MOLYREVIEW

IMOA

INTERNATIONAL MOLYBDENUM ASSOCIATION

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The Helix, a complex duplex bridge

Photo: Financial Dynamics/Christopher Frederick Jones

The Helix, the new pedestrian bridge of Singapore's Marina Bay, was named for its resemblance to a DNA strand. It is an elegant, lightweight work of art. It is also a solid and corrosion-resistant structure, which brilliantly combines the use of advanced design tools and molybdenum-containing duplex stainless steel. Inaugurated in the summer of 2010, the Helix underscores the energy and vitality of this city-state.

With 5 million inhabitants concentrated over a surface area of barely 650 square kilometers, Singapore combines highly organized urban density with innovative and groundbreaking architecture. In addition to its strategic geographic location in the heart of the Malacca strait, it also serves an important role in Asia's economic and financial world. Singapore, known as the Switzerland of Asia, has become a top destination for tourists from all over the world.

In 2006, Singapore justified this flattering reputation by initiating a vast development program around Marina Bay, a lagoon located at the edge of the city-state's historic center, a highly popular area in recent years. The funnel at the bay's northern entrance, already crossed by an expressway, features a park with a floating stadium that hosted the Youth Olympics in August 2010. A few hundred meters away stands a replica of the London Eye ferris wheel, offering a breathtaking view of the marina!

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Molybdenum markets – an end-use analysis

Molybdenum is widely used around the world in many markets and product forms. The largest end-use market is the oil and gas industry and the largest product use is as an alloying element in Mo-alloy steels. The markets are well diversified in terms of both applications and maturity, assuring a continuing demand for molybdenum. Because molybdenum is used in many environmental and energy-related applications, its use should grow at a faster rate than the growth rate of the world economy.

That molybdenum is of great importance to the world is self-evident to those who have labored to mine, refine and provide Mo for many industries over the years. We know that demand comes from all directions and continues to grow from year to year. But how much will this demand grow in the future? In order to insure a ready supply of the metal it is important for the molybdenum industry to understand markets and their dynamics. The International Molybdenum Association, assisted by the Steel & Metals Market Research Company (SMR), Austria, recently completed a detailed analysis of molybdenum end uses to understand markets better. This article summarizes the results of that study.

The analysis was based on more than 100 face-to-face discussions and 150 telephone interviews with key Mo end users. End-use segments investigated were oil and gas, including refinery and refinery catalysts; power generation; chemical and petrochemical process industries, including chemical catalysts; automotive and other transport; building and construction; aerospace and defense; mechanical engineering; consumer goods, medical applications and electronics. The analysis brought forth some surprising information.

Total worldwide molybdenum use

In 2009, global Mo use in all applications amounted to 212,000 metric tons, which includes both new and recycled molybdenum. Most recycled Mo is introduced as scrap in steelmaking. In total, for all applications, approximately 15% of Mo input material originates from scrap.

Molybdenum is used in engineering steels (34%), stainless steels (26%), chemical products (13%), tool and high-speed steels (10%), cast iron (7%), superalloys (5%), and Mo metal (5%).

The largest material use categories are Mo-alloy steels (constructional engineering steels) and stainless steels. Combined, both categories' first-use Mo accounts for around 60% of Mo input worldwide. An enormous tonnage of steel in a multitude of different alloy steel types is behind the use of Mo in engineering steels. The steel tonnage is so large because these steels usually contain less than 1% Mo, often only 0.1 to 0.2%. The stainless steel tonnage is substantially less, but the amount of Mo still accounts for 26% of the total Mo usage. This is because Mo in stainless steel is mainly used in Type 316 stainless steels (2–2.5% Mo), duplex steels (usually 3% Mo), and to a smaller extent, ➔

Content

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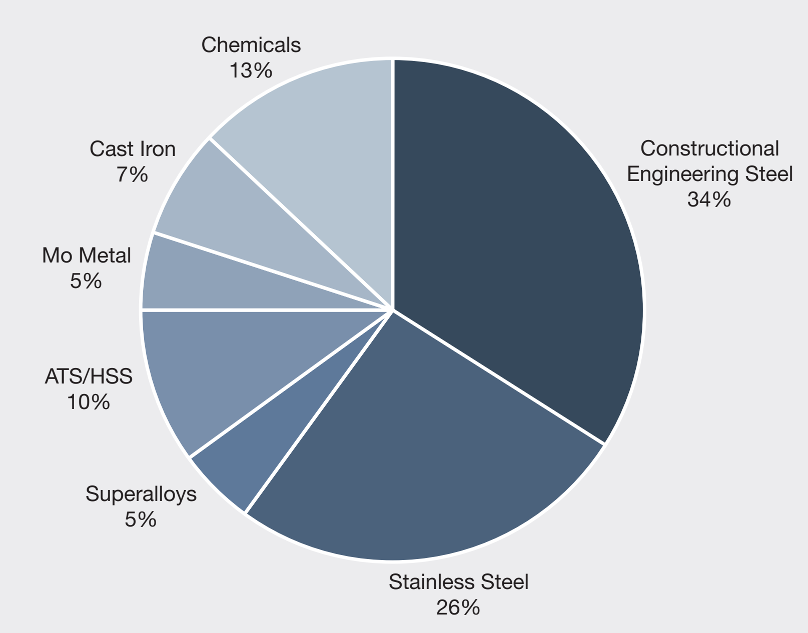
high-performance alloys (as much as 6% Mo). Between 25 and 30% of Mo used to make stainless steels is added in the form of recycled scrap. Therefore, only about 20% of newly mined Mo goes into stainless steel, compared to 26% of all Mo, new and recycled.



First use of Mo in the year 2009 (including Mo in scrap)

End-use markets

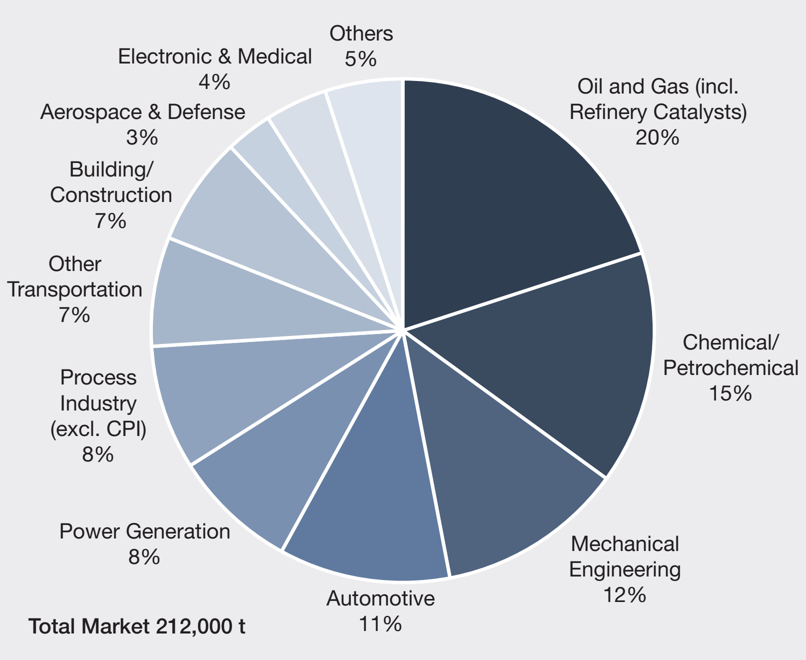
Oil and gas industry – The oil and gas industry, including refineries, dominates Mo end-use applications. This market segment used 43,340 metric tons of Mo in 2009, or 20% of the global Mo market. Applications here include refinery catalysts, downhole hardware and flow-control products, heat exchangers and gas pipelines. Well and gas transportation applications are the main market drivers and they will continue to grow in the near future as energy needs continue to grow. For instance, line pipes for natural gas pipeline projects have become a large business, particularly in China in recent years with the second West-to-East pipeline. Further growth in this segment will depend on crude oil prices, which look robust. Current high price levels are definitely a “stimulus package” for this segment and should have a positive impact on future Mo use. Refinery catalysts (used in fuel desulfurisation) are also growing as the increased efficiency (longer lifetime) is compensated by a higher Mo content and growing use as a result of stricter sulfur regulations especially in developing countries. A wide range of Mo-containing steels, stainless steels, and corrosion resistant nickel alloys are used in oil and gas production and refining applications. Aside from the general growth of this industry, rapid growth in Mo use is likely to occur because of increased use of highly corrosion-resistant materials as wells are drilled in deeper and more hostile environments.

