Common Elements in Tool Steels

Selected information from the following website:
http://www.simplytoolsteel.com/alloying-elements.html

Below is a listing of the common elements found in alloying tool steel and high-speed steel. The chemical symbol, atomic number, type of metal, atomic weight, density and melting point are listed.

Iron – Symbol Fe, Atomic number 26, Transition metal, Atomic weight 55.845 g/mol, Density 7.784 g/cm3, Melting Point 2800 deg. F

Iron is the base metal of all steel grades. It is a soft silvery gray lustrous metal. Iron, carbon and many other alloying elements are combined to form tool and high speed steels.

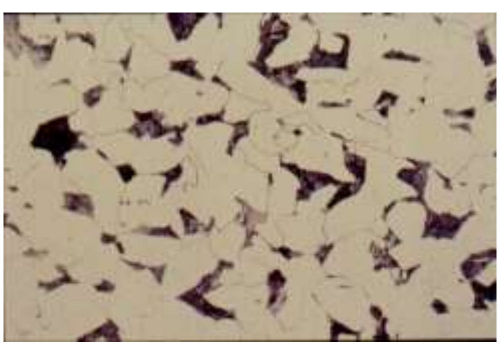
COMMON ALLOYING ELEMENTS

Carbon – symbol C, Atomic number 6, Nonmetal, Atomic weight 12.0107 g/mol Density 1.8-2.1 g/cm3, Melting Point 6381 deg. F

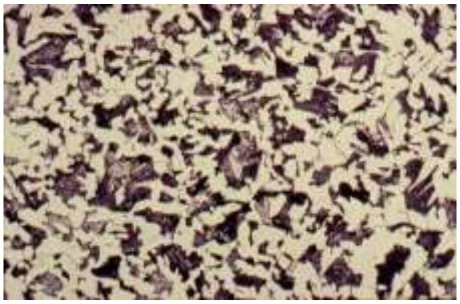
This is the most important and influential alloying element in steel. Without carbon, steel would not exist. Carbon is the element that combines with the other elements to provide hardness and strength. With increasing carbon content, the strength and hardenability of the steel increases, but its ductility, machinability, formability, and weldability are decreased.

Presenter's Notes:

Low carbon steel: 0.05-0.3% carbon content.



Medium carbon steel: Approximately 0.250–0.6% carbon content. Balances ductility and strength and has good wear resistance; used for large parts, forging and automotive components.



High-carbon steel (ASTM 304): Approximately 0.9–2.5% carbon content. Very strong, used for springs and high-strength wires.

*Ultra-high-carbon steel: Approximately 2.5–3.0% carbon content. These steels that can be tempered to great hardness. Used for special purposes like (non-industrial-purpose) knives, axles or punches. Most steels with more than 2.5% carbon content are made using **powder metallurgy**.*

Note that steel with carbon content above 2.14% is considered cast iron – brittle with limited workability, etc. ***NOTE: As for carbon, a little of any of the following alloy ingredients goes a long way!***

Manganese – symbol Mn, Atomic number 25, Transition metal, Atomic weight 54.938045 g/mol, Density 7.21 g/cm3, Melting Point 2275 deg. F

Manganese is used as a deoxidizer. It contributes to strength and hardness, but to a lesser extent than carbon. Manganese imparts a deeper hardening depth. Manganese has a strong effect on increasing the hardenability of steel by reducing the critical cooling rate and can reduce heat treating distortion.

Silicon – symbol Si, Atomic weight 14, Metalloid, Atomic weight 28.0855 g/mol, Density 2.3290 g/cm3, Melting Point 2577 deg. F

Silicon is used as one of the main deoxidizers in steelmaking. Silicon is a strong promoter of hardenability and increases scale resistance. Silicon helps improve toughness and provides a greater depth of hardening.

Sulfur – symbol S, Atomic number 16, Nonmetal, Atomic weight 32.065 g/mol, Density 1.96 g/cm3, Melting Point 239.38 deg. F

For most steels a maximum limit is specified to control the level. Sulfur combines with manganese to form manganese sulfides. which is one of the undesirable inclusions found in steel. Sulfur is intentionally added to improve machinability by increasing lubrication and small chip formation.

