FINDING THE IDEAL MATERIALS FOR GEARS

When designing and manufacturing gears, the materials used will depend on what type of gear is being made and how and where it will be used.

By BRIAN DENGEL

When designing an individual gear or a gear train, the choice of material will either be the primary factor on which the gear geometry is based or the gear performance will dictate the proper material selection. There are various raw materials that are commonly used in gear construction, and each one has a sweet spot where its mechanical properties stand out as the superior choice. The main categories of materials are copper alloys, iron alloys, aluminum alloys, and thermoplastics.

COPPER ALLOYS

When designing a gear that is going to be subjected to a corrosive environment or needs to be non-magnetic, a copper alloy is usually the best choice. The three most common copper alloys used in gearing are brass, phosphor bronze, and aluminum bronze. Brass is an alloy of copper and zinc. The amount of zinc varies in the different brass alloys, and its presence changes the ductility of the alloy.

Low zinc content maintains a high level of ductility in the brass alloy, whereas a higher concentration of zinc reduces the alloy's ductility. The copper base of brass alloys contributes to its ease of machining and its antimicrobial benefit. Gears typically produced from brass alloys are spur gears and gear racks that will be used in low-load environments such as instrument drive systems.

Phosphor bronze is another copper alloy that combines copper with tin and phosphorus. The addition of tin to the copper increases the strength of the alloy and improves its corrosion resistance. The addition of phosphorus improves both the wear resistance and the stiffness of the alloy. The increased corrosion and wear resistance make phosphor-bronze alloy an excellent choice for high-friction drive components. Worm wheels are produced using this alloy as it resists the wear generated by the friction when the wheel is in mesh with a worm, and it can resist degradation due to the lubricant.

Aluminum bronze is a third copper alloy that is found in gearing. This alloy combines copper with aluminum, iron, nickel, and manganese. Aluminum-bronze alloys have a higher wear resistance than phosphor-bronze alloys, and they also have superior corrosion resistance. The addition of the iron improves the wear resistance of this alloy. The nickel and the manganese add to its corrosion resistance. Aluminum-bronze alloys can resist corrosion due to oxidation, exposure to salt water, and exposure to organic acids.

When designing a gear that is going to be subjected to a corrosive environment or needs to be non-magnetic, a copper alloy is usually the best choice. (Courtesy: KHK-USA)

The additional wear resistance of these alloys allows for the design of gears that can handle significantly more load than similarly sized gears made from phosphor bronze alloys. Typical gears produced from aluminum bronze alloys include crossed axis helical gears (screw gears) and worm wheels.

IRON ALLOYS

When a gear design requires a superior material strength, iron alloys are the best choice. In its raw form, gray iron can be cast and machined into gears. Typically, cast iron is used in applications where phosphor bronze is a suitable alternative, but the application is not constrained by the material's magnetic fields. Steel is an alloy of iron, carbon, and other trace elements. There are four major designations of steel alloy. These are carbon steel, alloy steel, stainless steel, and tool steel. Carbon-steel alloys are used for almost all types of gearing because they are easy to machine, they have good wear resistance, they can be hardened, they are widely available, and they are relatively inexpensive. Carbon steel alloys can be further classified into mild steel, medium-carbon steel, and high-carbon steel. Mild steel alloys have less than 0.30% carbon content. High carbon steel alloys have a carbon content greater than 0.60%, and the medium-content steels fall in between. These steels

Gears made from aluminum alloys include spur gears, helical gears, straight tooth bevel gears, and gear racks. (Courtesy: KHK-USA)

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Aluminum alloys are a good alternative to iron alloys in applications that have a need for a high strength-to-weight ratio. Aluminum alloys are typically one-third the weight of steel alloys of the same size.

are a good choice for spur gears, helical gears, gear racks, bevel gears, and worms.

Carbon steels can be induction hardened or laser hardened with a maximum hardness of HRc 55. Alloy steels like AISI 4140 contain additional elements such as aluminum, chromium, copper, and/or nickel. These other elements, when alloyed with the iron and carbon, create steels that are stronger, easier to machine, and offer more corrosion resistance than plain carbon steel. These alloys typically are used to make spur gears, helical gears, gear racks, spiral bevel gears, and worms.