Transportation industry – It is surprising that the transportation industry, with 18% of global Mo usage, is the second largest market. This segment includes passenger cars, heavy and off-road vehicles, ships and trains. Alloy engineering steels and tools steels are the major Mo-alloyed steel types found here. Typical applications in road transportation are car and truck engine parts such as crankshafts, piston rods, turbochargers, bellows, manifolds and power train parts including clutches and gear boxes – wherever high strength and toughness are important. Tool steels are used in cutting and forming tools and in plastic mold die steels for the auto industry. Mo stainless steel plays only a minor role in automotive applications. Shipbuilding is the second largest sub-segment of this market. Here Mo-alloy steels are used for propulsion systems, power trains, and rudderstock applications. Stainless steels are used in heat exchanger and tank components. A relatively new and growing application for Mo is in tank ships used to haul chemicals. These ships often employ huge tanks, large enough to hold an average size house, and are made from Type 316 or 2205 stainless steel. Mo stainless steels also find use in transport containers and road trailer tankers.

Chemical and petrochemical industry (CPI) – Chemical and petrochemical process equipment applications come in a close third in global Mo usage at 15%. This is no surprise, as this is the main segment for both austenitic and duplex stainless steels and corrosion-resistant nickelalloys having high Mo content. Some of these alloys contain up to 16% Mo! Typical CPI uses are tanks, distillation columns, tube and pipe (80% welded/20% seamless), flow control (valves, pumps), heat exchangers (tubing) and instrumentation tubing. In the developed countries, maintenance, replacement, and expansion of existing production lines are the dominant factors for Mo use. The construction of new chemical plants occurs only rarely in Europe and America.

In Brazil, Russia, India and China (the BRIC countries) and other emerging markets, new plant construction has been the main driver for Mo use over the last few years. However, during the recent economic downturn, investment in new plants has been relatively low everywhere. This has been true even for the emerging biotechnology, pharmaceutical, and life science product segments, where products such as vitamins and food additives are made. The market situation has started to improve since mid-2010, and the chemical industry has begun to invest again in new production facilities. A further increase in CPI activity is expected for 2012.

Mechanical engineering and heavy equipment – This diversified segment is particularly strong in Europe currently, and is regaining momentum in the USA. It is the fourth largest Mo segment at 12% of total Mo usage. ➔



End-use of Mo in 2009 (including Mo in Scrap)

The segment comprises Mo used in equipment for mining, heavy machinery, recycling, forging, rolling, bending, cutting, stamping and woodworking. Many metal-cutting tools are made of high-speed tool steels that retain their sharp cutting edges at the high temperatures, generated by high cutting speeds. These high-speed steels contain large amounts of Mo, sometimes as much as 10%.

Power generation – At 8% Mo usage, electric power generation is an interesting segment that could provide enormous Mo growth opportunities. However, projected use is uncertain. This is because many strongly opposing economic and environmental forces are at play and many new technology options exist within this arena. Electric power generation also includes Mo uses that partially compete with one another. Mo can be found in materials for traditional coal-fired, nuclear and oil or gas-fired plants, and in newer biomass and waste-to-energy equipment. Mo will also be found in equipment used for the emerging alternative energy sources such as tidal, wind, solar and geothermal.

It would take a wizard to sort out and predict which energy options will dominate and how much Mo will be required in the future. For example, the future acceptance of new coal-fired plants is linked to the reduction of CO_2 emissions. To reduce CO_2 it will be necessary to improve the efficiency of the next generation of coal-fired plants substantially. This will require working temperatures approaching 640°C in the so-called "supercritical" plants. This development could support the use of Mo-containing nickel alloys for the high-temperature boiler parts. However, it still will take at least 5–10 years before such new plants might start to generate energy commercially, if indeed they ever do come into widespread service. Even so, the plants will still produce some CO_2 and other air pollutants. Nuclear energy is a CO_2-free baseload alternative to coal-fired plants. The latest designs have introduced Mo-containing stainless steel for reactor containment vessels. However, the tragic events in Japan have already dampened the recent enthusiasm for the nuclear option in several countries. At the same time, the incident could help promote nuclear energy, since an accident like the one in Fukushima is virtually impossible in plants using one of the new "passive-safe" designs. One of these is the Areva design which features a so-called "core catcher" that uses molybdenum alloy steels.

Of the various options, wind energy is expected to grow at the fastest rate, but it is starting from a very low base. Wind plants are not without their problems, including the need for improved trouble-free operation. New steel grades with higher Mo content are being developed for this application. The goal is to provide longer maintenance-free operation at increasing windmill sizes of 6 MW or more. These new alloy steels are intended for use in the gears, transmission shafts and structural rings of these very large machines. One thing certain is that Mo usage should grow at least in step with the anticipated global growth of electric energy consumption.

Process industry (excluding CPI) – The process industry, excluding chemical processing, accounts for approximately 8% of Mo consumption. Major subsegments are metal and steel production, food processing, glassmaking, textile manufacturing, pulp and paper production, and desalination. Mo-containing stainless steels are important here. For example, food processing relies extensively on equipment made from Type 316 stainless steel. The textile and paper industries use equipment made with Type 316 and duplex stainless steel, and high-performance austenitics where Mo contents reach 6%. The last decade has seen the introduction of all major Mo-containing duplex stainless steel grades in membrane and thermal separation desalination plants. Major plant types are reverse osmosis, multi-stage flash and multi-effect distillation. Major desalination projects have been completed in the United Arab Emirates, Bahrain, and Algeria. After two years of sluggish activity, the market situation in the process industry started to improve in 2010, leading to optimism for strong market growth in 2011/12.

Architecture, building, and construction – This is a "mixed bag" of applications including construction of buildings, roads, bridges, and related equipment ranging from heating furnaces to swimming pools. This market accounts for about 8% of total Mo consumption. Most of the Mo used in the segment is found in stainless steels where Type 316 predominates, but newer Mo-containing duplex and ferritic grades are seeing increased use. Stainless steels find application in structural and ornamental tubes, ➔

masonry wall ties, anchors, reinforcing bars, bridge support parts, tunneling equipment, swimming pool equipment, drinking water pipes and fittings, façade and interior cladding, elevators, wire mesh, extrusions, street furniture (benches, lampposts, handrails) and domestic and industrial chimney linings. Mo-containing ferritics are growing in importance as materials for water tubes and pipes. For cost reasons, the Ni-free ferritic stainless steel 444 is replacing austenitic Type 316 in these applications. The two steels have the same Mo content, so the use of 444 has no consequence for Mo usage. The ferritic steels are more cost-competitive and less sensitive to price volatility than austenitic steels, a fact that helps Mo-containing ferritics to gain market share against alternatives like plastics, coated carbon steels, and aluminum.

