Material Properties and Performance Considerations for High-Speed Steel Gear-Cutting Tools

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Users of gear-cutting tools probably do not often consciously consider the raw material from which those hobs, broaches or shavers are made. However, a rudimentary awareness of the various grades and their properties may allow tool users to improve the performance or life of their tools, or to address tool failures. The high-speed steel from which the tool is made certainly is not the only factor affecting tool performance, but as the raw material, the steel may be the first place to start.

High-Speed Steels

High-speed steels are so named because of their ability to machine other materials at high speeds. They are complex, iron-based alloys made of various carbide-forming elements, plus sufficient carbon, so when heat-treated, they exhibit a microstructure of a hard steel matrix containing harder carbide particles. High-speed steels are designed to provide the following attributes:

- High hardness,
- High wear resistance/abrasion resistance,
- High red hardness, and
- Good toughness.

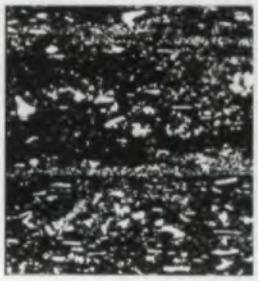
All of those attributes are influenced by the chemical composition of the alloy. In addition, the manufacturing of the steel can influence toughness.

Compositions of High-Speed Steels

The characteristic elements found in most high-speed steels are chromium (Cr), molybdenum (Mo), tungsten (W) and vanadium (V). Carbon is present only to the extent needed to form the desired carbides and to provide the high matrix hardness after heat treatment. Therefore, the carbon content is generally increased in direct proportion to the rest of the carbide-forming elements. Some high-speed steel grades also contain cobalt (Co). The nominal compositions of a number of high-speed steels are shown in Table 1.

Table 1—Nominal compositions of some high-speed steels, approximate weight percent.

Grade	C	Cr	W	Mo	V	Co
T1	0.75	4	18	-	1	-
M1	0.85	4	1.5	8.5	1	-
M7	1.0	4	1.5	8.5	2	-
M42	1.1	4	1.5	9.5	1	8
M2	0.85	4	6	5	2	-
M3	1.2	4	6	5	3	-
M4	1.4	4	6	5	4	-
M35	1.0	4	6	5	2	5
T15	1.6	4	12	1	5	5
Rex 45	1.3	4	6	5	3	8
Rex 54	1.45	4	6	5	4	5
Rex 76	1.5	4	10	5	3	9
Rex 121	3.4	4	10	5	10	10



▪ Hardened steel	HRC 62/66
▪ Cr carbide (D2)	HRC 68/70
▪ Mo & W carbides	HRC 74/76
▪ Vanadium carbides	HRC 82/84

▪ More or harder carbides promote higher wear resistance

Figure 1—Microstructure of high-speed steel, showing typical carbide morphology.

High-speed steels generally contain about 4% chromium. Chromium is mainly responsible for through hardenability, the ability to uniformly harden a large section during heat treating.

High-speed steels attain their maximum hardness after tempering at 1,000°F or hotter. The characteristic of gaining hardness upon exposure to elevated tempering temperatures is called secondary hardening. It provides high-speed steels with their basic resistance to softening while in service, and it comes from a combination of tungsten and molybdenum. Empirically, it has been found that a total tungsten and molybdenum content, wherein the amount of tungsten plus twice the amount of molybdenum stands at about 18%,

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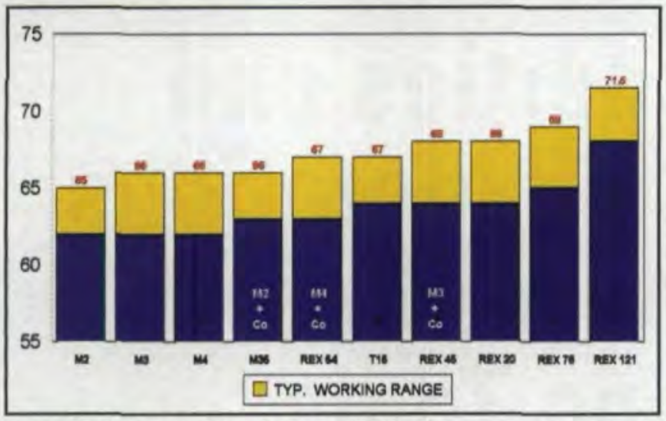


Figure 2—Typical working hardness (HRC) of some high-speed steels. (Typical maximum hardness shown in red.)