In addition to induction and laser hardening, these alloys can be carburized, or case hardened. The maximum hardness for these alloys is HRc 63. The added strength allows for gears of the same size to handle additional load and resist wear for more cycles. Stainless steel alloys have a minimum chromium content of 11% and are an alloy of many trace elements including nickel, manganese, silicon, phosphorus, sulfur, and nitrogen. They are subdivided into ferritic

AISI Designation	Alloy Type	Chemical Composition
10XX	Carbon Alloy steels	Plain carbon steel, Mn 1.00% max
11XX		Resulfurized, carbon steel
12XX		Resulfurized / Rephosphorized carbon steel
15XX		Plain carbon, Mn 1.00-1.65%
13XX	Manganese Alloy steels	Mn 1.75%
23XX	Nickel Alloy steels	Ni 3.50%
25XX		Ni 5.00%
31XX	Nickel-Chromium Alloy steels	Ni 1.25%, Cr 0.65-0.80%
32XX		Ni 1.75%, Cr 1.07%
33XX		Ni 3.50%, Cr 1.50-1.57%
34XX		Ni 3.00%, Cr 0.77%
40XX	Molybdenum Alloy steels	Mo 0.20-0.25%
44XX		Mo 0.40-0.52%
41XX	Chromium-Molybdenum Alloy steels	Cr 0.50-0.95%, Mo 0.12-0.30%
43XX	Nickel-Chromium-Molybdenum Alloy steels	Ni 1.82%, Cr 0.50-0.80%, Mo 0.25%
47XX		Ni 1.05%, Cr 0.45%, Mo 0.20-0.35%
46XX	Nickel-Molybdenum Alloy steels	Ni 0.85-1.82%, Mo 0.20-0.25%
48XX		Ni 3.50%, Mo 0.25%
50XX	Chromium Alloy steels	Cr 0.27-0.65%
51XX		Cr 0.80-1.05%
50XXX		Cr 0.50%, C 1.00% min
51XXX		Cr 1.02%, C 1.00% min
52XXX		Cr 1.45%, C 1.00% min
61XX	Chromium-Vanadium Alloy steels	Cr 0.60-0.95%, V 0.10-0.15%
72XX	Tungsten-Chromium Alloy steels	W 1.75%, Cr 0.75%
81XX	Nickel-Chromium-Molybdenum Alloy steels	Ni .30%, Cr 0.40%, Mo 0.12%
86XX		Ni .55%, Cr 0.50%, Mo 0.20%
87XX		Ni .55%, Cr 0.50%, Mo 0.25%
88XX		Ni .55%, Cr 0.50%, Mo 0.35%
92XX	Silicon-Manganese Alloy steels	Si 1.40-2.00%, Mn 0.65-0.85%, Cr 0-0.65%
93XX	Nickel-Chromium-Molybdenum Alloy steels	Ni 3.25%, Cr 1.20%, Mo 0.12%
94XX		Ni 0.45%, Cr 0.40%, Mo 0.12%
97XX		Ni 0.55%, Cr 0.20%, Mo 0.20%
98XX		Ni 1.00%, Cr 0.80%, Mo 0.25%

Table 1: AISI identifies steel alloys using a four-digit sequence.

stainless steels that are magnetic, austenitic stainless steel that are nonmagnetic, martensitic, and precipitation hardened. The austenitic stainless steels are designated as 300 series stainless steels, whereas the ferritic stainless steels are designated as the 400 series stainless steels. The most common stainless steel is 304 alloy. It contains 18% chromium and 8% nickel.

For gearing, 303 stainless is typically used. In 303 alloy, the chromium content is reduced to 17%, and 1% of the alloy is sulfur. Because of the addition of the sulfur, 303 alloy has improved machinability compared to 304 alloy. When improved corrosion resistance is required, 316 alloy is the better choice. This alloy has 16% chromium, 10% nickel, and 2% molybdenum; 316 and 303 alloy are used for spur gears, helical gears, and bevel gears. Gear racks are typically made from 304 alloy. 440C is the most common ferritic stainless steel, and 17-4PH is the most common precipitation hardened stainless steel.