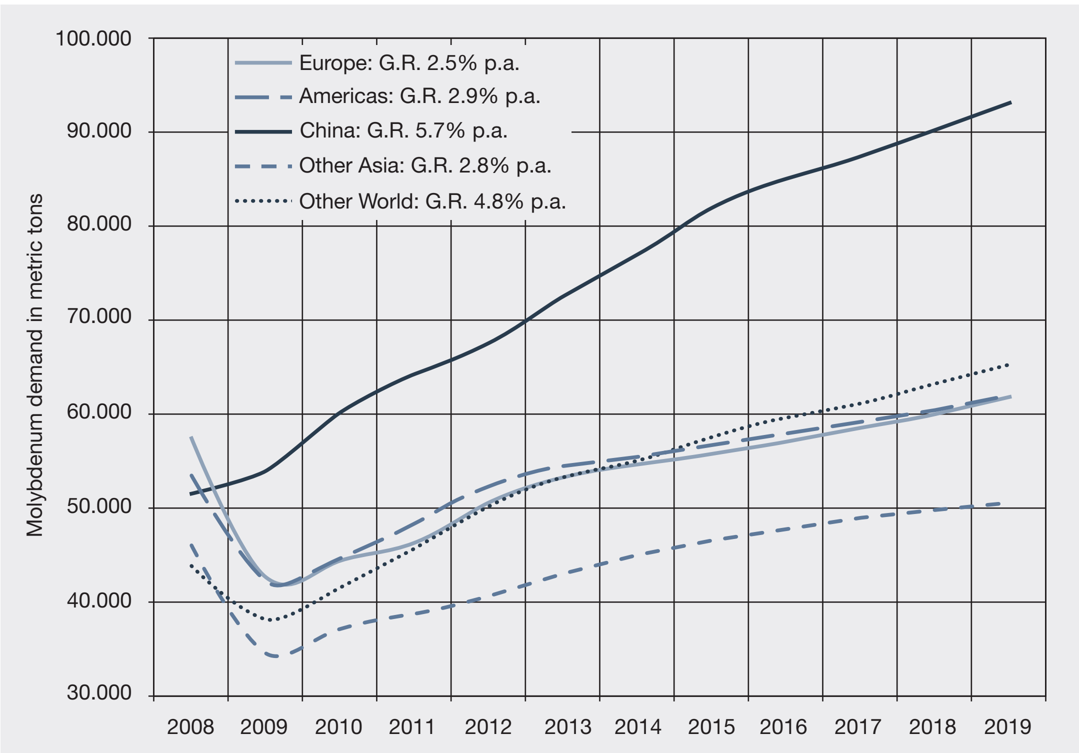
Aerospace and defense – Wrought and cast Mo-containing materials are used in aerospace applications, including nickel-base superalloy jet engine components, landing gears, fasteners, and airframes. For defense purposes, diverse military specification engineering steels such as 17 CrNiMo 7-6 and Armox™ 560T (0.4–0.5% Mo) are applied. This segment accounts for about 3% of total Mo consumption.

Consumer goods, medical and electronics applications – This segment is relatively small in terms of overall usage. It is unique in that Mo is usually used in its elemental form, Mo metal.The segment is also something special because it often comes closest to affecting our everyday lives. Some examples are the manufacture of large flat TV screens, lighting equipment, semiconductors, and in medical X-ray targets and tubes. This segment uses about 3% of all Mo consumed.

Conclusion

In summary, we can say that molybdenum usage has a well-balanced end-use structure distributed between capital goods (approximately 75%) and consumer products (25%). Its use is well positioned relative to industry maturity among late, mid- and early cyclic industries, which will help to ensure sustainable future growth. Applications in high-growth industry segments like renewable energy (wind turbine gears and shafts), transportation (turbo-charged engines, lightweight chassis and lighter power trains) or building and construction (stainless steel rebar and swimming poolliners) will ensure that molybdenum will outperform other metals with anticipated growth rates above global GDP growth.

IMOA forecasts that Mo consumption will grow at a worldwide rate of 4.5% per year to the year 2020. China, India and some other markets will grow at above average rates. Europe, the Americas and some other Asian markets will most likely climb only in a range of 2–3% per year on average over the same period. Overall, the Mo market will grow by around 100,000 metric tons, or 50% of present use, within the next 10 years. This solid growth will provide the strong basis for a successful molybdenum industry in the coming years. (mm)



Forecast of Mo demand by region around the world

Continued from page 1

The Helix, a complex duplex bridge

To the south is an imposing cultural and hotel complex of undeniable beauty and structural innovation. Projecting out into the bay, the Art & Science Museum rests on the water like an open lotus. Just behind it stands the audacious tripod of the Marina Bay Sands Hotel: three towers connected at their 200-meter summit by a 1.3-hectare park that is longer than the height of the Eiffel Tower and includes a 146-meter long infinity pool!

Overlooking Marina Bay, the lotus-shaped Art & Science Museum and the stunning three-legged Marina Sands Hotel. Photo: MBS-Newhome

The last link of a prestigious "Green Loop"

The entire edge of the bay has been developed as a 3.5-kilometer "green loop" trail enabling pedestrians to admire the architecture that illustrates Singapore's dynamism. To close the loop of this prestigious promenade, the Urban Redevelopment Authority (URA) of Singapore launched an international competition in 2006 for the design and construction of a pedestrian and vehicular link to connect both sides of the bay's entrance. A consortium composed of Australian and Singaporean architects and an international engineering firm developed the winning project. Their design showed great aesthetic and technical originality. A true architectural success, The Helix brilliantly concludes the development of Marina Bay.

The stroke of genius

The architects chose to reserve one bridge for vehicular traffic, thereby simplifying its design and allowing a greater budget for the pedestrian portion. This enabled the pedestrian bridge to become the technical work of art we see today. Its structure and name, The Helix, are inspired by the spiral shape of a DNA strand, perfectly in line with Singapore's idea of its destiny: "life and continuity, rebirth and growth".

Because a single helix would not have been rigid enough, the designers' stroke of genius was to employ a double helix, with one nestled inside the other. The outer helix spirals clockwise, and the narrower inner helix spirals in the opposite direction. The two helices are connected by a hoop frame that reinforces them, making the structure perfectly stiff and creating an inner corridor for pedestrians. The designers had incredible vision to create such an elegant structure, but 3D software proved indispensable in bringing the intricate and complex design to life. In building the bridge, stainless steel was a logical choice from the outset. Aside from the purely mechanical aspects involved, the climatic conditions of Singapore heavily influenced the designers' choice of metals. The bridge would need to withstand the humid, tropical, and heavily salt-laden atmosphere of Singapore, as well as meet the design requirement of a 100-year minimum lifespan. Stainless steel enabled the designers to achieve these goals.

The Helix: choosing a high-performance steel

The choice of stainless steel was a key element of the project in light of the financial and mechanical constraints, as well as the manufacturing and maintenance specifications. The designers excluded painted steel as an option when it became apparent that the structure would be composed of a great number of individual components. The bridge's large metal surfaces and the many connecting and fastening points would all be exposed to the elements, and thus vulnerable to corrosion.

Although some stainless steel bridge projects use austenitic steels, engineers are increasingly using duplex stainless steels which offer a combination of very high corrosion resistance and mechanical properties. Engineers for The Helix continued this trend by specifying 2205 duplex stainless steel which they had used previously in the region on the Stonecutters Bridge in Hong Kong. Duplex 2205 is a two-phase alloy combining the qualities of ferritic and austenitic stainless steels.

The chemical composition of 2205 ensures a balanced microstructure that provides improved mechanical properties compared to single phase austenitic steels. The high chromium content and, most importantly, the molybdenum addition ensure high corrosion resistance, eliminating the risk of tea-staining and pitting that can occur on less highly alloyed stainless steels in humid, marine environments. →

Specifications and nominal composition of Duplex 2205

International steel N°		Chemical composition, % by weight, typical values					
EN	UNS	C	N	Cr	Ni	Mo	Others
1.4462	S32205, S31803	0.02	0.17	22	5.7	3.1	–

Chosen for its resistance to corrosion in a tropical environment, duplex stainless steel with molybdenum allows the design of a structure to be as aesthetic as it is robust. Photo: Financial Dynamics/ Christopher Frederick Jones

The duplex alloy also reduces future maintenance costs which are limited to periodic cleaning of the structure. Thus, in building The Helix, 2205 duplex stainless steel was superior to austenitic and ferritic stainless steels. All these qualities are a direct result of the molybdenum present in the grade and played an essential role in the design team's material decision.

An economical design through duplex

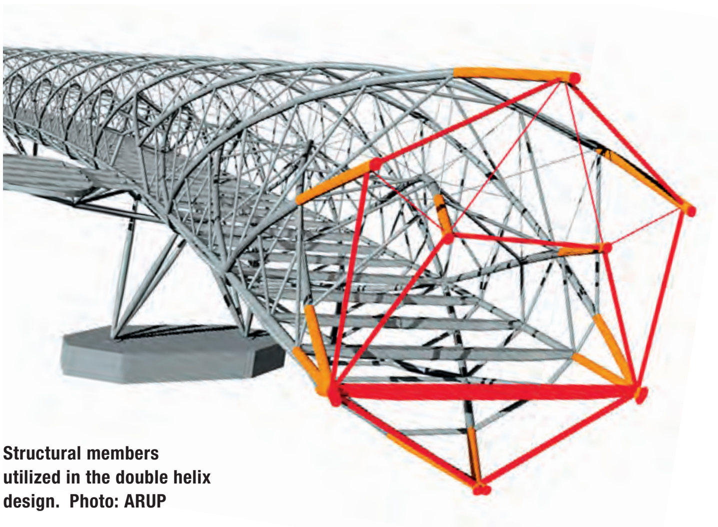
Duplex 2205 provided a distinct design benefit due to its high strength. Superior mechanical strength, particularly in large spans where weight is critical, is necessary in structures like The Helix. The bridge weighs roughly 1,700 tons (equivalent to about 1,130 vehicles), but was designed to support itself, needing no supporting beams or cables. The 3D software allowed the designers to fully use the high strength of 2205 to optimize the structure's design and reduce the number of metal components.