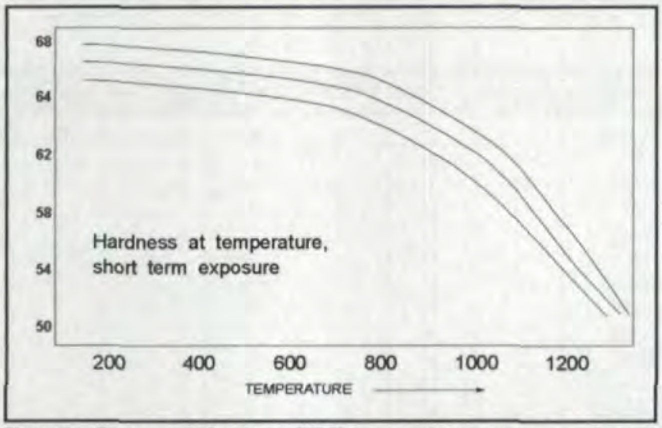


Figure 3—Decrease in hardness (HRC) from room temperature to elevated temperature for high-speed steel. (Hypothetical graph only, to illustrate the relationship.)

is satisfactory to provide the required temper resistance. Thus, high-speed steels may contain 18% W with essentially no Mo, or they may contain 8–9% Mo with only 1–2% W, or they may contain some intermediate level of both. In any case, it is common that the net combined levels are comparable among most grades.

Vanadium, present primarily as vanadium carbides, provides extremely high wear resistance. The hardness of vanadium carbides exceeds that of tungsten or molybdenum carbides (see Figure 1). As a consequence, high vanadium high-speed steels are more abrasion resistant, but they may also be more difficult to grind than lower vanadium grades, specifically because of the high hardness of the carbides.

Some high-speed steels may also contain cobalt. Cobalt is not a carbide-former, but stays dissolved in the matrix and acts to strengthen the matrix by increasing the overall hardness, as well as the hot hardness and resistance to softening.

Because the effective combined tungsten and molybdenum contents are comparable for many high-speed steels, it is primarily the vanadium and cobalt contents that distinguish the performance properties of the different steels.

Hardness

Normal high-speed steels are capable of attaining a hardness of HRC 63 minimum, and most are used in the range of HRC 62–68. (See Figure 2.) Hardness is a measurement of the resistance to plastic (permanent) deformation, especially in compression. Hardness tests measure the size of the impression (deformation) left by a fixed indenter, and materials are ranked on a relative scale. A tool with insufficient hardness may experience flattening, indenting or mushrooming in use. Room temperature hardness also has an effect on short-term hot hardness. For a given grade, the higher the room temperature hardness, the higher the elevated temperature hardness (see Figure 3). Although high hardness contributes to wear resistance, the two characteristics are not one and the same. It is important to note that the variation in hardness among the many high-speed steels is relatively minor, compared with their variations in wear resistance.

Wear Resistance

In gear-cutting tools, wear commonly occurs as erosion of the cutting edge or flank, cratering on a tool face or abrasion on any contact area of the tool. Wear resistance can vary somewhat due to hardness, but it is more strongly influenced by the type and volume of carbide particles present in the microstructure. For example, tools made of M2, M3 and M4 will show a significant increase in wear resistance, even at identical hardnesses, due to the progressive increase in the volume of vanadium carbides. For that reason, the most common grade of high-speed steel used for general purpose hobs and broaches has shifted from M2 through M3 to M4 over recent history, especially as steelmaking technology and grinding capability have improved to better handle the increased vanadium. It should be noted that the overall carbide *volume* plays a large role in wear resistance, as well as the carbide *type*.

