

The Toolmakers: Part II

Modern society has evolved and progressed in no small part due to the availability of cutting tools made of high-speed steel.

Metallurgy Lane, authored by ASM life member **Charles R. Simcoe**, is a yearlong series dedicated to the early history of the U.S. metals and materials industries along with key milestones and developments.

A shortage of tungsten during World War I forced many high-speed steel users to fall back to carbon steel, a 50-year technology regression. After the war, a major research effort in high-speed steels at Watertown Arsenal, Mass., looked at substituting molybdenum—tungsten’s sister metal—in J.A. Mathews’ successful T-1 alloy. This work was done during the late 1920s and early 1930s, and substituted approximately 9.5% Mo for the 18% W in the T-1 alloy—a roughly 1:1 atomic replacement. Major accomplishments included using a borax coating during heat treating to protect the surface and incorporating molten salt baths to heat the steel during hardening. A significant drawback of all previous high-molybdenum tool steels was the excessive loss of surface carbon during heating.

It was widely known that large deposits of Mo were present in the Colorado Rocky Mountains. Within a few years, consumption rapidly increased partially due to the growing adoption of Mo in engineering alloy steels. With increased supply from the Climax Molybdenum Co., the price finally became competitive with tungsten for use in high-speed steel. Price alone, however, was not the main driver for replacing W with Mo: Technical acceptance in the industrial marketplace among tens of thousands of tool makers,

tool room foremen, and machinists was the final hurdle. The Watertown Arsenal work was interesting, and many applications were discovered for the new tungsten-free, molybdenum high-speed steel within various arsenals around the country. However, it never gained acceptance in industry as a T-1 competitor.

Major breakthrough

The first significant breakthrough regarding commercial development of Mo high-speed steels was discovered by Joseph V. Emmons at the Cleveland Twist Drill Co. In 1933, he received his patent and published a technical paper in which he briefly reported that all-molybdenum steels (tungsten-free) were inferior to T-1. Emmons also pointed out that substituting small amounts of Mo for some of the W was not worthwhile. His major discovery was that a Mo-W ratio of roughly 4:1, for a total of 10% of the steel, offered a critical composition that could compete against T-1’s 18% tungsten recipe. His paper, “Some Molybdenum High Speed Steels,” won the coveted Henry Marion Howe Medal in 1933, an annual award still presented by ASM International.

Cleveland Twist Drill significantly boosted the manufacture of Mo high-speed steel by ordering more than \$1,000,000 worth, based solely on confidence in Emmons and his 15-year quest for the best T-1 replacement. Many modern high-speed steel compositions still fall under various patents issued to Emmons.

Industrial practices, however, die hard and at the time of America’s entry into World War II, more than 80% of high-speed steels were still of the tungsten type. The War Production Board provided encouragement for the massive technological shift to molybdenum by denying the tool steel industry the tungsten it required to maintain production. Thus, Mo high-speed steels became the dominant type during World War II and beyond.



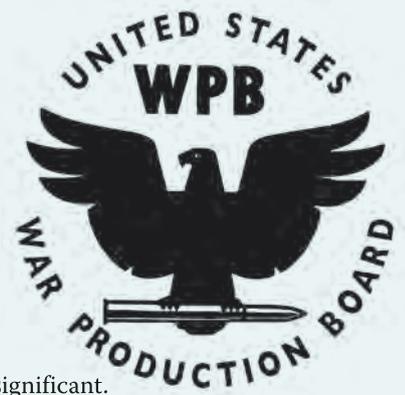
99.99% pure molybdenum crystal. Courtesy of Jurii/Wikimedia Commons.



99.98% pure tungsten rods with evaporated crystals, partially oxidized with colorful tarnish; high-purity tungsten cube for comparison. Courtesy of Alchemy-hp/Wikimedia Commons.



Beautiful bits from Cleveland Twist Drill Co., circa 1933, the first company to commit to Mo high-speed steel.