The structure consists of a 10.8-meter diameter outside helix and a 9.4-meter diameter inside helix. The outer helix is composed of a twisted strand of 6 tubes, while the inner uses only 5 tubes. The latter is offset vertically downwards in relation to the former, enabling them to cross at the pedestrian deck every 2.75 meters. Hoop frames composed of compression struts and tension rods interconnect them, ensuring the necessary stiffness. The stress calculations and the 3D design software ensured that the tubes of the two helices could have the same outer diameter of 273 millimeters (a major aesthetic criterion) without adversely affecting the functional specifications. The tubes' wall thickness varies only according to their location in the structure and the loads they support.

The 3D software allowed the designers to use only two bar sections for the two helices: a straight section and a slightly curved one, which minimized fabrication and erection costs. Moreover, the structure supports all ancillary equipment like the pedestrian deck, rain shields, and the impressive lighting system, without having to add further components. Simply put, the qualities of 2205 duplex stainless steel and computer-aided design engineering simplified and streamlined the design. This smart design process enabled The Helix to use one-fifth the steel of a conventional box girder bridge of the same length, cutting down on material, construction, and maintenance costs.

Rigorous manufacturing and assembly requirements

The choice of 2205 also provided benefits in terms of component manufacturing and assembly. The Helix was manufactured in several segments due to restrictions on the type of trailer used and Singapore's traffic laws. A special off-site workshop was built to machine and assemble the segments. As many welds as possible were performed in this workshop to avoid contaminating the duplex with carbon steel likely to rust and stain the structure. Welding temperatures were strictly controlled to avoid modifying the phase balance of the duplex stainless steel, and to control its tendency to warp when heated, which could have affected the profile of the curved tubes. The tubes forming the two helices were butt welded while the struts and tension rods were securely bolted in place. These fabrication and assembly precautions guaranteed the integrity of the joints and assemblies. ➔



Structural members utilized in the double helix design. Photo: ARUP

Beneath the stainless steel curves, pedestrians are protected from the sun and tropical rain by shade canopies. Photo: Financial Dynamics/ Christopher Frederick Jones

The new bridge can withstand the weight of 16,000 people. The behavior of the structure was tested to resist vibration phenomena caused by a large number of people moving at the same time, such as during marathons or parades. The walkway rises to 8.80 meters above the water between the piles, high enough to allow maritime traffic to pass between Marina Bay and the channel connecting it to the sea.

A masterpiece of elegance and lightness

The Helix's elegance comes from the outline of its curve and the originality of its reverse helices. The structure begins with a slow grade, where 12-meter long concrete ramps join the metal structure to each bank, and then curves slightly on the horizontal plane so the walkway runs alongside the vehicular bridge. The 280-meter spiral bridge consists of three central 66-meter spans and two 41-meter approach spans. The connections between spans rest on four concrete piles, each supporting a pair of inverted 2205 duplex stainless steel tripods. The 6-meter wide deck rests on 9-meter beams that connect each side of the double helix. Four elliptical viewing pods, positioned inside the curve of the bridge facing the spectacular view of Marina Bay, are cantilevered over the length of the span. The grace of The Helix is felt immediately due to the balance between the winding of the helices. The outer helix makes four complete turns while the inner helix makes five.

Adding to Singapore's skyline

Pedestrians are protected from the sun and tropical rains by a fine metal mesh and tinted glass canopy suspended between the upper hoops of the smaller helix. These also contribute to the bridge's gorgeous night-time appearance, enhanced by the lighting system whose integration and effects were taken into consideration during the design stage.

The finish of the stainless steel surface is particularly well suited to enhance the effects of the lighting arranged along the metal volutes of the inner helix and embedded in openings in the structural tubes. The metal components were beadblasted and polished with olivine (a magnesium silicate) to optimize the reflection of new-technology light emitting diode (LED) lights. They were also passivated to remove any trace of oxidation (discoloration) formed during welding and machining, and to form a protective passive film over their surfaces. Spotlights incorporated in the hoops of the outer helix illuminate the metal mesh sun screen and glass panels, causing them to glow at night. Finally, a series of lamps turned outward from the structure emphasizes the finesse and lightness of the curved helix. The lighting is programmed to vary in intensity and color to match the bridge's luminous ambience according to the occasion. The Helix not only serves as a remarkable engineering achievement and a unique pedestrian experience, it also adds to the majesty and natural beauty of Marina Bay and downtown Singapore. (tp)

At the foot of the Marina Sands Hotel, The Helix offers the variety of its luminous ambiences. Photo: Kak Wai Lin

The discovery of molybdenum

What scientific discovery is most important to the molybdenum industry? The discovery of molybdenum of course! Prior to the mid-eighteenth century no one knew that molybdenum existed. The element was discovered using simple tools one would find in a school chemistry laboratory. These tools – which included perseverance and hard work – are still effective in today's high-tech world.

The idea of the lone genius is a classic myth – the single brilliant person, slaving away for years, who finally reaches that "Eureka" moment. This certainly happens from time to time, but it is an unusual occurrence. Typically, technology and science advance in a slow, step-by-step process involving the collaboration and efforts of many people. As physicist Isaac Newton famously said, "If I have seen a little further, it is only because I stood on the shoulders of giants." His words ring especially true when considering the discovery of molybdenum. It took almost 150 years, many chemists and many small steps to identify and isolate molybdenum as a pure metal. This metallic element, number 42 on the periodic table, is now vital to our modern world.

Molybdenum trioxide powder is used today by steel companies when adding molybdenum to stainless and alloy steels in the melt shop. Photo: Molymet

In the beginning

The story of molybdenum's discovery begins with numerous mistakes. Molybdenum is extracted from molybdenite, a metallic grey mineral once mistaken for galena, a lead compound. After molybdenite was determined not to be galena, it was often mistaken for and even used like graphite as a lubricant (graphite is also commonly found in pencils). In 1751, the Swedish chemist Bengt Andersson Quist proved not only that molybdenite was different from galena, but also that it contained an entirely different substance from those already known.

The German chemist Carl Wilhelm Scheele continued Quist's research. Scheele was remarkably accomplished, having discovered many other elements including oxygen, hydrogen, chlorine, and barium. Unfortunately, other scientists often wrongly received credit for many of his important achievements. This happened so frequently that the biochemist and popular science-fiction writer Isaac Asimov gave him the nickname of "hard-luck Scheele." However, based on the publication dates of his books, we now know Scheele to be the true force behind these remarkable achievements.

Perseverance and hard work

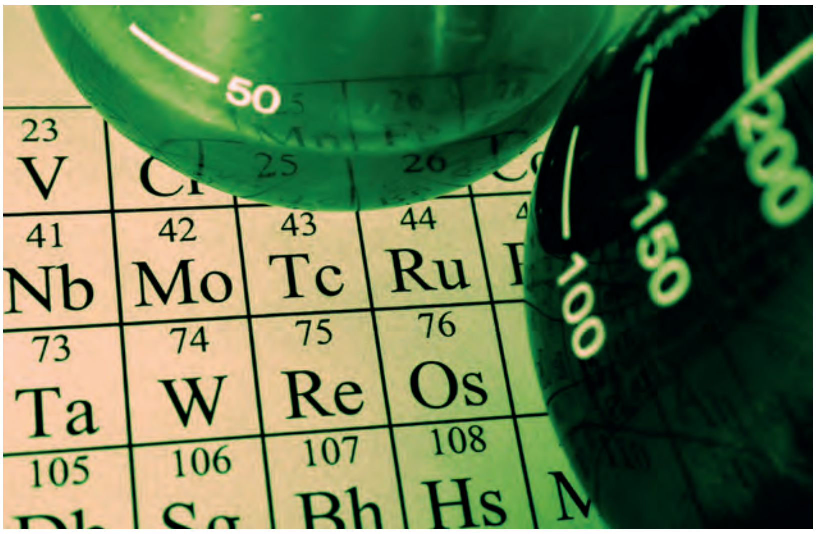
Scheele's role in the discovery of molybdenum was that of identification. His experiments tested how minerals reacted with nitric acid. His results led him to the same conclusion as Quist, that molybdenite was very different from Galena. However, Scheele went farther. When he heated nitric acid with molybdenite and with graphite, he found that the reaction with graphite produced carbon dioxide (CO_2), while the reaction with molybdenite produced a "white earth", now known as molybdic acid. The difference in reaction products convinced Scheele that molybdenite was neither graphite nor lead, but instead a mineral containing an entirely new element, which he named molybdenum, after the Greek "molybdos" (lead-like).

