that these alloying agents provide to the steel, as discussed below, these types of steel alloys are traditionally chosen for gear applications. Table 1 summarizes the standard compositions of these three popular steels, and a few relevant mechanical properties.
Table 1

<table>
<thead>
<tr>
<th>Composition (weight %)</th>
<th>5210 low</th>
<th>5210 high</th>
<th>4320 low</th>
<th>4320 high</th>
<th>8620 low</th>
<th>8620 high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.98</td>
<td>1.1</td>
<td>0.17</td>
<td>0.22</td>
<td>0.18</td>
<td>0.23</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.15</td>
<td>0.3</td>
<td>0.15</td>
<td>0.3</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.25</td>
<td>0.45</td>
<td>0.45</td>
<td>0.65</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Chromium</td>
<td>1.3</td>
<td>1.6</td>
<td>0.4</td>
<td>0.6</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Molybdenum</td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.3</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.3</td>
<td>1.65</td>
<td>2</td>
<td>4</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Copper</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.03</td>
<td></td>
<td>0.04</td>
<td></td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.03</td>
<td></td>
<td>0.04</td>
<td></td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>5210</th>
<th>4320</th>
<th>8620</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (brinell)</td>
<td>187</td>
<td>163</td>
<td>149</td>
</tr>
<tr>
<td>Modulus (Gpa)</td>
<td>190</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>7.7</td>
<td>8.03</td>
<td>8.03</td>
</tr>
<tr>
<td>Tensile (Mpa)</td>
<td>1866</td>
<td>579.2</td>
<td>536.4</td>
</tr>
<tr>
<td>Yield (Mpa)</td>
<td>1410</td>
<td>609.5</td>
<td>385.4</td>
</tr>
</tbody>
</table>

Importance of alloying elements

Steel in its basic form is a mixture of iron and carbon. Increasing the carbon content increases the strength and hardness but reduces the ductility. Producing a gear that is strong, hard, and resistant to brittle failure is important, so special alloying metals are added to the steel. The addition of the elements allows the carbon levels to be kept moderate, preventing brittle failure. The three most prevalent costly metals used to alloy with gear steel are nickel, molybdenum, and chromium. The properties given by each of these metals are highly sought after, which explains why they are so popular despite their high, often fluctuating, cost.

Nickel is alloyed into the steel to increase its strength and toughness, specifically in the ferrite phase. Because it does not form carbides, nickel remains in solution throughout the ferrite phase. This addition of nickel increases both the hardenability and the impact strength of the steel.

The properties imparted by chromium for the purpose of gear steels are increased hardness and increased high temperature strength. Chromium also enhances the corrosion and
oxidation resistance of the steel by forming a protective layer of chromium-oxide on the surface, but this is not as critical when the gear system is properly lubricated with oil. Chromium can also enhance the chloride resistance and other acidic resistance of the steel alloy in a combination of other alloying elements. Unlike nickel, chromium is a strong carbide former, and because of this the mechanical properties can be maximized when using a combination of the two in a steel alloy.

Molybdenum is added to steel to increase the hardenability. It has the ability to provide a secondary hardening during the tempering of quenched steel, and also enhances the creep strength at high temperatures.

These three metals alloyed together into the steel produce a material that is strong and tough due to the nickel, hard and corrosion resistant because of the chromium, and thoroughly hardened by the molybdenum. They have good performance even at elevated temperature, and have some resistance to oxidation and corrosion. Obviously, these metals are critical to the composition of modern gear steels which is why they are used despite high prices.

**Treatment Methods**

Surface toughness and hardness of gears is a vital mechanical property that can contribute to part longevity. The toughness of the part can directly correlate to erosion and wear rates from tribological effects. There are several relatively simple and inexpensive treatment methods that can effectively harden gears during part processing. These fall into two general categories of case hardening and through hardening. Some case hardening methods include carburization, nitriding, and flame hardening.

The case hardening process is used mainly when the part needs a high surface durability, but the core of the part may remain softer and more ductile to absorb energy. During treatment,
a thin surface layer of the part is additionally hardened through exposure to specific atmospheres or processes. Carburization is the most prevalent case hardening process, typically used for only low carbon content and low alloy content steels. The parts are loaded into a furnace and heat treated in a sealed atmosphere of carbon monoxide gas. Other carbon-rich material can also be added to the furnace, to add to the amount of carbon that diffuses into the desired part. Nitriding steel parts is usually done on parts that have already undergone a form of heat treatment. These parts are treated again under an ammonia gas atmosphere. Nitrided steel parts retain their hardness in higher temperature applications as well. A third case hardening process in little use today is cyaniding. This process was once favored because it could be run much faster than the above two, and incorporated compounds of both. However, due to the toxicity of the reagents it has greatly declined in use.

Through hardening increases the strength of the whole part through a series of annealing, normalizing, tempering, and quenching steps. Through hardening is performed on steels with moderate amounts of carbon and other alloying additions. The overall hardness and strength of the part is not as high as case hardened components, but properties such as toughness and ductility are greatly improved. The highest achievable hardness comes from parts that are quenched and then tempered at elevated temperatures.