Nickel – symbol Ni, Atomic number 28, Transition metal, Atomic weight 58.6934 g/mol, Density 8.908 g/cm3, Melting Point 2651 deg. F

Nickel is a magnetic silvery-white lustrous metal. In combination with chromium, nickel produces alloy steels with greater hardenability. Nickel is not a carbide former. Nickel adds corrosion resistance.

Aluminum – symbol Al, Atomic number 13, Poor metal, Atomic weight 26.98015386 g/mol, Density 2.70 g/cm3, Melting Point 1220.58 deg. F

This is the most effective and frequently used deoxidizer in steelmaking. Small additions are used to insure small grain size. Aluminum will form with nitrogen and form hard aluminum nitrides, which is why it is added to nitriding steels.

Cobalt – symbol Co, Atomic number 27, Transition metal, Atomic weight 58.933195 g/mol, Density 8.90g/cm3, Melting Point 2723 deg. F

Cobalt improves red hardness and high temperature strength; it is frequently used in high-speed steels, hot forming tool steels, and high temperature materials. Cobalt does not form any carbides.

CARBIDE FORMING ELEMENTS

Presenter's Notes:

> *The 'carbide' or 'nano-carbide' tools that many of you use are different from the following carbide forming elements used in various alloys basically in that carbide is the main ingredient. In the carbide tool bit creation process the tungsten carbide nano-particle powder is fused into the finished tool bit shape using metal the melts at a much lower temperature (cobalt is common) effectively 'cementing' the particles into the finished form. This much different than in the alloy creation process where the carbides are formed during the processing of the alloy and are a much smaller percentage of the overall mix.*

Chromium – symbol Cr, Atomic number 24, Transition metal, Atomic weight 51.9961 g/mol, Density 7.19 g/cm3, Melting Point 3465 deg. F

Chromium is a steely-gray lustrous hard metal. Chromium is generally added to steel to increase resistance to corrosion and oxidation, to increase hardenability, and to improve high temperature strength. Chromium is a carbide former, which increases edge retention and wear resistance.

Molybdenum – symbol Mo, Atomic number 42, Transition metal, Atomic weight 95.94 g/mol, Density 10.28 g/cm3, Melting Point 4753 deg. F

Molybdenum is a silvery white metal usually alloyed together with other elements and is pronounced carbide former. It increases temper brittleness and promotes fine grain formation. Molybdenum also increases weldability and increases the tendency for secondary hardening during tempering.

Tungsten – symbol W, Atomic number 74, transition metal, Atomic weight 183.84 g/mol, Density 19.25 g/cm3, Melting Point 6192 deg. F

Tungsten is steel gray metal that is an excellent carbide former. It improves toughness and prevents grain growth. Tungsten increases high temperature strength and red hardness. It is primarily used in high speed steels and hot forming tool steels.

Vanadium – symbol V, Atomic number 23, Transition metal, Atomic weight 50.9415 g/mol, Density 6.0 g/cm3, Melting Point 3470 deg. F

Vanadium is a silvery gray metal. It is an excellent carbide former, which increases wear resistance. It forms the highest hardness carbides. It increases high temperature strength and resistance to softening.

CPM High Speed Steels

Selected Information from the following website:

https://www.crucible.com/eselector/general/generalpart1.html
https://www.crucible.com/eselector/general/generalpart4.html

Since 1970, most of the more highly alloyed premium high speed steels have been produced by the CPM (Crucible Particle Metallurgy) process.

The fine structures that result from rapid solidification in the CPM process offer premium characteristics for both the manufacturers of cutting tools and their users. The more uniform distribution and the finer size of carbides in CPM steels are especially evident in comparisons with larger diameter bars of conventionally produced high speed steel, where carbide segregation is more of a problem. Thus, while the benefits pertain to cutters of all dimensions, they are more pronounced in larger tools.

