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Racing bikes – steel's great comeback?

Advanced steels and frame designs may now be heralding a new age of racing bicycles. A UK-based racing team has brought steel frames back into the professional bicycle racing circuit. These new frames utilize high-strength, molybdenum-alloyed maraging steel.

The 100th running of the Tour de France took place in 2013. The first eighty or so editions were almost exclusively the domain of steel-framed machines. Despite the adoption of new materials such as aluminum, titanium and carbon fiber in the past thirty years, steel may be about to make a comeback thanks to advanced alloying and processing, resulting in astonishing material characteristics. Steel remains the material of choice for many other types of quality bicycles as well, such as mountain and city bikes where durability is of prime importance.

The frame

The frame is the core of any bicycle. Ideally, it is the result of the "perfect marriage" of material and design. However, its performance is a compromise between different, and sometimes conflicting, requirements. The relative importance of each depends on how the bike is to be used. These requirements include torsional stiffness, so the rider's effort isn't wasted in bending the frame sideways as he pedals rather than using that energy to progress forward; vertical stiffness, which if too great will make the ride uncomfortable; weight, aerodynamics, durability and, of course, cost.

Toward the end of the glory days of steel frames on the European professional circuit (the early to mid-1980s), artisan frame builders were doing great things with design to get the best overall result. Tubes had long been butted, a process whereby the wall thickness is increased where the stresses are greatest, and reduced to save weight where they are low. By the 1980s, tubes were also being produced in "non-circular" shapes to provide asymmetric properties. The builders even adopted internal helical stiffeners so the wall thickness could be further reduced.

Frame material development

In addition to improving the design of the tubes, bicycle makers used various alloys over the years, including molybdenum-containing steels. In steel, molybdenum is beneficial for strength and toughness, as well as for a number of other properties. For the racing cyclist, who has always sought minimum weight to save energy when struggling over mountain passes, higher strength means thinner tube walls. And good toughness means those thinner-walled frames will not break easily.

Developments in steel-frame tubing continue to this day, with specialist frame builders delivering unbelievable works of art with outstanding performance. Through the use of molybdenum and various other alloying elements, combined with sophisticated manufacturing processes, tube manufacturers have now produced a frame material having ›

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Cover photo: L'ombrière in the old port of Marseille was desinged by Foster + Partners. The 1000 m^2 canopy is clad with mirror polished Type 316L stainless steel and supported by eight duplex stainless steel columns which are also mirror polished. © Nigel Young/Foster + Partners

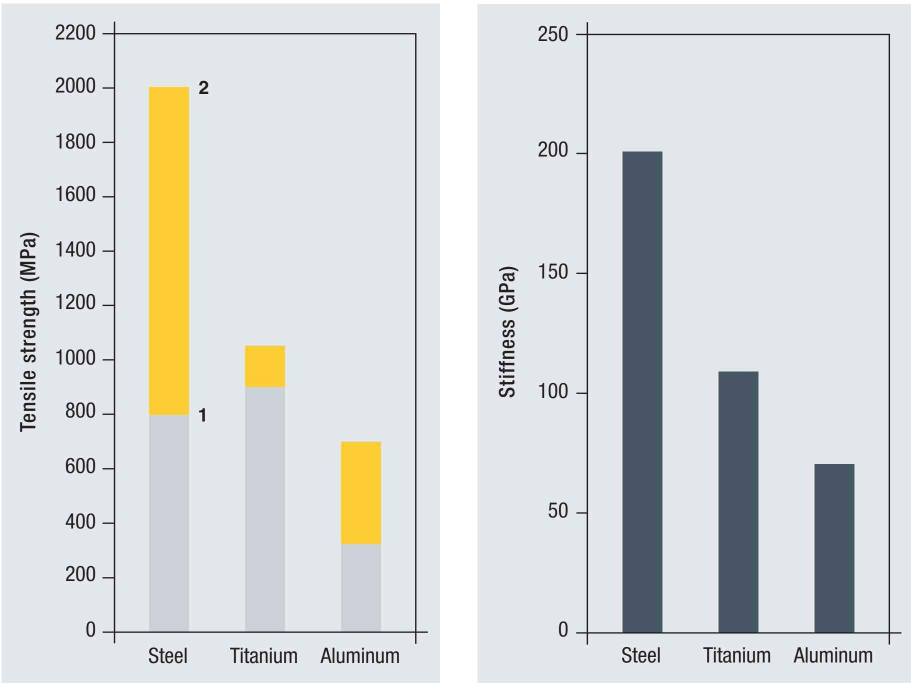
Steel is making a comeback in professional bicycle racing. © Andy Jones/Cycling Weekly

strengths reaching 2,050 MPa. This is over three times that of the steel used in buildings and bridges. This "maraging steel" gets its exceptional strength from two mechanisms, the well-known martensite reaction and a precipitation-hardening reaction utilizing molybdenum.