Red Hardness

Red hardness or hot hardness is the resistance to softening of high-speed steels at elevated temperatures, specifically temperatures approximating those an operating tool might experience. Roberts and Cary (Ref. 1) have given the following rule of thumb for good red hardness for high speeds:

Maintaining a hardness >52 HRC at 1,000°F and > 48 HRC at 1,100°F.

For most practical applications, maintaining as high a hardness as possible during the cutting operation is desirable. As mentioned earlier, red hardness can be influenced somewhat by room temperature hardness, but it is much more significantly affected by the cobalt content. Cobalt-bearing versions of the common high-speed steels were developed specifically to improve red hardness and permit higher cutting speeds. (See Figure 4.) Cobalt-bearing high-speed steels usually contain 5–8% cobalt. Examples of "pairs" of grades with and without cobalt are shown in Table 2. In each pair, the additional cobalt slightly increases the hardness, but greatly improves the red hardness.

Criteria for designing cobalt-bearing high-speed steels has always involved a balance between red hardness and cost. Prior to the development of

P/M (powder metallurgy) high-speed steels, M42 (M1 + 8% Co) was used in broaching, and M35 (M2 + 5% Co) was used in hobs, when increased hardness was desired. Although they permit higher cutting speeds, the cobalt grades offer only limited inherent wear resistance improvements over their non-cobalt counterparts. After the development of P/M steelmaking (discussed below), M3 with 8% Co (CPM Rex 45) and M4 with 5% Co (CPM Rex 54) were developed as cobalt upgrades from conventional M35 for hobs. The 5% V, 5% Co T15 replaced much of the M42 used in broaches. Thus, not only enhanced red hardness, but enhanced abrasion resistance could be obtained as well.

Toughness

So far, we have looked at the alloy additions made to high-speed steels to impart the properties of hardness, wear resistance and red hardness. Aside from cost, why aren't high-speed steels made with the maximum alloy content possible to achieve superior properties? The reason is that high-carbon, high-alloy steels are prone to alloy segregation. Tools produced from conventionally made, very highly-alloyed steels are prone to chipping and cracking during tool manufacture and use, and they can be difficult to grind because of the non-uniform carbide size and distribution inherent in the production processes used to make the steels. The segregation problem becomes more pronounced as the carbide-

Table 2—High-speed steel grade pairs with and without cobalt.

Grade	W	Mo	V	Co
M2	6	5	2	-
M35	6	5	2	5
M3	6	5	3	-
Rex 45	6	5	3	8
M4	6	5	4	-
Rex 54	6	5	4	5

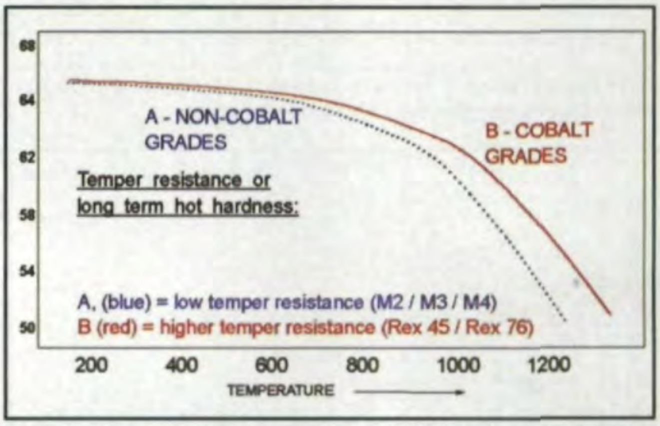
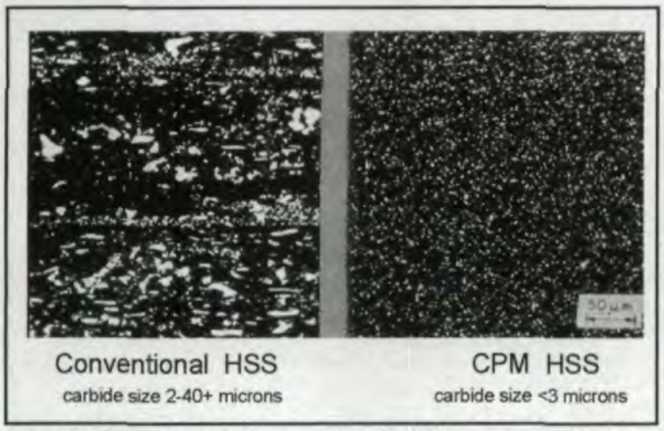