There are four principal benefits of CPM high speed steels for tool users:

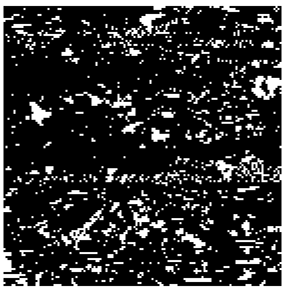
The primary benefit is the availability of higher alloy grades which cannot be manufactured by conventional steelmaking. These grades provide enhanced wear resistance and heat resistance for cutting tool applications. REX 20, REX 54, REX 76 and REX 121 are examples. These grades represent significant progress in the development of steels with unique characteristics. CPM Rex 20 equals or outperforms M42, yet is cobalt-free. CPM Rex 76 offers an excellent combination of high attainable hardness, toughness and wear resistance, and is an excellent substrate for advanced coatings such as TiAlN. Rex 121 has the highest attainable hardness and highest red hardness of any high speed steel.

Second, the increased toughness of CPM high speed steels not only provides greater resistance to breakage (particularly valuable in intermittent cut operations), but it also allows a tool to be hardened by 0.5 to 1.0 points higher on the Rockwell C scale without sacrificing toughness. Both longer tool life and higher cutting speeds can be realized.

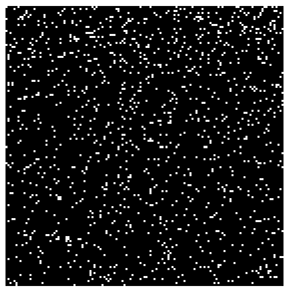
Third, CPM offers improved grindability with no reduction in wear resistance of the tool. This means reduced grinding-wheel wear. Grinding can be done more quickly with less danger of damage to the cutter, and it leaves an edge that produces a smoother finish on the work piece.

Fourth, the greater consistency in heat treatment and uniformity of properties of CPM high speed steels increases the degree of predictability for scheduling tool changes. This factor is particularly advantageous in multi-spindle machines, where a single cutter failure affects several spindles and usually requires changing all cutters (including some that may have a lot of life left).

Finer Carbide Size and Distribution



CONVENTIONAL HSS



CPM

This illustration shows the key metallurgical characteristics responsible for the successful application of particle metallurgy products. Both microstructures are for 2" diameter AISI T15 - CPM on right and conventionally produced on the left (500X, longitudinal cross section).

Note the very fine and uniformly dispersed carbide distribution in CPM steels compared to the segregated distribution and broad size range of the carbides in the conventional product. The finer carbide structure in CPM also results in finer grain size control.

For the same reason the carbides are fine and uniformly distributed, so are any sulfides that are formed. At Crucible, we take advantage of this characteristic to re-sulfurize to high sulfur levels where enhanced machinability is required without significantly affecting the toughness properties. This could not be done with conventional ingot processing.

The differences in microstructural control between CPM and conventionally ingot-cast high alloy tool steels of the same composition can have a decisively beneficial influence on the steel's behavior in certain tool manufacturing operations as well as on tool performance. Specifically, these potential benefits include:

a) Better annealed machinability

b) More consistent and safer heat treat response

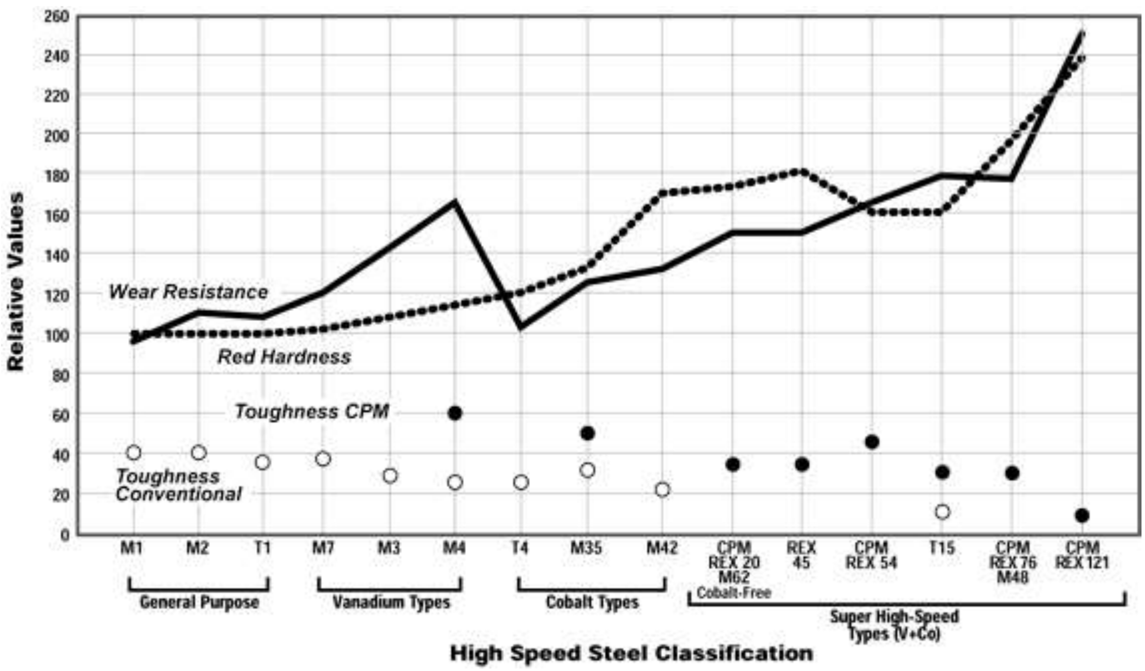
c) Significantly improved grindability

d) Good toughness characteristics

e) Larger size capability in full length bars

The High Speed Steel Comparagraph is a graphical presentation of the three properties usually considered when selecting a high speed steel for cutting tools - red hardness, wear resistance, and toughness.

CPM High Speed Comparagraph



At the bottom of the chart, we have grouped the high speed steels into four major categories - general purpose (e.g. M2), wear resistant (e.g. M3 and M4), cobalt-type (e.g. M35 and M42), and super high speed (e.g. Rex 20, Rex 45, Rex 54, T15, Rex 76, and Rex 121).

In general, red hardness increases with total alloy content and particularly with alloys responsible for high attainable hardness. There is a strong effect of increasing cobalt content on heat treat response and temper resistance. Thus M2 with less than 20 percent total alloy content, no cobalt, and an attainable hardness of 64-66 HRC, is at the low end of the red hardness curve; whereas CPM Rex 121 with 37 percent total alloy content, 9 percent Co, and an attainable hardness of 70+ HRC is at the top of the curve.

Wear resistance is affected by the heat treated hardness, but more importantly it is a function of the amount and type of hard alloy carbide present in the structure of the material. Of the alloying elements generally found in high speed steels, vanadium forms the most wear resistance carbides followed in decreasing order of effectiveness by tungsten, molybdenum, and chromium. Thus, although wear resistance tends to increase with total alloy content and attainable hardness, there are notable peaks in the wear resistance curve at the high vanadium compositions, e.g. CPM M4, CPM Rex 54, CPM T15, CPM Rex 76, and CPM Rex 121.

Toughness generally decreases with increased alloy content, particularly for the high cobalt, higher attainable hardness materials. However, the CPM high speed steels are consistently tougher than their conventional counterparts. Thus, some of the higher alloy CPM-produced grades may be as tough as, or tougher than, lower alloy conventionally-produced grades. In fact, CPM M4 exhibits the best toughness properties of any high speed steel we currently produce, conventional or CPM. Combined with its excellent wear resistant properties and good grindability (comparable to conventional M2) CPM M4 represents the best high performance “general purpose” high speed steel on the market today.

In applications where customers have traditionally used conventional M2 or M3 (e.g. broaches, form tools, hobs, milling cutters, etc.), the trend is toward upgrading to CPM M4, which is the toughest high speed steel we produce and is surpassed in wear resistance only by CPM T15, Rex 76, and Rex 121. CPM M4 will even out wear M42 in applications where red hardness is not the controlling property.

In applications where it has been traditionally necessary to use a high cobalt material for red hardness, e.g. M42, upgrading can be accomplished by progressing from M42 to CPM Rex 20, CPM Rex 45, CPM Rex 54, CPM T15, CPM Rex 76 or CPM Rex 121. All six CPM high speed steels offer both excellent red hardness characteristics and very good wear resistance properties compared to M42.

The objective of any end user should be to get from the left hand side of this chart to the right hand side thereby upgrading the cutting tool performance, and reducing the overall tooling and equipment costs.