Success

Scheele's discovery was very important, but he was unable to produce pure molybdenum. The closest he came, was to make a different molecular form called molybdenum trioxide (MoO_3). The Swedish chemist Peter Jacob Hjelm, Scheele's close friend and colleague, isolated pure molybdenum a few years later. Hjelm succeeded by heating Scheele's molybdenum trioxide with carbon. The carbon reduced the oxide to the elemental form of molybdenum, producing carbon dioxide in the process. Hjelm conducted his experiment in 1781 but his findings were not officially published until 1891. During the intervening 110 years many other chemists performed similar experiments. Nevertheless, we credit Hjelm with first isolating elemental molybdenum because there is strong evidence of his results in the many letters he sent to fellow chemists describing his research.

Carl Wilhelm Scheele

Hjelm's molybdenum metal found few industrial applications at first. Although it was very hard, it was too brittle for widespread use. The American William D. Coolidge, working for General Electric, solved the problem in 1906 when he discovered a way to make molybdenum more ductile, or stretchable. Dr. Coolidge developed the x-ray tube and is best known for his work to find an improved filament for incandescent light bulbs, leading to a way to produce ductile tungsten. Early uses of molybdenum metal were as filament supports in light bulbs and in vacuum tubes, undoubtedly applications attributable to Dr. Coolidge. ➔



Molybdenum in the Periodic Table.
Photo: istockphoto/hidesy

Today
The twentieth century brought dramatic discoveries in metallurgy, chemistry, and physics that identified uses for molybdenum in a vast array of applications. Today, molybdenum and its compounds are used in steels, stainless steels and other alloys as well as a number of chemicals. These materials find countless industrial and consumer applications, including armor plating, pipelines, antifreeze, architectural shapes, chemical process tanks, electronic and medical devices, fertilizer, submarines, cars, solar panels, turbines and spaceships to name but a few. We would have none of these benefits without the dedicated efforts of the many chemists who slowly paved the way toward molybdenum's discovery. (dk)

Mo-alloy steels – metallurgy and properties

Articles on molybdenum alloy steels frequently appear in MolyReview – with good reason these steels constitute the largest single use of molybdenum. Most of these articles discuss applications and make only passing reference to the properties that make the steels so useful. The purpose of this article is to give an understanding of what sets molybdenum steels apart from other steels. They stand out because molybdenum favorably affects metallurgical reactions that take place during heat treatment. These metallurgical reactions produce steel with high strength and simultaneously good ductility and toughness. No other alloying element accomplishes this more effectively than molybdenum.

Molybdenum alloy steels began their commercial use with the automobile. As automobiles increased in importance early in the 20th century, car speeds increased, and dependability and safety became ever more important. The steels used to build automobiles had to be stronger, and the existing plain carbon steels used to make them were inadequate to the task. The first molybdenum automotive steels were based on the Krupp armor steel used to protect ships in World War I. This steel contained 0.25% carbon, 3.25% nickel, and 1.50% chromium.

The family of Mo-alloy steels
Molybdenum was introduced to these steels as an alloying element in the period between the two great wars. The introduction was based on the discovery that Mo has a very pronounced beneficial metallurgical effect. Many Mo-alloy steels, containing Mo in the range of 0.1 to 0.4%, were developed during this period. These steels, which are to this day very popular, were classified and standardized for use by the American Society of Automotive Engineers (SAE) – a testament to their high value in automobile production.

Various "families" of Mo-alloy steels have been defined based on their chemical composition; the accompanying table shows their composition ranges.

Molybdenum alloy steel families – alloy composition range (wt. percent)

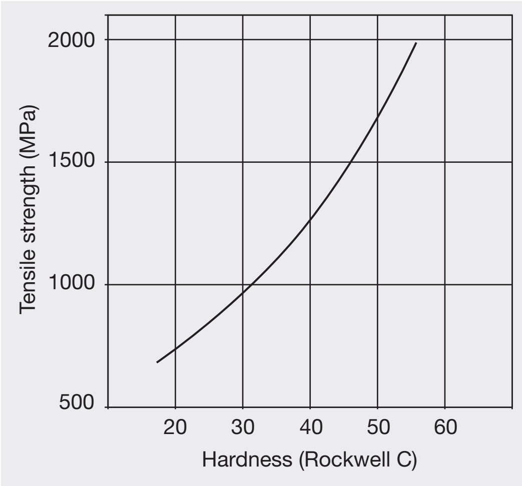
Alloy Steel Family	Cr	Ni	Mo
Molybdenum	–	–	0.20–0.52
Chromium-molybdenum	0.50–0.95	–	0.12–0.30
Nickel-molybdenum	–	0.85–3.50	0.20–0.25
Nickel-chromium-molybdenum	0.50–0.80	0.30–3.25	0.20–0.35

The most popular Mo steel is SAE 4340, which typically contains 0.25% Mo. It is also known as 40NiCrMo6, UNS G43400 and EN 34CrNiMo6. It is the "workhorse" of all alloy steels, and is the standard to which other similar steels are compared. SAE 4340 has a winning combination of mechanical properties created by its chemical composition and the effect of heat treatment (hardening and tempering) applied during manufacture. ➔

Metallurgy and hardenability

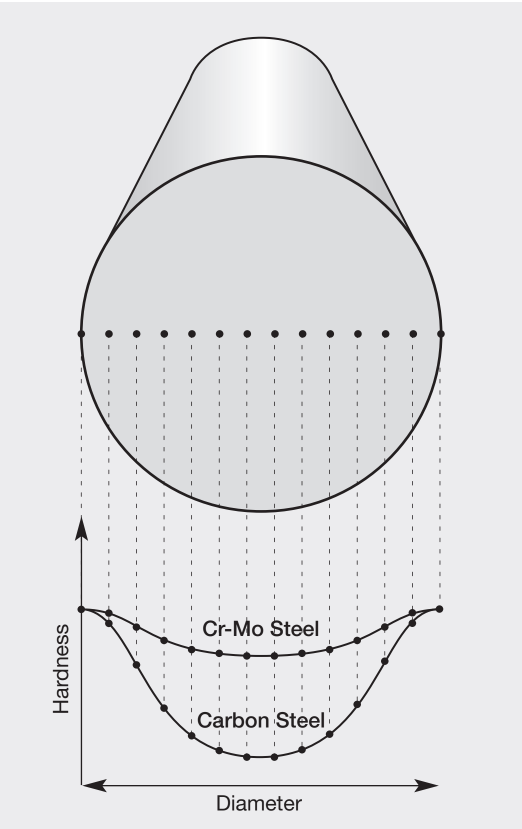
Steels are normally hardened (strengthened) by rapidly cooling (quenching) them from a high temperature (800° to 870°C for SAE 4340). This article will consider the terms "hardness" and "strength" to be interchangeable as illustrated in the figure on the right. The ability of steel to harden throughout a thick cross section is termed "hardenability." A plain carbon steel bar cannot be hardened evenly throughout a thick section. Its hardness drops from the surface to the centre. Thus carbon steel is said to have low "hardenability". Conversely a molybdenum-alloyed steel bar will exhibit much more uniform hardness through the cross-section with the same heat treatment and can be said to possess "high hardenability". This is one great advantage of Mo steels.

The hardness profile across the thickness of a steel component relates to metallurgical reactions that occur during quenching. The as-quenched hardness depends on the amount of a hard, strong metallurgical structure called "martensite" that forms during the quench. In Mo-alloy steels, the quenching process produces nearly 100% martensite, even in section sizes up to about 100 mm. In many low-alloy steels a soft, low-strength "pearlite" metallurgical structure forms in the center of thick sections.