This strength is nearly three times that of the strongest aluminum used for bicycle frames, and the alloy's stiffness is three times that of aluminum. These properties make a wall thickness of less than 0.5 mm, even as low as 0.3 mm (!) possible. Using less material means that, despite its higher density, steel can be used to produce a frame of similar weight as one in aluminum or titanium. Whilst a carbon fiber-reinforced plastic frame may be 15% lighter, it is widely recognised that it is less durable and will not provide the same "ride quality" for the discerning cyclist. Costs vary depending on the quality of the frame, but it is fair to say that steel will generally be the least expensive, and titanium or fiber-reinforced plastic the most expensive option.

The future

Madison Genesis, a UK-based team is currently taking steel back to the professional circuit, working with Reynolds tubing on maraging stainless steel frames with up to 1.25% molybdenum. Being able to compete in the most important event of the year (the Tour of Britain), and a national championship win, have persuaded them to expand their efforts in 2014. So top-end steel, which for so long ruled the roost of professional cycling, returns to the pinnacle of technical development. It is now able to prevail against its more fashionable competitors thanks to the contribution of molybdenum. (GC)



Bicycle frame materials with their typical range of tensile strengths in yellow (left) and their stiffness (right). The actual tensile strength depends on the alloy, the cold drawing method and the heat treatment. For steel it ranges from 1) cold-drawn chrome moly steel (1% Cr, 0.2% Mo) to 2) maraging stainless steel (12% Cr, 1% Mo).

Structural stainless steel

Decorative stainless steel panels are widely used in façades, roofs and elevators because they are attractive and long-lasting. Increasingly, engineers now use stainless steel for load-bearing structures in challenging environments. In many cases stainless steel is cost-effective if the whole life cycle of the installation is considered.

More than half of the annual production of steel worldwide is used in construction. Typically I-beams, plates and reinforcing bars in buildings and bridges are made of affordable carbon or low-alloy structural steel. Unfortunately, these grades of steel rust easily. This has an enormous economic and environmental impact on the world's infrastructure, affecting roads, bridges, buildings and systems that distribute oil, gas, water and waste water.

The annual cost of corrosion to industrialized countries is 3 to 4% of their GDP according to numerous studies. This figure includes only the direct cost of replacing damaged material and components. Indirect costs, such as loss of production, environmental impact, transportation disruptions, injuries and fatalities are estimated to be just as high.

Standard structural steels must be painted or covered with metallic coatings to minimize corrosion. In addition to the initial cost of such protection, coated steels require costly inspection, maintenance, and sometimes replacement over a structure's life. The indirect cost of maintenance such as loss of production and revenue can also be high. Sometimes it is simply impossible to access components of a structure to carry out inspection and maintenance.

Comparing life-cycle costs

Designers increasingly take into account the costs of a structure throughout its whole life, not only its initial cost. When life-cycle costs are considered, stainless steel becomes viable, particularly for structures requiring durability or where inspection and maintenance are impossible or very costly.

This is true even though stainless steel is significantly more expensive than carbon steel. There are ways to reduce the gap in material costs, however. Eliminating coatings decreases installed cost, and when using the higher-strength duplex stainless steel, it may be possible to trim section sizes (and weight) to further lower the initial investment.

When it comes to maintenance cost over an installation's life, the use of stainless steel eliminates coating maintenance costs and component replacement due to corrosion. Stainless steel construction may also provide a more sustainable solution, reducing emissions, resource depletion and waste.

Designing with structural stainless steel

Design codes and specifications for conventional structural carbon steel cannot be used with stainless steel, because the mechanical properties (specifically the stress-strain behavior) of the two materials are fundamentally different. Stainless steel therefore needs its own set of design rules.