Properties of tool steel

- Hardness
  — resistance to deforming & flattening

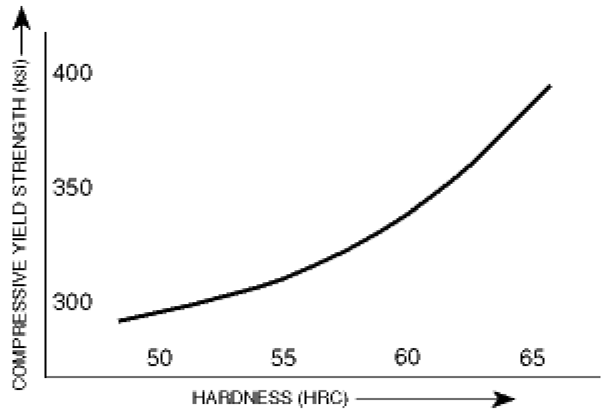
- Toughness
  — resistance to breakage & chipping

- Wear resistance
  — resistance to abrasion & erosion

Properties of Tool Steels — Hardness

Hardness is a measure of a steel’s resistance to deformation. Hardness in tool steels is most commonly measured using the Rockwell C test. Hardened cold work tool steels are generally about 58/64 HRC (hardness Rockwell C), depending on the grade. Most are typically about 60/62 HRC, although some are occasionally used up to about 66 HRC.

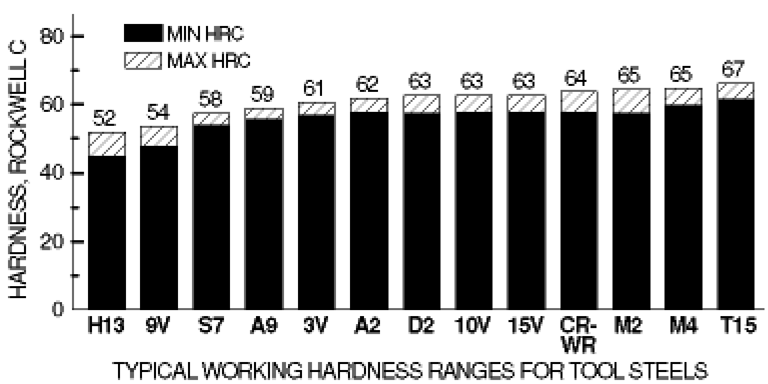
Hardness vs Compressive Yield Strength



Hardness testers work by using a standardized load to make an indentation in the test piece, then measuring the size of the indentation. A large indentation indicates low hardness (material is easily indented). A small indentation indicates high hardness (material resists being indented). Thus, the material's resistance to deforming (compression, indentation) is indicated directly by its hardness. When different steels measure at similar hardnesses, it is because the hardness tester made the same size impression in each. Thus, at the same hardness, different steels have similar resistance to deformation. The hardness test is basically independent of the grade of steel tested.

Tools which plastically deform in service possess insufficient hardness. Permanent bending of cutting edges, mushrooming of punch faces, or indenting of die surfaces (peening) all indicate insufficient hardness. Because a steel's resistance to indentation is directly related to the hardness, not the grade, corrective actions for deformation may include increasing hardness, or decreasing operating loads. Changing grades will not help a deformation problem, unless the new grade is capable of higher hardness.

Choosing for Hardness



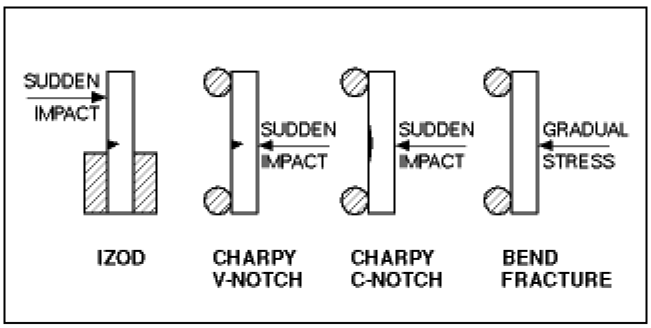
Small differences in hardness do not usually have a significant effect on the wear life of tool steels. Different tool steels are used at similar hardnesses, yet offer significant differences in expected wear life. Thus, hardness is not usually a primary factor in wear resistance, only in deformation resistance. The wear resistance of tool steels is more directly affected by their chemical composition (grade) as discussed below.

