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Tool steels depend on molybdenum

Many of the best tool steels require molybdenum to increase hardenability and toughness, and to form hard, wear-resistant carbides in the matrix. These attributes make molybdenum-containing tool steels the industry standard.

Most people may not recognize the importance of tool steels in their daily lives, but they are used to manufacture nearly every object in the world. Whether a component is made of metal, plastic or another material, chances are it was formed or shaped by a tool of molybdenum-containing tool steel. The tool steels discussed in this article are found in plastic-molding tools, cold-work tools and high-speed machining tools.


'Old Heroult No. 1' is now an ASM Historical Monument located in Pittsburgh, PA. © Crucible Industries LLC

Historical development

The first 'tool steel' (circa 1200 BCE) was probably a simple alloy of iron and carbon. Then as now, military needs drove materials development for swords, battleaxes, and other instruments of war. The famous 'Damascus steel' blades with their layered microstructure date to 540 CE, and similar Japanese blades date to 900 CE. The *crucible process* that used a ceramic crucible to melt and alloy iron appeared in 1740, ushering in the modern era of tool steels. During the 18th and early 19th centuries, metallurgy began to evolve from a branch of alchemy into a science. In 1868, steelmakers learned that tungsten greatly improved the properties of existing tool steels. They introduced vanadium as an alloying element in 1904 and chromium in 1910. Molybdenum, first studied in laboratory experiments in the late 1920s, came into widespread use during World War II due to tungsten's limited wartime availability. These four elements greatly improved steel's wear resistance by forming very hard alloy carbides.

Crucible melting produced steel in heats of only a few hundred kg. The Heroult electric furnace, introduced in 1904, produced steel in heats of more than a thousand kg, fundamentally changing tool-steel economics. However, both processes produced large, slowly solidifying ingots that were finished by traditional rolling and forging techniques.

The carbides of ingot-based tool steels were coarse and unevenly distributed because of the slow cooling rate, preventing the steels from reaching their ultimate potential. In 1970, atomized tool steel powder was first produced and compacted at high temperature and pressure into larger, fully dense shapes, bringing a substantial improvement to tool-steel performance. Atomization creates a uniform distribution of fine carbides in the steel. The process also tolerates higher carbon contents. These factors produce steels with higher hardness than previously possible. The powder-based process can also make near net shapes, minimizing the machining required to manufacture large die blocks.

Important properties

Tool steels have to be strong and tough to withstand the cutting and forming forces without chipping or breaking on impact. They derive their strength primarily from *martensite*, a hard phase that forms upon rapid quenching from high temperature. Martensite's strength and hardness increase as carbon content increases as illustrated in the figure below; so most tool steels are high in carbon. To regain some toughness