In Europe, Part 1.4 of Eurocode 3, EN 1993-1-4 *Design of steel structures*, *Supplementary rules for stainless steels*, was published in 2006[1]. It is based on many years of research carried out around the world and covers hot-rolled, welded and cold-formed structural sections. ›

Minimum specified values of design strength f_y for structural stainless steel hot-rolled plate

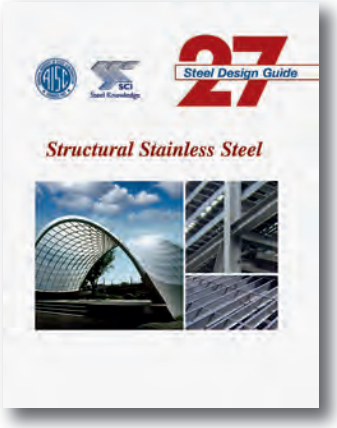
Type of stainless steel	US Specification			European Specification	
	Grade		Design strength[a]	Grade	Design strength[b]
	Common name	UNS designation	f_y MPa	EN designation	f_y MPa
Austenitic, without Mo	304	S30400	205	1.4301	210
	304L	S30403	170	1.4307	200
Austenitic, 2% Mo	316	S31600	205	1.4401	220
	316L	S31603	170	1.4404	220
Duplex, <0.5% Mo	2101	S32101	450	1.4162	450
Duplex, <0.5% Mo	2304	S32304	400	1.4362	400
Duplex, 3% Mo	2205	S32205	450	1.4462	460

a ASTM 240 and A276 **b** EN 10088

1 EN 1993-1-4:2006 Eurocode 3 Design of steel structures Part 1-4: General rules. Supplementary rules for stainless steels

In the US, guidance on design with lighter gauge stainless steel sections has been available for years[2], but there was no design specification covering hot-rolled and welded stainless steel structural sections. This required designers to work from first principles or use rules for carbon steel with additional safety factors, a significant obstacle. Moreover, the lack of a design standard required building enforcement officials to approve each application individually.

IMOA, in cooperation with stainless steel producers and other industry associations, initiated a project in 2009 to develop design rules for heavier stainless steel structural sections. The effort resulted in the publication of AISC Design Guide 27: *Structural Stainless Steel*, authored by Nancy Baddoo of the Steel Construction Institute in September 2013[3]. The guide can be downloaded from AISC's website at www.aisc.org/dg.



The Design Guide is a comprehensive document covering design rules for structural members and connections at ambient temperatures and in fire. It discusses material properties, grade selection and durability, and gives guidance on fatigue, fabrication and erection.

As always with stainless steels, grade selection is crucial. Molybdenum provides the improved corrosion resistance of grades like Type 316 (2% Mo, austenitic) or 2205 (3% Mo, duplex). These grades are, therefore, often specified in corrosive environments such as coastal regions, or where there is exposure to de-icing salts, heavy pollution or chemicals. Duplex stainless steels like 2205 are twice as strong as most austenitics, giving them an additional advantage in load-bearing applications.

Structural stainless steel applications

The key advantages of stainless steel for load-bearing applications include corrosion resistance and hence durability even in corrosive environments, better retention of strength in fires compared to carbon steel, high impact resistance, good cleanability and a pleasing appearance.