**Future Technologies**

Several other production processes exist that may hold promise in increasing alloyed steel’s mechanical properties and lead to more desirable or cost-effective solutions for the gear industry. Simple changes in processing may increase mechanical properties such as toughness or fatigue resistance, while entirely new alloying agents have also been heavily researched.
Shot Peening

One simple yet effective treatment for increasing the fatigue resistance and strength of steel parts is by using shot peening. In this treatment, the part is bombarded by many small pellets (shot) of a material, which causes small amounts of surface plastic deformation (See Figure 1). This impact causes a myriad of very small dimples on the surface of the part, and builds up residual compressive stresses. These compressive stresses can be as great as half the magnitude of the yield strength of the overall material. These compressive stresses help the part to better resist fatigue cracking and toughen the overall material.

![Figure 1: Shot Peening Process and resulting internal stresses. (The Metal Improvement Company)](image)

Laser Peening

Laser Peening, or Laser Shock Peening, imparts the same residual compressive stresses that regular shot peening does to the part. However, the process is much different, and the actual depth of the compressive stresses added to the piece can penetrate up to four times deeper than conventional shot peening. The process, as diagrammed in Figure 2 below involves first coating the work piece with a layer of paint or tape, and then submerging the part in a thin layer of water. A laser is directed at the material, vaporizing the water and ablative layer, producing a shock wave that travels into the work piece. This shock wave induces the residual compressive stresses in the material that strengthen it and increase its fatigue resistance.
Intensive Quenching

Another method of processing the gear to provide a hard surface loaded in compression is to intensively quench the material. The difference in cooling rates provide by this method develop internal stresses that preload the steel in such a manner that it is less prone to failure during operation. Intensive quenching involves rapidly and uniformly water quenching steel parts at faster rates than conventional oil or water quenching. Careful attention is made to eliminate cracking often associated with rapid quenching. Liquid water is rapidly forced over the surface such that a steam layer is not allowed to form, resulting in very rapid cooling rates. The rapid cooling is then interrupted at a calculated time by a computer and allowed to air cool. Intensive quenching creates a strong and uniform martensitic shell over the surface of the part. By utilizing intensive quenching, similar mechanical properties of the steel can be obtained as those with chromium, nickel, and molybdenum alloying agents.

Boriding Steel

New steel technologies have been looking at a special high strength alloy that is formed by adding a very small amount of boron to the steel. Boron steel is a cost effective way to get
similar properties to the expensive alloys previously used, but at a fraction of the cost. Boron can be introduced into the steel in much the same way as carburization. The boron atom also diffuses interstitially into the steel matrix, with the additional advantage of decreasing the overall iron lattice size, thereby making the steel slightly denser and more crystalline. This steel has a significant increase in both strength and toughness over comparable carbon steel, especially with borided surface treatments. Figure 3 is a micrograph of the borided surfaces.

Figure 3: Magnified image of a cross section of steel with a borided surface treatment. The image shown was selectively borided using a Nd:YAG laser process. Adopted from Tayal.

Boron alloying of low carbon steel is a promising avenue for reducing cost in forged gear alloys. While the addition of boron to steel has only recently been investigated, current research suggests that it has superior mechanical properties and lower production costs. Boron alloy steels also have excellent wear resistance. Researchers of the recent article "A Study of Boron-Bearing Wear-Resistant Alloy Steel Liner" found that the servicing cycle of a boron steel ball mill liner was 1.6 times longer than a high manganese liner. A group of Chinese researchers also found that a high boron steel hammer had a 55.8% and 41.9% longer service life over a
chromium alloy and nickel alloy steels respectively. The authors of a recently published article "Abrasive wear behavior of boronized AISI 8620 steel" demonstrating the wear behavior of a boronized AISI 8620 steel was decreased due to the increased hardness of the boride layer. Methods of boronizing steels are currently being heavily researched, but it may prove to be an effective way for decreasing the cost of producing gear quality steels. Mann revealed in his article "Boronizing of cast martensitic chromium nickel stainless steel and its abrasion and cavitation-erosion behavior" that boronizing a cast chromium–nickel steel (13Cr–4Ni) decreased the elongation and strain energy of the steel thus resulting in poor cavitation-erosion resistance. He did however also demonstrate that the wear resistance of the boronized steel was much higher than the 13Cr-4Ni steel alone. Consequently more research might need to be performed in improving the corrosion resistance of boronized steels if they are to be used for gear applications. Titanium boride surface hardening is similar to boriding steel and might also be a cost effective method of increasing surface hardness of stainless steels without much need for expensive alloying elements such as chromium and nickel. These articles have also largely discussed that the amount of boron added to stainless steels must be closely monitored as residual boron decreased hardenability due to Fe_{23}(CB)_6 which can be a preferential ferrite nucleation spot.

Conclusion

It has been demonstrated that there are cost effective methods of improving the quality of steels that meet the demands required for gear components. While it will take further research into alternative methods before industry can take advantage of them, there are certainly processes that have great potential to reduce gear manufacturing cost in the near future. Boronizing steel has been shown to greatly increase the wear resistance and strength of steels
without much need for expensive alloy elements such as chromium and nickel, and seems likely to be a key area of interest for the future of the gear industry.
Bibliography