Properties of Tool Steels — Toughness

Toughness, as considered for tooling materials, is the relative resistance of a material to breakage, chipping, or cracking under impact or stress. Toughness may be thought of as the opposite of brittleness. Toughness testing is not as standardized as hardness testing. It may be difficult to correlate the results of different test methods. Common toughness tests include various impact tests and bend fracture tests.

In impact testing, a small sample is held in a fixture and fractured by a moving impacter, such as a calibrated weight on a pendulum. Toughness is reported as the amount of energy, usually measured in foot-pounds or joules, that the sample absorbs before it breaks. Brittle materials will absorb little energy before fracturing. In bend fracture testing, a fixtured sample is subjected to gradually increasing amounts of pressure, usually side or bending pressure, until it breaks.

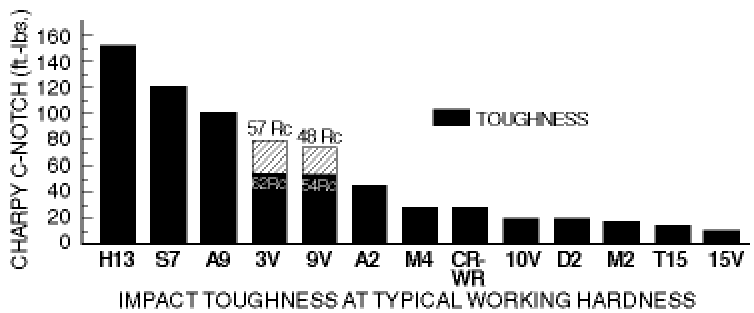
Methods of Toughness Testing



Most tool steels are notch-sensitive, meaning that any small notch present in the sample will permit it to fracture at a much lower energy. Solid carbide is even more notch-sensitive than tool steels. Thus, in addition to inherent material properties, the impact resistance of tool components is significantly impaired by notches, undercuts, geometry changes, and other common features of tools and dies.

In service, wear failures are usually preferable to toughness failures (breakage). Breakage failures can be unpredictable, catastrophic, interruptive to production, and perhaps even a safety concern. Conversely, wear failures are usually gradual, and can be anticipated and planned for. Toughness failures may be the result of inadequate material toughness, or a number of other factors, including heat treatment, fabrication (EDM), or a multitude of operating conditions (alignment, feed, etc.) Toughness data is useful to predict which steels may be more or less prone to chipping or breakage than other steels, but toughness data cannot predict the performance life of tools.

Choosing for Impact Toughness



Properties of Tool Steels — Wear Resistance

Wear resistance is the ability of material to resist being abraded or eroded by contact with work material, other tools, or outside influences (scale, grit, etc.) Wear resistance is provided by both the hardness level and the chemistry of the tool. Wear tests are quite specific to the circumstances creating the wear and the application of the tool. Most wear tests involve creating a moving contact between the surface of a sample and some destructive medium. There are 2 basic types of wear damage in tools, abrasive and adhesive. Wear involving erosion or rounding of edges, as from scale or oxide, is called abrasive wear. Abrasive wear does not require high pressures. Abrasive wear testing may involve sand, sandpaper, or various slurries or powders. Wear from intimate contact between two relatively smooth surfaces, such as steel on steel, carbide on steel, etc., is called adhesive wear. Adhesive wear may involve actual tearing of the material at points of high pressure contact due to friction.

We often intuitively expect that a harder tool will resist wear better than a softer tool. However, **different grades, used at the same hardness, provide varying wear resistance.** For instance, O1, A2, D2, and M2 would be expected to show increasingly longer wear performance, even if all were used at 60 HRC. In fact, in some situations, lower hardness, high alloy grades may outwear higher hardness, lower alloy grades. Thus, factors other than hardness must contribute to wear properties.

Hardness of Carbides

Alloy elements (Cr, V, W, Mo) form hard carbide particles in tool steel microstructures.
The amount and type present influence the wear resistance.