TOOL STEEL ALLOYS

The fourth group of alloys is tool steels. These are steel alloys with traces of cobalt, molybdenum, tungsten, and/or vanadium. These elements add heat resistance and durability to the steel.

AISI identifies steel alloys using a four-digit sequence (Table 1). The first two digits designate the alloy family, and the last two digits designate the fractional percentage of carbon. For example, a 1020 carbon steel has a 0.20% carbon content, whereas a 1045 carbon steel has a 0.45% carbon content.

ALUMINUM ALLOYS

Aluminum alloys are a good alternative to iron alloys in applications that have a need for a high strength-to-weight ratio. Aluminum alloys are typically one-third the weight of steel alloys of the same size. A surface finish known as passivation protects aluminum alloys from

Aluminum alloys are a good alternative to iron alloys in applications that have a need for a high strength-to-weight ratio. (Courtesy: KHK-USA)

oxidation and corrosion. This is similar to rust on steel alloys; however, it coats the surface, protecting it from further damage. Aluminum alloys are more expensive than carbon steel but less expensive than stainless steel. However, they are easy to machine, thus offsetting the increase in material costs.

Aluminum alloys cannot be used in high-heat environments as they begin to deform at 400°F. The common aluminum alloys used in gearing are 2024, 6061, and 7075. The 2024 aluminum alloy is a cousin to aluminum bronze because it is also an alloy of aluminum and copper. However, in this case, the proportions are inverted. The copper in 2024 gives this alloy high strength but significantly lowers its corrosion resistance. 7075 aluminum combines zinc and magnesium with the aluminum to form a high strength alloy that is resistant to stress loading. 6061 aluminum is an alloy of aluminum, silicon, and magnesium. It is a medium-strength aluminum alloy that has good corrosion resistance and is weldable. All three of these aluminum alloys can be heat-treated to improve their hardness. Gears made from aluminum alloys include spur gears, helical gears, straight tooth bevel gears, and gear racks.

THERMOPLASTICS

Thermoplastics are the best choice for gears where weight is the most important criteria. Gears made from plastics can be machined like metallic gears; however, some thermoplastics are better suited for manufacturing via injection molding. One of the most common injection molded thermoplastic is acetal. This material is also known as polyacetal or polyoxymethylene (POM). Polyoxymethylene is available in two forms: It is either produced as a homopolymer (POM-H), or it is produced as a copolymer (POM-C). Gears can be made from either polymer. These can be spur gears, helical gears, worm wheels, bevel gears, and gear racks.

The advantages of POM are its dimensional stability under large temperature ranges, its low coefficient of friction, and its resistance to creep. It is an excellent material for wear surfaces because it is self-lubricating, but POM is a poor material for applications subject to shock loading due to its brittleness. For these types of applications, nylon is a better choice. Nylon 6/6 is a polyamide that consists of two monomers with six carbon atoms each. Nylon is excellent at absorbing vibration, but when exposed to moisture, it becomes dimensionally unstable. Nylon also experiences changes in dimension when subjected to significant changes in temperature. Like acetal, nylon has a low coefficient of friction. Nylon has a high mechanical strength. Nylon can be produced with molybdenum impregnated into it in order to produce a self-lubricating feature. Nylon can also be produced with fiberglass or carbon fibers embedded into the material in order to increase the strength. Nylon makes an excellent material for all types of gears including worm wheels, gear racks, spur gears, and straight tooth bevel gears.

UNOBTAINIUM

There is one material for gears that has yet to be developed. It is the ideal material for all gear designs. This material is known as unobtainium. This material is extremely lightweight, has a hardness greater than that of a natural diamond, has a coefficient of friction of 0.001, is dimensionally stable in all environments, neither corrodes nor rusts, is easily machinable, and has a raw material cost of 1 cent per pound. Once invented, it will make all other materials obsolete and will greatly improve gear train efficiency.

There is one material for gears that has yet to be developed. It is the ideal material for all gear designs. This material is known as unobtainium, the stuff of "Avatar."

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