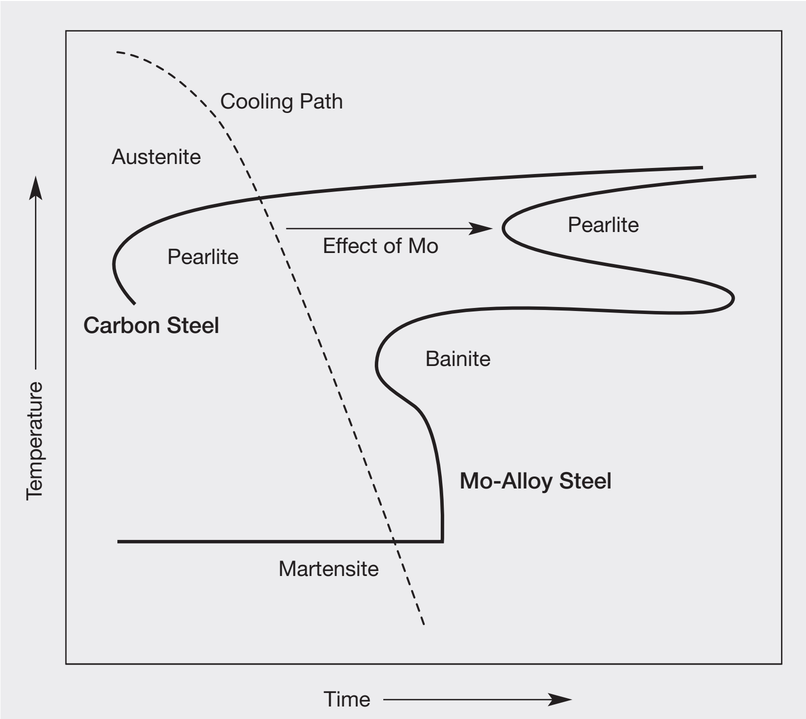
Hardness and tensile strength are directly correlated.

Heavy construction equipment makes extensive use of Mo-alloy steels. Photo: istockphoto.com/ Birkholz



The cut surface of a bar with hardness measurement indentations across the diameter. Molybdenum helps produce uniform hardness throughout the thickness of a bar.

The relationship between section size (which controls the cooling rate at the center of the section) and metallurgical structure can be illustrated by a so-called "transformation diagram," which is a plot of temperature versus time, with various resulting metallurgical structures superimposed upon the plot. By tracing a cooling curve on the diagram one can determine the structures produced on cooling. The transformation diagram on page 12 illustrates how cooling a thick section from high temperature (where the alloy exists in a form called "austenite") produces soft pearlite in carbon steel, and hard, strong martensite in a Mo-alloy steel. In other words, molybdenum in a Mo-alloy steel delays the transformation from austenite to pearlite so that martensite forms instead. ➔



Transformation diagram showing that Mo delays the transformation to soft pearlite so much that upon cooling Mo steel will form martensite.

Tempering versus strength and other properties
The hard martensite produced by quenching is too brittle to be used "as is" for most applications. This brittleness can be reduced by a subsequent "tempering" step. Tempering consists of heating the steel at temperatures in the range of 230°C to 650°C for several hours, which lowers the hardness and strength slightly but greatly improves ductility and toughness, factors more important than hardness itself.

If the application requires a section size larger than 100 mm, Mo steels are still very useful. In sections up to 250 mm a "bainitic" metallurgical microstructure forms upon quenching in preference to the pearlite that would occur in other steels (the cooling path in the transformation diagram drops less steeply because the thicker steel cools more slowly and therefore goes through the Bainite "nose"). Bainitic structures have uniform hardness across these thick sections, and have moderately high hardness and strength after tempering. This ability to form bainite is another factor that separates the Mo steels from other strong steels, allowing attractive combinations of strength, hardness, toughness, and fatigue resistance in thick sections.

Molybdenum also makes steel much more resistant to becoming brittle during high-temperature tempering, a phenomenon called "temper embrittlement". It occurs in many steels upon tempering in the range of 450°C to 560°C. It is due to the movement and concentration of phosphorous and sulfur within the steel during tempering. Molybdenum hinders this movement and therefore helps in avoiding the drop in toughness.

Improvement with modern steel making technologies
Anything can be improved, even SAE 4340. One early example occurred in the aircraft industry of the 1940s when more stringent quality requirements were imposed. To meet the need, producers adopted electric-arc furnace melting to produce "aircraft-quality" SAE 4340 having greatly reduced concentrations of sulfur and phosphorus – elements that can render a steel brittle.

The rapid advance of steel technology during the mid-twentieth century (1950 to 1970) made available an increasing number of steels having higher and higher strengths. The SAE 4340 composition has been used as a model to develop improved steels for heavy-section applications. As section-size requirements increased, more nickel and molybdenum were added to increase hardenability. In some cases, the carbon content was reduced to 0.30% to increase toughness and improve weldability. For example, 300M is a vacuum-melted low-alloy steel having very high strength; it is essentially SAE 4340 with higher silicon and vanadium content, and slightly more carbon and molybdenum. It combines a tensile strength of 2,000–2,070 MPa with excellent toughness, fatigue strength, and ductility. 300M can be through-hardened in cross-sections up to 115 mm, and is used in aircraft landing gears, high-strength bolts, and airframe parts.

In the past fifty years, the emphasis in melting technology has been on reducing non-metallic inclusions, elemental impurities, and the number and severity of surface and internal defects in mill products. Today, processes like vacuum degassing, electro-slag melting, vacuum-arc remelting, and vacuum induction melting are used for this purpose. They reduce the amount of oxygen, sulfur and phosphorous in the alloy, thereby reducing the amount of non-metallic inclusions and improving microstructure. These technological advancements have further improved the performance of alloys like 300M.

The gold standard
Designers and engineers who build high-performance machines still consider SAE 4340 the gold standard of alloy steels. The other members of this family of steels are also held in high regard. Their key applications may often go unnoticed, hidden beneath the hoods of cars, in the belly of airplanes or ships, or in many other useful machines. However, they are without doubt the parts we count on the most, not only to keep us moving but to keep us safe as well. (rw)

Moly drills through mountains in mega-moles

An early lesson in life is that the shortest way between two points is a straight line. Unfortunately, when it comes to building roads, railroads, metro-lines and pipelines, the straight-line route is often blocked. Obstacles can be overcome by going underground via a tunnel to set things straight! For this, the large "tunnel boring machine" or "TBM" is a marvel of engineering ingenuity. These machines drill holes through earth and rock, through mountains and beneath rivers – wherever large diameter bores are required. The tunnels carry trains or cars or large amounts of water. Important features for the performance of TBMs are the wear plates made of moly-alloyed steels to resist the abrasive action of hard rock.

Tunnel drilling takes place every day all around the world. You may not be aware of nearby projects because they are happening out of sight. This article will shed some light on the efforts and equipment involved and on molybdenum's important role in tunnel boring technology.

The citizens of Switzerland, and maybe some of the rest of us, remember a great debate that took place over twenty years ago. Should we spend 7.2 billion Euros – almost 935 Euros for every resident – for a 57-km tunnel through the Alps to enable high-speed rail service to Italy? Probably forgotten by most in the interim, the "Gotthard Base Tunnel" recently made global headline news as the second of two "mega-tunnel" bores was completed. It is the longest transit tunnel in the world, exceeding the Seiken tunnel in Japan by over 3 km.

The need

Why build such a large and expensive tunnel? Certainly not simply to impress the world. The tunnel is justified by its economics and the convenience it will deliver when it begins to operate in 2017. The route from Germany to Italy will be shortened by 40 km and greatly flattened. This will allow longer trains to carry loads up to 4,000 tons, more than twice the loads of today's trains. Freight train speeds of 160 km/h will also be twice those of today's trains. Passenger trains will pass through the Alps at 250 km/h, shortening the trip from Zurich to Milan by a full hour. These changes improve convenience and lessen environmental impact. One measure of these improvements is the anticipated 50% reduction in the 1.2 million trucks that now thunder through the Alps on roads each year.