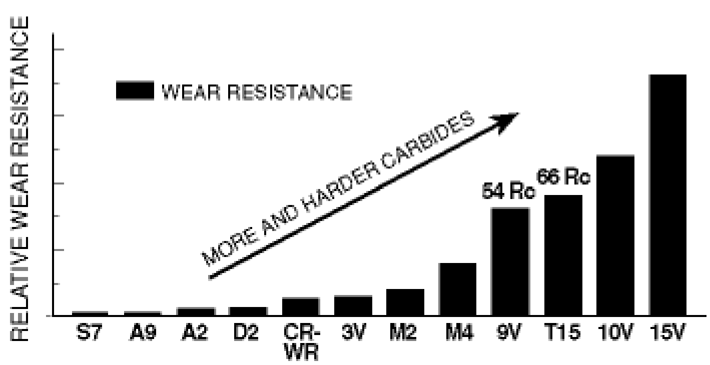
• HARDENED STEEL	• 60/65 HRC
• CHROMIUM CARBIDES	• 66/68 HRC
• MOLYBDENUM CARBIDES	• 72/77 HRC
• TUNGSTEN CARBIDES	• 72/77 HRC
• VANADIUM CARBIDES	**• 82/84 HRC**

Tool steels contain the element carbon, in levels from about 0.5% up to over 2%. The minimum level of about 0.5% is required to allow the steels to harden to the 60 HRC level during heat treating. The excess carbon above 0.5% plays little role in the hardening of the steels. Instead, it is intended to combine with other elements in the steel to form hard particles called carbides. Tool steels contain elements such as chromium, molybdenum, tungsten, and vanadium. These elements combine with the excess carbon to form chromium carbides, tungsten carbides, vanadium carbides, etc. These carbide particles are microscopic in size, and constitute from less than 5% to over 20% of the total volume of the microstructure of the steel. The actual hardness of individual carbide particles depends on their chemical composition. Chromium carbides are about 65/70 HRC, molybdenum and tungsten carbides are about 75 HRC, and vanadium carbides are 80/85 HRC.

These embedded carbide particles function like the cobblestones in a cobblestone street. They are harder than the steel matrix around them, and can help prevent the matrix from being worn away in service. The amount and type of carbide present in a particular grade of steel is largely responsible for differences in wear resistance. At similar hardnesses, steels with greater amounts of carbides or carbides of a higher hardness, will show better resistance to wear. This factor accounts for differences in wear resistance among, say, O1, A2, D2, and M4. Ideally, tool steels would contain as much carbide volume as needed for the desired wear performance. In fact “solid carbide” tooling is typically 85% or 90% tungsten carbide particles, in a matrix of 10% or 15% cobalt to hold them together. Chemically, the microscopic carbide particles in tool steels are similar to the carbide particles in solid carbide tools. However, very high amounts of carbide particles can lead to problems in grinding, or lower toughness. More comments on the effect of carbides on toughness and grindability are discussed in the following section: **Effect of Steel Manufacturing on Properties.**

Because of their high hardness, vanadium carbides are particularly beneficial for wear resistance. When present in significant amounts, vanadium carbides tend to dominate other types in affecting wear properties. For instance, M4 high speed steel’s chemical content is nearly identical to M2 high speed steel, except M4 contains 4% vanadium instead of 2%. Despite the high levels of molybdenum and tungsten carbides (about 6% tungsten, 5% molybdenum) in each grade, the small difference in vanadium content gives M4 nearly twice the wear life of M2 in many environments. In cold work tool steels, the carbide content in general, and to a limited extent the vanadium content in particular, may sometimes be used as a rough predictor of potential wear life.

Effect of Carbide Content (esp. VC)
on Wear Resistance
HRC 58-62 except as noted

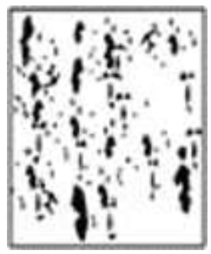


Steels with high volumes of carbide particles, or high hardness types of particles, usually exhibit the best wear resistance. Vanadium carbides, because of their hardness and chemistry, are the most effective at enhancing wear properties; chromium carbides are among the least effective.