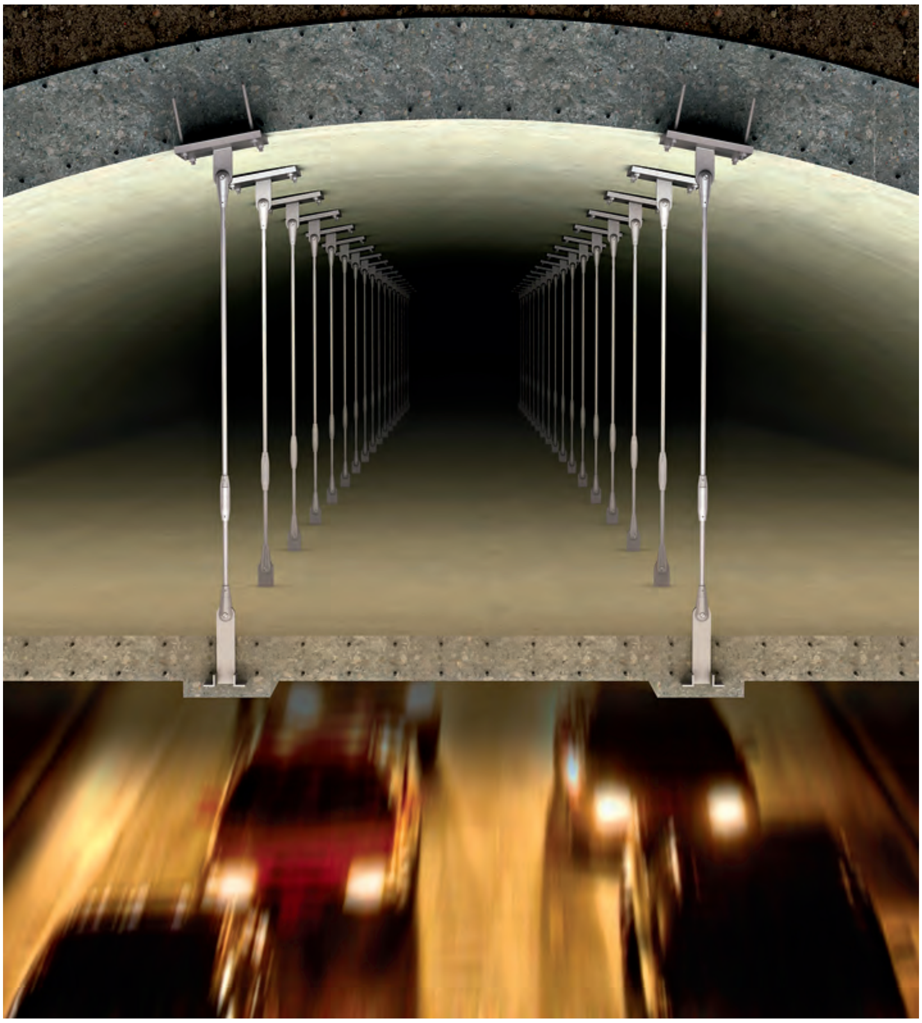
The Passerelle Mobile footbridge in Lyon-Confluence, designed by PCCP and ALTO, has 2205 duplex stainless steel structural members. Their strength allowed a considerable reduction of the size and thickness of the sections and the weight of the bridge. © ALTO and PCCP

2 American Society of Civil Engineers (2003) Specification for the Design of Cold-Formed Stainless Steel Structural Members, SEI/ASCE 8-02, Reston, VA
3 Baddoo, N R, AISC Design Guide 27: Structural Stainless Steel, AISC, September 2013

2205 duplex stainless steel escape tunnel on a floating production, storage and offloading (FPSO) vessel. © BP p.l.c.

Among the most iconic structural applications are monuments such as Arlington's Air Force Memorial, Dublin's Spire or St. Louis' Gateway Arch, and sculptures like the Cloud Gate (known as "The Bean") in Chicago or the impressive Ombrière canopy in Marseille, featured on the cover of this issue. Pedestrian bridges like The Helix in Singapore and San Diego's Harbor Drive Bridge, both previously covered in MolyReview, also have high visibility.

Stainless steel structural components are often used in commercial buildings to support glass curtain walls. For example, the smallest connections in New York's 5th Avenue Apple Cube are almost invisible, allowing nearly unobstructed views. Like stainless steel canopies, handrails and street furniture, connectors require little maintenance. Fasteners, anchoring systems and support angles for wood, stone and masonry are often inaccessible or difficult to replace and benefit from structural stainless steel's good corrosion resistance. Wood and masonry can themselves be corrosive to other metals and are likely to absorb moisture and corrosive chemicals over time.



Tunnel ceiling suspended from a duplex stainless steel system, North-South Bypass Tunnel, Brisbane, Australia. © Ancon

Road tunnels are harsh environments for materials. Maintenance costs are high and a structural failure or fire can have severe consequences. Stainless steel is therefore deployed in tunnel construction for linings and their support frames, maintenance walkways, fixings and fasteners, lighting and signage supports and ground-support rock anchors. The CLEM7 Tunnel under the Brisbane River, the longest road tunnel in Australia, has many advanced safety features. In the event of a fire or explosion, a high-tech ventilation system comprising 100 jet fans will rapidly extract smoke to a longitudinal duct high above the road deck. A duplex 2205 stainless steel system suspends the massive concrete slabs, which form the duct in the highly corrosive environment.