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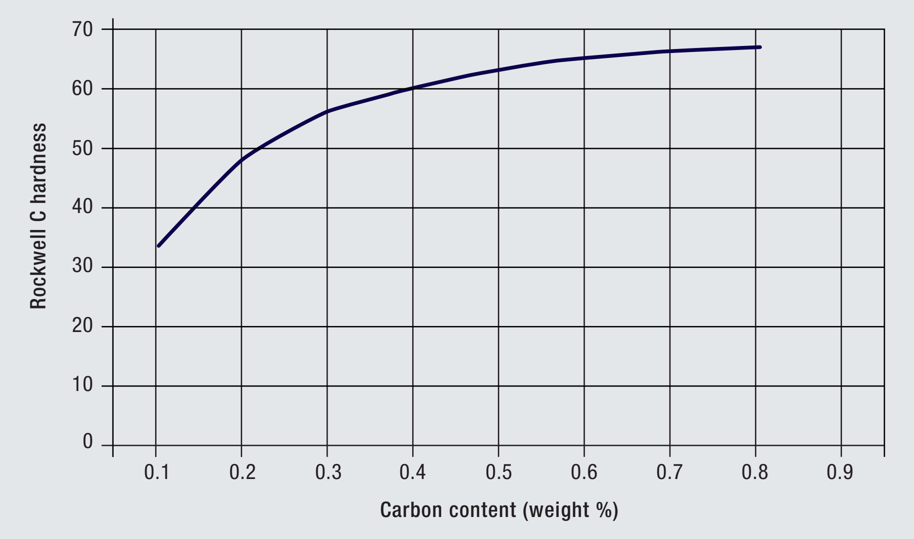
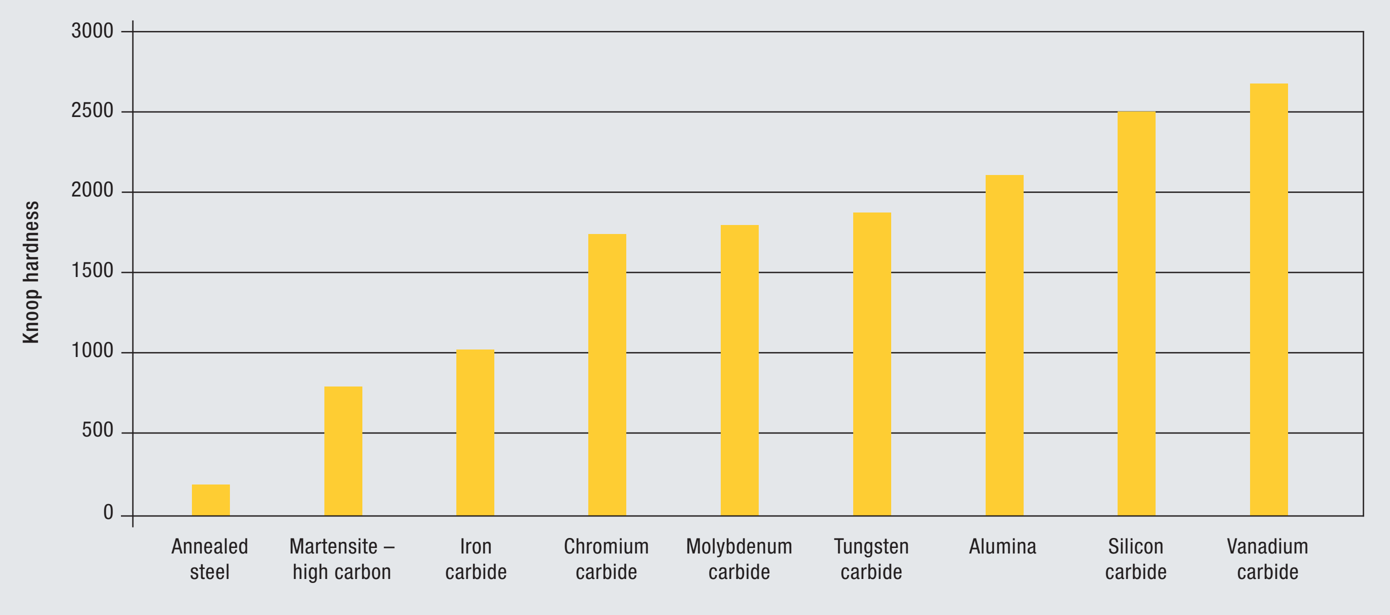
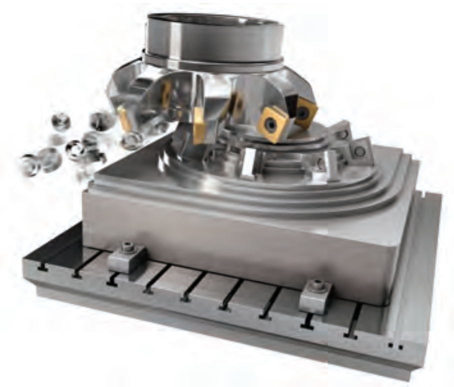


The hardness of martensite increases with increasing carbon content.



Different alloy carbides and alumina are much harder than steels.



This milling tool is made of a molybdenum-containing tool holder steel, the cutting edges are inserts of a different material. © Uddeholm

martensite has to be tempered after quenching. Depending on the tempering temperature, this can reduce hardness and strength slightly, but through the precipitation of additional fine alloy carbides, it improves wear resistance. Wear resistance is the third important property of tool steels, because it determines the length of tool life before it needs replacement.

The best tool steels incorporate a large number of fine, hard carbides in the martensite matrix. Molybdenum, tungsten, and vanadium all produce very hard carbides as shown in the figure above. However, no element increases *hardenability* (the ability to be hardened in thick sections, where quenching is slow) of these steels better than molybdenum and also increases the strength and toughness after tempering. As a result, many tool steels contain molybdenum, some grades in amounts up to 11% by weight.