Effect of Steel Manufacturing on Properties

The maximum practical limit to the amount of carbide-forming elements which may be added to a steel for wear properties depends on the ability to maintain a reasonable distribution of those carbides throughout the steel's microstructure. When steels are manufactured, they are melted in large batches, containing the desired chemical composition. The batches are poured into ingot molds, and solidify into castings which are subsequently forged or rolled into bars. During the solidification process, the carbides are formed. Under conditions of long slow solidification, these carbides form interconnected "segregated" networks, because they do not stay dissolved in the liquid steel. Large amounts of carbide particles result in more segregation, and thus more non-uniformity in the steel microstructure.

Carbide Size and Distribution



The alloying elements Cr, V, W, and Mo form hard carbide particles in tool steel microstructures. The amount and type of carbides influence wear resistance. Carbides are intended to improve wear resistance, but their non-uniform size and distribution (i.e., segregated networks) can impair toughness and grindability. Grades containing a high volume of hard carbides, like high speed steels and high vanadium cold work grades, may be particularly affected.

This carbide segregation causes two basic problems. First, areas of high concentrations of hard carbide particles may be difficult to grind, resulting in fabrication difficulties. Second, when these segregated areas are physically elongated during rolling or forging, they result in a directionally oriented microstructure, and reduce the material toughness along the transverse direction. Vanadium levels over about 3% are high enough to cause particular grinding and toughness difficulties. For this reason, despite its benefits for wear resistance, vanadium is usually limited to about 2-1/2% max. in conventionally manufactured tool steels.

Some sources for specialty HSS tools that you may not have looked at recently:

Doug Thompson's 10V and 15V tools are a very popular option:
http://www.thompsonlathetools.com/

Also, Jerry Glaser's 10V and 15V tool designs are back on the market:
http://www.glaserhitec.com/shop/

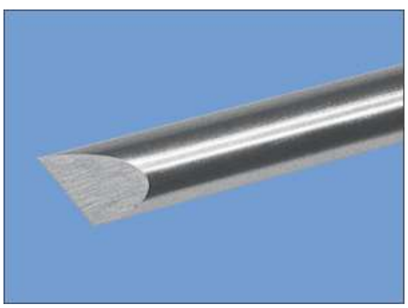
Dave Schweitzer of D-Way tools has been shipping M42 tools for some time:
http://www.d-waytools.com/tools-gouges.html

Your pre-hardened M2 tool blanks came from MSC Direct: https://www.mscdirect.com/browse/tn/?searchterm=M2+tool+blank&hdrsrh=true#navid=12105897+4288207824+4288147681&searchterm=M2+tool+blank

Some of the many woodturning tools that can be made from a pre-hardened (RC 63 to 65) M2 HSS rod

If we grind only one facet directly across the bar we have the Coving Tool seen in the tool catalogs. This tool is used as a scraper to cut coves in smaller spindle turnings.

If we grind two facets on the rod back at a skew angle of 25 degrees or so we have a Round Skew as seen in the tool catalogs.



The Pyramid Point tool has three facets ground at a 45 degree angle. This is a scraper tool that can be used for layout work, to turn beads and other simple tasks. It is not prone to catches and any one of the three sides may be used as the 'up' side.

If you bring back the angle of the grind on this tool to 30 degrees or more you have a Detail Point tool that can be used to get into much smaller spaces on a finial or other turning. If used aggressively to take a larger cut this tool will be prone to catch.

If we grind a flat on the top half of the bar and then grind a ‘standard’ or ‘swept back’ gouge bevel on the lower half we have a ‘fluteless gouge’ or ‘skew-chisel-gouge’ (skewchigouge) as seen in the tool catalogs. The top can be ground at an angle as shown on the left or as a flat extending back some distance as shown on the right to let you only bother with one surface when re-sharpening.

Grinding Tips:

- When removing a large amount of metal the coarser the grit in your wheel the better. Most folks who do a lot of tool shaping use a 36 to 40 grit wheel for the major shaping phase. The finer the grit the more time on the wheel and the more you heat the steel.
- Heating or cooling the metal too quickly will cause micro cracking leading to a chipped edge in use, let the blank air cool when it gets too hot.
- High Speed Steel like M2 will hold its hardness to much high temperatures than high carbon steel but permit the blank to cool when you begin to see blue on the edge, don’t go too far into the red and never all the way to orange.