Stainless steel is also used for explosion- and impact-resistant structures such as blast and security walls, gates, security barriers and bollards. It can absorb considerable impact without fracturing due to its excellent ductility and strain-hardening characteristics.

On offshore structures, escape routes are required for personnel in the event of explosion and fire. They can vary from semi-open walkways to fully enclosed high-integrity fire- and blast-rated tunnels, an example of which is the escape tunnel suspended on the side of the Skarv FPSO (Floating production, storage and offloading) vessel. The tunnel is over 200 meters long and comprises an inner carbon steel truss and an outer 2205 duplex stainless steel envelope.

The water treatment, pulp and paper, nuclear, biomass, chemical, pharmaceutical, and food and beverage industries make extensive use of stainless steel in platforms, barriers, gates, ladders, stairs, cable trays and equipment supports.

Engineers are increasingly selecting stainless steel for load-bearing applications that benefit from its durability, attractive appearance, strength, ductility, toughness and formability. The broader availability of design guides makes it easier to specify stainless steel for applications that require durable, resilient and sustainable structures and go beyond decorative panels. (NB)

Structural stainless steel case study: UK's first desalination plant

London is a surprising location for a desalination plant considering its cool, wet climate. Predictions based on climate change and population expansion, however, indicated that London water demand could outstrip existing freshwater supply in the next few years. Therefore, the UK's first desalination plant, the Thames Gateway Water Treatment Works in East London, was opened in 2010. The plant treats brackish Thames River water to produce up to 150 million liters of clean drinking water each day, enough to supply up to one million Londoners. It will be used to supplement supplies during extended periods of low rainfall, maintain supplies in the event of incidents at other water facilities and support future demand growth.

A framework of duplex stainless steel beams support the lamella clarifiers. © Interserve

Plant design with carbon steel – The Gateway plant utilizes the world's first high-efficiency four-step, rather than the more common two-step, reverse osmosis desalination process. Brackish river water passes four times through semipermeable membranes to achieve a high level of salt removal.

The water first passes through lamella clarifiers, containing a coarse filter medium, to remove solid particles. The clarifiers are large open tanks, supported by a framework of 78 I-beams. These beams need good strength and stiffness.

Desalination Plant at Thames Gateway Water Treatment Works, East London. © Interserve

They also must be highly corrosion resistant, not to be compromised throughout the 60-year design life of the plant. The beams were initially specified as epoxy-coated carbon steel, but it was recognized that there would be a high risk of damage to the coating during installation and maintenance. This would have resulted in rusting of the carbon steel beams and subsequent damage to the £7 million desalination membranes.

Using molybdenum-containing stainless steel instead – Unlike carbon steel, the surface of stainless steel is protected from corrosion by an adherent layer of chromium-rich oxide that reforms immediately if damaged, self-healing the surface. Thus, the engineers, concerned about the durability of the epoxy-coated beams, specified 2205 duplex stainless steel instead. This grade has high strength, requires little maintenance and is durable in brackish water without coating, thanks to the addition of 3% molybdenum. This grade is also approved for contact with drinking water by the Drinking Water Inspectorate (DWI), the independent regulator of drinking water in England and Wales.

Minimizing costs – Simply replicating the carbon steel beams in stainless steel would have led to a 74% cost increase, so several measures were undertaken to reduce cost. Firstly, the superior strength properties of duplex stainless steel were exploited. A web depth of 500 mm was selected for the fabricated beams, to be cut from 2-meter wide plate, reducing offcut wastage. The flange dimensions were sized to optimize bending strength, while keeping beam deflection within acceptable limits. As a result, the total weight of the stainless steel beams was reduced from 140 tonnes to 75 tonnes, allowing considerable cost savings. (NB)

Coloring the world

Molybdenum compounds have been used in commercial pigments for over a hundred years. They continue to play an important role in today's sustainable and environmentally safe colorings.

Color comes to us as visible waves directly from a light source and from light reflected off objects. An object might have a natural color or it might take its color from a pigment. Pigments are particles of a coloring substance, added to give color to paints and solid materials like plastics. Molybdates began to play an important part in the pigment world about one hundred years ago and continue to do so today.