Getting started

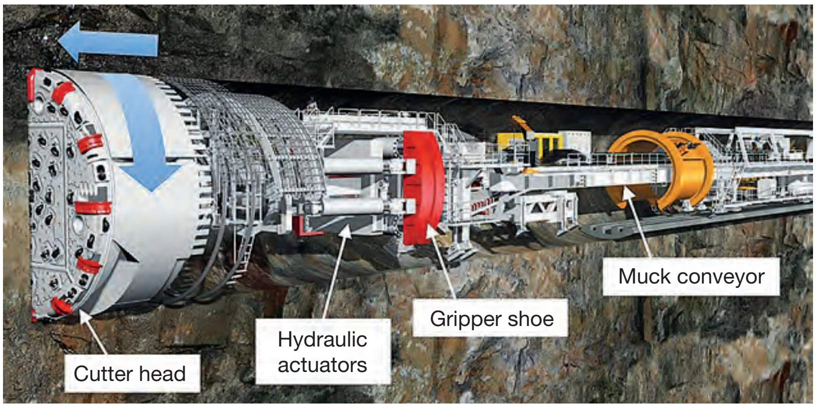
When planning a hole or tunnel the most important question is "what diameter bore is required?" Small diameter holes are made by various kinds of drills. In the old days, large-diameter tunnels were bored by hundreds or thousands of laborers digging and blasting their way through. Nowadays the work is done by a gigantic TBM. These machines can bore through all types of soil and rock at rates far exceeding those of drill-and-blast operations, at lower cost and with improved safety.

Planning and preparation work for the Gotthard Base Tunnel began in 1993. The construction of access tunnels and assembly caverns, to provide sites for assembly and launching of the large TBMs, was done by conventional methods using heavy equipment and blasting. Four nearly identical TBMs began boring the two tunnels in 2003, starting in parallel from the north and south ends of the planned tunnels. Most of the 57-km distance was bored through rock, with only a short center section being blasted.

The machine

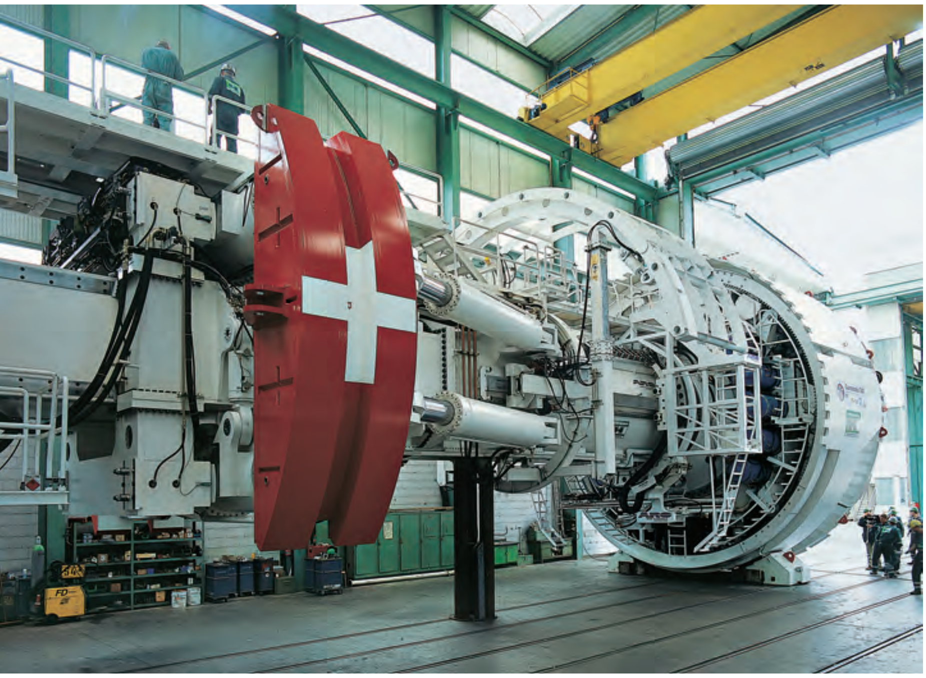
A TBM can be visualized as a giant steel mole eating its way through hard rock. The machines are never seen in their entirety; they are so large, their individual parts (90,000 in the case of the Gotthard tunnel) must be assembled in place at the bore mouth.

The first unsuccessful attempt at building a large-tunnel boring machine was Henri-Joseph Maus's Mountain Slicer, intended to dig the Fréjus Rail Tunnel between France and Italy in 1846. It consisted of more than a hundred percussion drills mounted in front of a locomotive-sized machine. It took many more tries and over 100 years for the first functioning TBM to be developed by James Robbins in the 1950s in the USA.



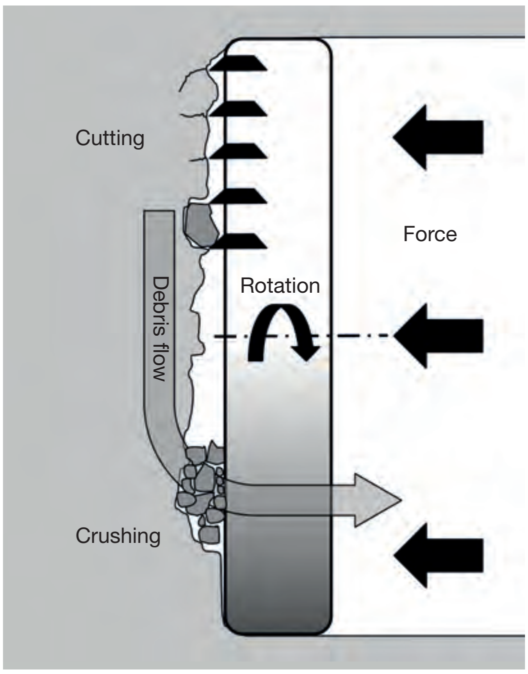
The tunnel boring machine as it rotates, cuts and pushes it's way through solid rock. Photo: Herrenknecht AG

Modern machines consist of three basic sections: cutter head, hydraulic cylinder and gripper. The cutter head is a large rotating disc containing many small, hardmetal (tungsten carbide) cutting discs that cut the face rock under tremendous pressure. The gripper section contains shoes that are forced against the bore sidewalls to hold the machine in place as the cutter head pushes against the rock face. The hydraulic section in the center of the machine provides the pressures necessary for the cutter head and gripper shoes to do their jobs. ➔



View of the gripper shoes: They brace left and right against the tunnel wall. The hydraulic cylinders then move the machine forward. Photo: Herrenknecht AG

The cutter head diameter is that of the bore to be drilled, about 9 meters in the case of the Gotthard Base Tunnel. The cutting discs rotate with the cutter head and cut the rock along concentric circles, while buckets integrated in the circumference of the cutter head pick up the freshly cut rock or “muck” from the bottom of the bore and drop it onto the muck extraction system, usually a conveyor belt. The belt moves the muck to the rear of the machine where it is transferred to trains. Much of the muck is reused as a component of the concrete that lines the tunnel. The four TBMs have digested and recycled approximately 24 million tons of excavated material while drilling the Gotthard tunnel.



Schematic drawing of the arrangement of cutters on the rotating cutter head, and the movement and crushing of the cut rock.

Key characteristics of the Herrenknecht AG gripper type TBMs used for the Gotthard project

• Length incl. advancing tail piece	440 m
• Weight (TBM only)	2,700 t
• Diameter of cutter head	8.83–9.58 m
• Number of electric drives	10
• Number of cutter discs	62
• Total maximum power	3,500 kW
• Daily energy consumption	63 MWh
• Daily tunnel advance rate	35–40 m

The gripper shoes are convex steel structures attached to both sides of the TBM. They extend under hydraulic pressure and anchor the TBM against the tunnel walls. They support the TBM while boring, reacting against both the rotational torque of the cutter head and backward pressure on it.

The cutter head – the most important machine part

The cutter head is where the work of a TBM takes place. Cutter heads have evolved dramatically since first used in 1952 in response to the tremendous demands placed upon them. Early cutter head designs employed small 28-cm cutter discs mounted on large spokes with large buckets. Bucket openings have become smaller and more refined in shape with time, because TBMs crush the broken rock into small uniform pieces instead of producing large and small chunks. Modern cutter heads resist cracking by the use of flexible components and special welding techniques. Current cutter-head design uses strategically placed wear-resistant plates to counter torque when the head is pushing against a loose face of rock or large blocks. One of the biggest steps forward is the recent use of large 51-cm cutter discs. With the evolution in cutter-head design, boring efficiency and resistance to harsh operating conditions have increased. These improvements require machine components that are highly resistant to wear and impact. The designers of modern TBMs, therefore, specify high-performance materials in combination with an appropriate design for each prevailing geological situation to dramatically reduce downtime and maintenance requirements.