Scientific understanding progresses

Fast forward 40 years past Taylor and White's discovery of high-speed steel heat treatment, and 15 years since Bain and Jeffries published their theory of secondary hardening. While practical development of Mo high-speed steels steadily progressed during this time, little was done to develop a more fundamental understanding of the materials. A young metallurgy professor at Massachusetts Institute of Technology, Morris Cohen, set out to develop an understanding of the nature of high-speed steel tempering. Beginning in 1939, several studies were published by Cohen and a series of graduate students who wrote their doctoral theses on high-speed steel.

The first paper, by M. Cohen and P.K. Koh in 1939, set the tone for many that followed. They reviewed the literature on secondary hardening, which showed that most researchers believed the high-speed phenomenon was caused by transformation of residual austenite to martensite during tempering. A considerable amount of residual austenite was always seen in the microstructure of as-cooled high-speed steel, but it was replaced by martensite after tempering. Cohen and Koh studied changes in properties after heat treating at various temperatures and times. The variable of time at tempering temperature had never been examined adequately. In addition to x-ray diffraction of solid samples, they studied changes in electrical and magnetic properties, length, volume, and hardness. They concluded there were four stages to the reactions in high-speed steel during tempering:

1. Formation of iron carbide (Fe_3C)
2. Precipitation of carbide in retained austenite
3. Transformation of retained austenite to martensite
4. Precipitation of alloy carbides in martensite

Cohen and Koh's paper showed for the first time in American technical literature that retained austenite did not transform to martensite at the tempering temperature, but rather on cooling. Time spent at the tempering temperature conditioned residual austenite for its subsequent transformation. The basic conclusion was that stages two and three contributed the secondary hardening. This conclusion continued the conventional wisdom that somehow the transformation of retained austenite was the cause of secondary hardening, or *red hardness*, and that the eventual formation of alloy carbides upon long exposure to tem-

peratures of 1100°F or higher was insignificant.

During the next decade, Cohen and his students continued their research studies on steel. Some of the work pertained directly to high-speed steel, while other research applied more broadly to steels in general. The work on tempering of high-speed steel showed that little was understood about the tempering of all hardenable steels. Such a study was undertaken by Antia, Fletcher, and Cohen and reported in 1944. One of the last papers in the high-speed steel series, by Cohen and Blickwede, explored the effects of vanadium and carbon on 6% tungsten, 5% molybdenum high-speed steel. This new steel was becoming very popular in industry under the M-2 designation.

Walter Crafts and John Lamont of Union Carbide and Carbon Research Laboratories published another paper in 1948 of great importance to high-speed steel. They studied the effects of alloying elements on ordinary engineering steels, so they increased the amount of alloy until it approached the level found in tool steels. Secondary hardening peaks were found after tempering, even though these steels did not contain residual austenite from quenching. This work finally killed the retained austenite theory, stubbornly held since the days of H.C. Carpenter more than 40 years earlier. Tiny carbide particles were found forming at tempering temperatures corresponding to the high-speed steel hardening peak. These small carbides were found by x-ray refraction to be alloy carbides of Mo_2C , W_2C , or VC in various Mo, W, and V steels. This research supported the now 25-year-old theory of Bain and Jeffries, which stated that alloy carbides were the direct cause of secondary hardening in high-speed steels.

Hats off to the tool makers

It is now nearly 150 years since the first alloy tool steel was invented by Robert Mushet and more than a century since Taylor and White's discovery of specialized heat treatment. In this brief historical time, our modern technological society came into being in no small part due to the availability of advanced cutting tools made of high-speed steel. The early pioneers who contributed to these special steels will forever be known as the "tool makers."

During World War II, the War Production Board rationed commodities such as gasoline, metals, rubber, paper, and plastics, enabling the massive technological shift to molybdenum by denying the tool steel industry the tungsten it required to maintain production.



Morris Cohen was educated and served his career at MIT. He was awarded the ASM Gold Medal in 1968, the National Medal of Science presented by President Carter in 1976, and elected to the National Academy of Science, Engineering Division. Courtesy of MIT.

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