A colorful history

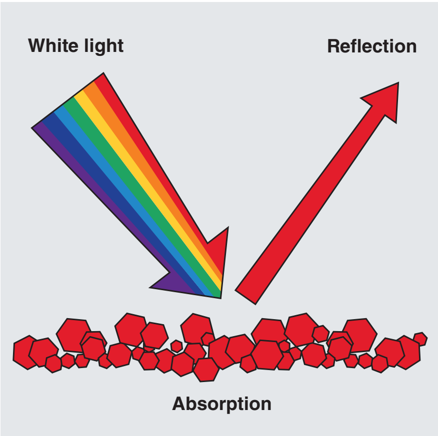
Pigments were vital to the earliest human art. In the Lascaux caves in Southwestern France, prehistoric artists mixed burnt wood, clays, and oxides of iron and manganese with water and animal fat to produce colored drawings depicting wildlife and hunting scenes. From early historic times, people also used inorganic oxide pigments to color bowls and other useful objects. These simple pigments were used later to color religious manuscripts. In the 15th century, "natural earth pigments" (oxides of iron colored by impurities) appeared in architectural decoration.

Innovative 19th century artists like Turner and Delacroix used new synthetic pigments to incorporate color into paintings. Common pigments of the time included Chinese White (zinc oxide), Chrome Yellow (lead chromate) and Cadmium Yellow (cadmium sulfide). In 1863, H. Schultze first identified molybdate as a possible pigment constituent in his studies of lead, chromium and molybdenum compounds. The resulting early 20th century pigments are now known as molybdate pigments.

Throughout the 20th century, chemists developed many oxide-based inorganic pigments and a wide array of organic pigments with bright, pure colors. Today, pigments are loosely categorized as commodity/high-performance and inorganic/ organic. Molybdenum compounds are found in commodity and high-performance inorganic and organic pigments.

Function and performance

A pigment absorbs light of certain wavelengths from the light striking its surface and reflects wavelengths that produce its color. For example, a red pigment absorbs the violet, blue, green and orange wavelengths, reflecting red. Scientists can manipulate pigment compounds to control which wavelengths are reflected and which are absorbed.



A simplified example of the function of pigments. Only the red part of the white light, which contains the spectrum of colors, is reflected from a red pigment surface, the rest is absorbed.

Depending on the application and the manufacturing process, different pigment properties are important. Some of them are:

- Lightfastness, the ability of a pigment to resist discoloration over time by light
- Heat stability, the ability of a pigment to resist elevated temperatures
- Tinting strength, the ability of a pigment to alter the color of the paint or plastic
- Hiding power/opacity, the ability of a pigment to obscure the background of a contrasting color
- Resistance to chemicals such as acids or solvents

More recently, toxicity and environmental impact have come to the fore in pigment science, generating a push to replace older, sometimes toxic, pigments. New compounds can also help improve sustainability. In buildings, for example, metal roof coatings now can employ a pigment specially designed to absorb infrared radiation if passive heating is required, or to reflect solar energy if cooling is desired. In each case, the pigment lowers energy costs.

Molybdenum pigments today

Molybdate orange is a mixed-phase crystal containing varying proportions of lead chromate, lead sulfate and lead molybdate[1]. In experiments with molybdenum, H. Schultze noticed that the yellow mineral Wulfenite (lead molybdate, $PbMoO_4$) was colored strongly red when it occurred with Crocoite (lead chromate, $PbCrO_4$). Modifying lead chromate with molybdate allows the resulting molybdate orange pigment to ›

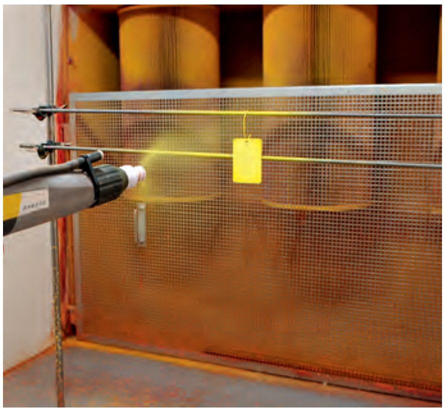
1 Typically the contents range from 75–90% lead chromate, 3–15% lead sulfate and 10–15% lead molybdate.

take hues from bright red-orange to red-yellow. Due to its brightness, it rapidly became a popular pigment in the 1930's. Today, the pigment is known as Pigment Red 104. It is generally described as having good opacity, durability, and heat stability and is especially noted for its solvent resistance. Usage is around 12,000 tons per year, primarily for industrial coatings and coloring plastics. In recent years, toxicity concerns[2] limited its use in consumer products such as children's toys. Its toxicity derives from the lead and chromate components of the pigment, not from the molybdate. The EU has scheduled it to be phased out by 2015.