The parts most exposed to wear are the hardmetal cutter discs that carve into the rock front. The disc is fixed to a tapered barrel made from wear-resistant steel resting in sealed bearings. Detached rock fragments remain trapped between the cutter head and fresh rock until crushed to a smaller size that can escape to the muck buckets. To limit wear and protect the cutter discs, abrasion-resistant steel plates are mounted on the cutter head. Several tons of wear plates are usually replaced on the cutter head of a TBM each time it undergoes regular maintenance. In addition, many downstream structures such as dump moulds, crushing equipment or sieves, are also exposed to abrasion and impact. These components often operate in a wet environment where ➔

Chemical composition of wear-resistant special structural steels used for important components in TBM's

Target hardness (HB)	Max. plate gage (mm)	Chemical composition (max. %)					
		C	Si	Mn	Cr	Ni	Mo
400	100	0.20	0.80	1.50	1.00	–	0.50
450	100	0.22	0.80	1.50	1.30	–	0.50
500	100	0.28	0.80	1.50	1.00	1.50	0.50
600	40	0.40	0.80	1.50	1.50	1.50	0.50

they are subject to corrosion. Wear- and erosion-resistant structural steel is the material of choice for all these applications.

Molybdenum – the most important machine material

A wear-resistant material should be hard and tough because it must resist abrasion by hard particles without fracturing into pieces. Special wear-resistant structural steels are used for the conditions encountered in the TBM. These steels are heat treated to produce a fine martensitic or martensitic-bainitic microstructure that provides an optimum combination of hardness and toughness. A steel's hardness increases as carbon content increases, but high carbon also reduces toughness, which is undesirable. (See the article on Mo-alloy steels in this issue for a detailed explanation). Abrasion-resistant steels are normally used with hardness ranging from 400 to 600 HB (Brinell hardness – see table above). This means, for example, that steel with a mean hardness of 400 HB will contain 0.15 to 0.20% C, which provides both good toughness and adequate hardness.

Carbon is not the only factor involved in obtaining the required properties. Many of the wear parts are very thick. The molybdenum, nickel and boron present in wear-resistant steels ensure a uniform property profile through the thickness of these components (good hardenability). In particular, molybdenum has two important metallurgical functions in such steels. First, it enhances the steel's through-section hardenability, and in this respect is much more effective than other alloying elements such as manganese, nickel or chrome. Second, moly provides good tempering resistance, meaning it limits hardness loss during secondary heat treatments performed to improve the steel's toughness. Moly achieves this beneficial combination of effects through the relatively low addition of 0.2 to 0.5%, keeping the alloy cost at an acceptable level.

Conclusion

The opening of the Gotthard Base Tunnel is scheduled for 2017. Around one ton of molybdenum was needed to provide strength, toughness and erosion resistance to the 350 tons of wear plate used in digging this tunnel. Thanks to the excellent properties of the wear plates this is a small amount of material compared to the 25 million tons of rock removed.

Additional TBMs are engaged in many other tunneling projects around the world. A relatively small-diameter machine is now boring to help deliver drinking water to the suburbs of Washington D.C., USA. A new TBM-drilled transit tunnel will open soon in Pittsburgh, Pennsylvania, USA, site of the IMOA AGM this year. Vehicles using the tunnel will carry people under the Monongahela River to the sports stadiums that are the homes of the Pittsburgh Steelers American football team and the Pittsburgh Pirates baseball team. The largest diameter tunnel ever contemplated is now being planned to go completely under the waterfront and across the city of Seattle, Washington, USA. It will replace an earthquake-threatened overhead viaduct and speed north/south vehicular traffic.

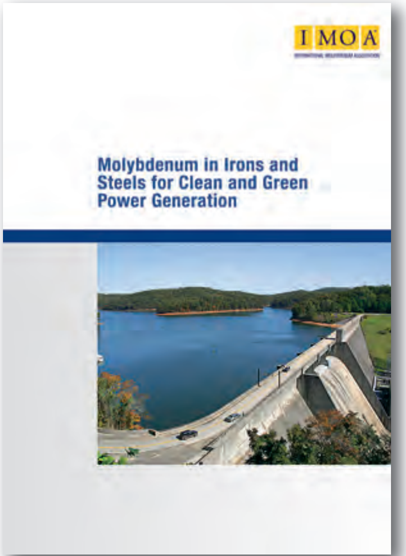
Everyone reading this article can look around (or underneath) and find examples of TBMs at work. These giant machines, with the help of molybdenum-alloyed steels, bring great benefits to society, shortening the distance from point A to point B. (hm)

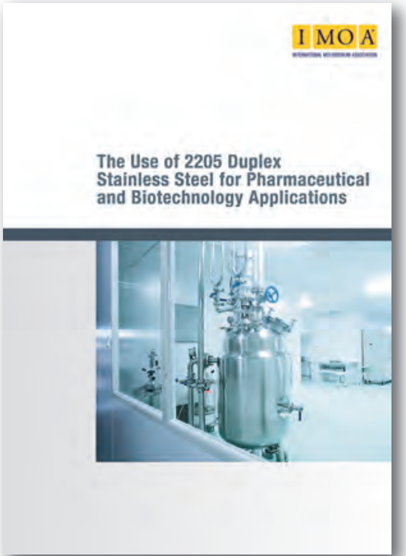
Cutter head after break-through in one of the Gotthard tunnel pipes. Photo: Herrenknecht AG

IMOA news

New IMOA publications

Molybdenum in Irons and Steels for Clean and Green Power Generation
This is IMOA's first brochure on molybdenum use in alloy steels. It explains the metallurgical benefits of using molybdenum alloyed high strength steels and castings and shows where these enhanced materials are used in wind turbines and hydroelectric power plants. This brochure is for engineers at steel companies, component manufacturers, engineering firms and operators active in wind and hydropower generation. Available as hard copy and PDF.





The Use of 2205 Duplex Stainless Steel for Pharmaceutical and Biotechnology Applications
This new IMOA brochure introduces 2205 duplex stainless steel and summarizes the properties that make it ideal for high purity applications. The pharmaceutical and biotechnology industry sector typically uses standard Type 316L austenitic stainless steel for processing equipment and is less familiar with the benefits that the more corrosion resistant 2205 grade can offer. This brochure also provides information on fabrication and electropolishing of 2205 and on US and European standards, including the recent addition of 2205 into ASME BPE-2009. It is aimed at engineers and specifiers in these industries. Available as hard copy and PDF.

Practical Guidelines for the Fabrication of Duplex Stainless Steel
The second edition of this popular IMOA brochure has now been released in Japanese. The International Stainless Steel Forum, ISSF and the Japanese Stainless Steel Association, JSSA have been instrumental in providing the translation. The brochure, which is also available in English and Chinese, explains how the fabrication of these materials differs from standard austenitic stainless steels and provides parameters for most fabrication operations. The brochure is for fabricators, specifiers and users of duplex stainless steels. Available as PDF in Japanese and hard copy and PDF in English and Chinese.

Seminar on molybdenum in steel, November 7-8, 2011 in Taipei, Taiwan

IMOA and CBMM, with hosting partners National Taiwan University and China Steel Corporation are jointly organizing a free seminar "Fundamentals and Applications of Mo and Nb Alloying in High-Performance Steels". The seminar will be held at the Howard Plaza Hotel in Taipei and is for metallurgical engineers and metallurgists at steel plants and laboratories across Taiwan. Please contact IMOA if you are interested in attending this event.

REACH – Registration, Evaluation, Authorisation (and restriction) of Chemicals

The European Chemicals Agency has published the REACH risk assessment dossiers for molybdenum and molybdenum compounds that were prepared by the Molybdenum Consortium (MoCon) during 2007-2010.
To view: http://apps.echa.europa.eu/registered/registered-sub.aspx#search
For information on how to obtain a Letter of Access to make your REACH registration for a MoCon substance, go to http://www.molybdenumconsortium.org/letter-of-access.html