Figure 4—Improved resistance to softening, in HRC, at elevated temperature for cobalt-bearing high-speed steels. (Hypothetical graph only, to illustrate the relationship.)



Conventional HSS
carbide size 2-40+ microns

CPM HSS
carbide size <3 microns

Figure 5—Comparison of microstructures (carbide morphologies) of conventional high-speed steel and CPM high-speed steel.

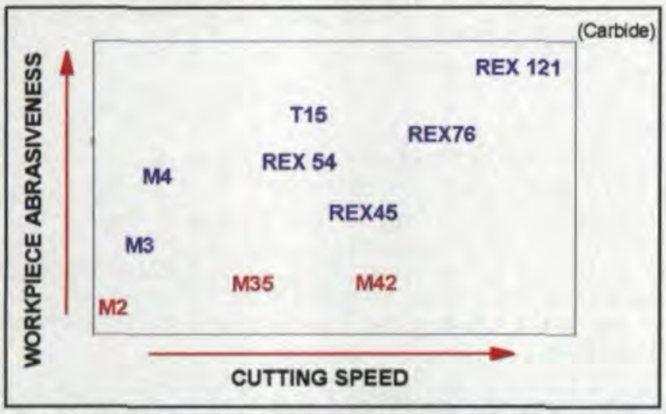


Figure 6—Relative working conditions and appropriate high-speed steel **grades. (Cobalt grades shown in red, non-cobalt grades in blue.)**

forming elements are increased.

P/M Eliminates Segregation

When designing conventionally made alloys for high performance, segregation problems will always limit the maximum amount of alloy content that can be added. In order to permit the manufacture of high-speed steels with higher performance levels, P/M methods are used.

At Crucible Service Centers, the CPM (Crucible particle metallurgy) process begins with a homogeneous bath of liquid steel, similar to conventional melting. Instead of being poured into ingot molds, the molten metal is atomized into spherical powder particles. The powder is loaded into containers, which are sealed and consolidated into a solid under heat and pressure. The resulting CPM product is fully dense and exhibits a uniform distribution of very fine carbides. Figure 5 illustrates the differences between conventionally produced and CPM bars of T15 with 2" diameters.

Prior to the P/M process, conventionally produced high-speed steels were limited in maximum alloy content due to segregation. High alloy grades were not only difficult to produce, but also were brittle and difficult to machine and grind. Thus, they were impractical for certain applications. The P/M process made possible the development and production of high-speed steels with overall higher alloy content for improved performance. Significantly, it has permitted the development of high vanadium grades for increased wear resistance without reducing the grindability. In addition, the P/M microstructure imparts a big benefit in toughness.

Selection Criteria for High-Speed Steels

How do you translate metallurgical properties into a selection process for the proper high-speed steel for your application? By examining the performance properties desired (or lacking) in current tooling and looking for alternate high-speed steels that may offer the needed properties, improved performance may be expected. Figure 6 shows some theoretical working considerations and appropriate high-speed steel grades.