Bismuth vanadate yellow, known as Pigment Yellow 184, typically incorporates 1–5% molybdenum in the $(BiVMo)O_4$ mixed-metal oxide, when it is produced by aqueous precipitation. It comes in bright greenish-yellow to reddish-yellow colors and has high opacity and excellent solvent and heat resistance. Molybdate stabilizes the color and confers corrosion protection very similar to that obtainable with lead chromate[3].

This pigment was first synthesized in 1924 and commercialized around 1985. It produces yellows equivalent to those of the toxic chromium or cadmium-containing pigments and can also be used to mix colors such as beige, orange and green. Between 2,000 and 5,000 tons are used annually for high-quality automotive and industrial paints, coil coating, indoor and outdoor architectural paints and plastics coloring. It is an excellent replacement for pigments containing lead or cadmium where weather resistance is important. It also enhances the color stability of organic pigments. Free of lead and very stable, these pigments pose low environmental and health risk and appear frequently in food packaging.

Rare Earth – molybdenum oxide pigments is an emerging group of what might become the next class of high-performance pigments, combining molybdenum with rare earth metals like cerium, lanthanum, and samarium to make new colored oxides. These green-yellow pigments are stable and environmentally benign. Molybdenum will play an important role here in replacing traditional lead, cadmium, and chromium pigments.



Powder coating with bismuth vanadate.
© Cappelle

Complex inorganic color pigments are a new class of high-performance pigments created from oxides containing two or more metals, boasting outstanding resistance to dissolution by chemical agents. These complex oxides use the transition metals V, Cr, Mn, Fe, Co, Ni, and Cu to form their basic oxide structure and color. Adding molybdenum modifies their color. As a class, they are the most stable and durable type of colorants commercially available.

Bismuth vanadate pigments are used in the yellow paint of ski mobiles.
© Shutterstock.com/Andrey Stratilatov

The molybdenum corner of the pigment world

The worldwide annual market for all kinds of pigments is about 8 million tons with a value of nearly $20 billion. Molybdenum-containing pigments account for a small part of the six-million-ton inorganic pigment market. However, increasingly they play an important role in meeting the need for environmentally friendly pigments, and can be expected to occupy a greater percentage of the market in years to come. Molybdenum helps make our world greener in more ways than one! (CK)

2 Lead chromate molybdate sulfate red (C.I. Pigment Red 104) is described as "a substance of very high concern because of its CMR properties" by the European Chemicals Agency (27 November 2009). [CMR: the abbreviation for Carcinogenic, Mutagenic and toxic to Reproduction]
3 US Patent 4,455,174. Arthur A. Tracton, Coatings Technology Handbook, Third Edition 2005

Keeping it cool

Molybdenum heat sinks are essential to power semiconductor devices that manage the flow of electricity in electronic equipment because they prevent overheating. Molybdenum's good thermal and electrical conductivity, combined with its low coefficient of thermal expansion, make it the ideal material for this application.

A modern, well-functioning infrastructure requires a reliable electric power supply. This is extremely important because of the high cost of downtime and unexpected shutdowns. At every step along the way, from generating electricity at huge electric power plants, to controlling power distribution, and operating machines and appliances, molybdenum heat sinks assure the reliability of all electrical systems.

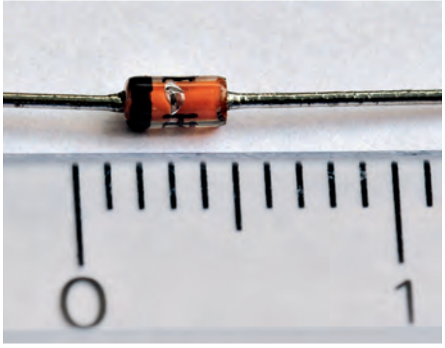
Semiconductors and power

The electric power flowing through any electrical device, large or small, needs to be controlled, modulated, and dispensed within the system. A simple low-power example is the tiny silicon diode. There are four in each rectifier bridge found in many small home appliances. Such a bridge might handle currents of less than an amp. The diodes and heat sinks in these bridges are very small, perhaps only a few tenths of a millimeter in diameter and thickness. At the other end of the power spectrum are devices that allow the precise operation of large industrial motors and power distribution systems. They can be built using either traditional monolithic silicon-based semiconductors or sophisticated integrated circuits created on specialty ceramic substrates. They must deal with electrical currents in the order of hundreds of amps. The heat sinks for monolithic devices can be up to 100 mm in diameter and 2–3 mm thick, which in the power semiconductor world is quite large.