During high-speed machining of metals, tools become very hot. The most highly alloyed tool steels are known as high-speed steels (HSS) because their carbides are very stable at the high temperatures encountered in high-speed machining and the matrix is temper resistant, enabling HSS tools to retain superior cutting ability.

The dishwasher interior was cold formed with tools of molybdenum-containing tool steel. © Uddeholm

Selected AISI tool steel categories with nominal composition ranges

AISI category/grade group	AISI grade designations	Carbon	Chromium	Molybdenum	Tungsten	Vanadium	Cobalt
Cold working/air-hardening, medium alloy	A2–A10	0.70–2.25	1.00–5.25	1.00–1.40	0.00–1.25	0.00–4.75	–
Cold working/high-carbon, high-chromium	D2–D7	1.50–2.35	12.00	1.00	–	0.00–4.00	–
Plastic mold	P2–P21	0.07–0.35	0.60–5.00	0.20–0.75	–	–	–
High-speed/tungsten base	T1–T15	0.75–1.50	4.00–4.50	–	12.00–20.00	1.00–5.00	5.00–12.00
High-speed/molybdenum base (standard)	M1–M36	0.80–1.30	4.00	4.50–9.50	1.50–6.00	1.00–4.00	0.00–12.00
High-speed/molybdenum base (ultrahard)	M41–M62	1.10–1.35	3.75–4.50	3.75–11.00	1.50–10.50	1.15–3.25	5.00–12.00

Classification

The widely used AISI method of tool steel classification contains eleven grade groups designated by letters. Most of these grade groups contain molybdenum-alloyed steels. The following briefly summarizes the grade groups used for cold-forming, plastic-molding, and machining tools. The table above shows their composition ranges.

Cold-work tool steels (A and D grades) bend or shape other materials at and near ambient temperature. Tool-steel dies produce a wide array of products, including auto-body and home-appliance panels, stainless-steel sinks, electronic components, battery cases, and heart pacemaker cases. Cost is very important in cold-working operations, so these grades contain low alloy content to minimize tooling costs. Nevertheless, some 3,400 metric tons of molybdenum were used for these steels in 2012, providing as an example, the hardenability required in large dies for components such as auto-body panels.

Mold steels (P grades) form and mold plastic parts. These parts vary widely in size, and include items such as Lego® bricks, gears, mobile phone cases, baskets, buckets, automotive and aircraft interior panels, and automotive bumpers. Some 5,300 metric tons of molybdenum were used for this application in 2012, again mostly in large molds to ensure through-hardening.

High-speed steels (M grades) are used for machining tools for drilling, turning and milling. They retain their strength, hardness, and wear resistance at high temperatures produced by very high cutting speeds. For example, high-speed lathe-turning may produce surface speeds resulting in temperatures of approximately 500°C at the interface of the tool and workpiece. With 14,000 metric tons in 2012, HSS use the most molybdenum.

Alternatives to high-speed tool steels

Molybdenum-containing HSS face strong competition from alternative tool materials such as cemented tungsten carbides and ceramics. These materials are much harder than HSS, potentially resulting in longer tool life. However, they are also brittle and more expensive. They require large, heavy and rigid machinery to be effective. The choice is therefore dictated by the demands of the job and variables such as vibration, cutting forces, dimensional tolerances and surface finish requirements. High vibrational loads, cutting forces, and impact loading are likely to cause chipping or fracture of a brittle cemented carbide or ceramic cutting edge. HSS tooling can also be given a much sharper cutting edge than cemented carbide or ceramic tooling, allowing shallower depths of cut and tighter finished-part tolerances. Thus, each of these cutting tool materials has its proper place in the machining world, defined by the specifics of the individual job.

Summary

Molybdenum greatly enhances the performance of the tool steels that are essential in any kind of manufacturing industry. The tool steels discussed here represent about 7% of total molybdenum use. The cost and versatility of molybdenum-alloyed tool steels makes them effective competitors to tool materials such as tungsten carbides and ceramics. The high productivity and high recycle content of molybdenum-containing tooling portend that molybdenum will continue to play a major role in the shaping of manufactured parts. (Curtis Kovach)