A common start is a conventional high-speed steel, such as M2. On the low end of alloy content and performance expectations for high-speed steels, M2 is fine for general-purpose applications and adequate for jobs involving less abrasive workpieces, shorter runs or lower accuracy tolerances.

When improvements in tool life (increased number of parts per tool or of parts per sharpening) are desired, M3 and ultimately M4, with their increased vanadium content, can be expected to offer significant improvements over M2. Under the same cutting conditions, M4 would provide better wear resistance and better edge retention. Similarly, M4 would be a better choice if the workpiece is more abrasive, or if higher accuracy is required.

Because they share the same basic matrix chemical composition—except for an increasing volume of vanadium carbides—M2, M3 and M4 are designed to be used under similar cutting conditions; that is, no significant increase in feeds or speeds would be inherent in such a substitution. T15 is sometimes also considered, because of its 5% vanadium content, for abrasive applications as well. In that case, the benefit of the cobalt is primarily to allow slightly higher hardness to accompany the higher carbide volume for wear resistance.

When productivity issues drive material selection (increased parts per hour, increased cutting speeds), the cobalt-bearing grades permit higher cutting speeds. As discussed, the conventional high-speed steels M42 and M35 do not add any inherent wear resistance or tool life when compared to their non-cobalt-bearing counterparts, but they will stand up better to the higher temperatures encountered at higher cutting speeds. In hobs operating at high speeds, high-performance CPM Rex 45 and CPM Rex 54 offer superior red hardness common to cobalt-bearing grades, plus the excellent wear resistance of M3 and M4 vanadium levels. When cutting speeds are not severe, T15 may also be considered.

When both higher cutting speeds and even higher wear resistance are required, the CPM super high-speed steels offer the simultaneous improvement of both. Both CPM Rex 76 and the new CPM Rex 121 offer combinations of very high red hardness and wear resistance. Those grades have been used, along with appropriate coatings, in dry-cutting applications. They also may provide an alternative to solid carbide tooling in applications where carbide tools are too fragile, or where machine rigidity or stability may be inadequate for carbide tools.

The proper selection of high-speed steel for your application should also take into consideration the normal failure mode of the tools. Upgrade to a material that provides an enhanced level of the property which addresses that failure mode. For instance, if the typical failure mode in an M2 tool is simply abrasion or wear, a higher vanadium grade, such as M3 or M4, will probably offer satisfactory relief. A cobalt version of the existing grade, such as M35 (M2 + Co) or Rex 45 (M3 + Co) might not add sufficient wear resistance. However, if the desire is to increase cutting speeds, a grade with high red hardness or temper resistance, such as Rex 76, may offer benefits over other cobalt-bearing grades. (See Figure 6.)

The development of coatings has added another level of complexity to the selection process. A good coating may allow higher cutting speeds by decreasing frictional heating at the tool-chip interface. When coated, tools can be used under cutting conditions that the uncoated tool could not withstand. However, the function of the coating is affected by the properties of the substrate, so choose the substrate to match the coating and cutting conditions. For coatings that permit high cutting speeds, it may be important to choose a substrate suitable for high cutting speeds, a substrate that offers extreme temper resistance or red hardness, such as CPM Rex 76.

The recent interest in dry cutting gives even greater concern to temperature exposure. CPM Rex 121 provides the ability to retain its cutting properties at high temperatures. Designed to be a material to bridge the gap between traditional high-speed steels and carbide, CPM Rex 121 offers significantly higher wear resistance and red hardness than other high-speed steels. When considering coated tools, discuss the application with the tool manufacturer, the coater and materials supplier, each of whom may have important contributions to make toward the eventual success of the tool.

Tool design and manufacturing, the caliber of the heat treating process, and coatings will all contribute to the successful performance of a tool. But, the choice of which material to use for raw material should not be overlooked. To ensure a high-performance tool, start by picking a high-performance high-speed steel. ⭘

Reference

1. Roberts, George and Robert Cary, *Tool Steels*, 4th ed., American Society for Metals, Metals Park, OH, July 1985.

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