No matter what the design, all devices are fragile. Silicon and ceramic materials are brittle and can easily fracture and fail if they are subjected to high stresses or impact. Electrical current passing through a device creates heat that can be catastrophic to semiconductors. Heat must, therefore, be dissipated so that the devices do not lose their electrical properties during service and so that thermal stresses, which can lead to mechanical failure of the device, are minimized. Regardless of the semiconductor's size, molybdenum heat sinks help to remove heat from the system.

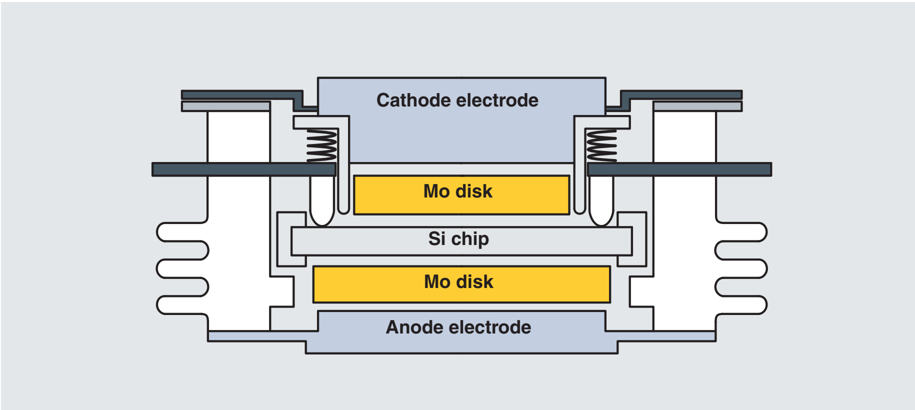
Molybdenum is the material of choice

A good heat sink material for these applications needs more than just a high coefficient of thermal conductivity. It must also be a good electrical conductor because electricity to and from the device has to pass through it. Because the heat sink is brazed to the device in order to provide the best possible electrical and thermal contact, it must expand and contract on heating and cooling at a rate similar to that of the device. A large disparity may cause the device to crack and fail. Meeting these criteria – high thermal conductivity, high electrical conductivity, low coefficient of thermal expansion (CTE), and reasonable cost – requires a balance to obtain the most reliable overall component design.



A typical Zener diode containing a tiny silicon semiconductor sandwiched between two molybdenum metal heat sinks. © Medvedev/CC-BY-SA-3.0 (http://creativecommons.org/licences/by-s/3.0/deed.en)

Molybdenum provides the optimal combination of physical properties at an acceptable cost. For this reason, it was the material of choice in the first power semiconductor designs of the early 1950s, and remains so today. Despite their good electrical and thermal conductivity, copper and aluminum are not suitable alternatives. ›



Schematic drawing of a gate-communicated thyristor (GCT) power semiconductor, showing molybdenum metal heat sinks. Source: Powerex

Railway locomotives have reliable and long-lasting power control and distribution.
© Shutterstock.com/mdgn

Comparing physical properties of semiconductor and heat sink materials at 20°C.

Material	CTE (ppm/°C)	Thermal conductivity (W/mK)
Selected semiconductors (S) and ceramic (C) substrates		
Si (S)	2.8 [a]	150
Al_2O_3 (C)	6.7	21
BeO (C)	8.0	275
AlN (C)	4.5	250
Selected potential heat sink materials		
Mo	5.0	140
Cu	16.9	398
Al	23.0	240
Kovar® (Fe30 Ni)	5.3	17
Mo-30 Cu [b]	7.1	205
Mo-40 Cu [b]	8.7	215

Source: NIST, except **a** (C. A. Swenson) and **b** (Plansee SE)

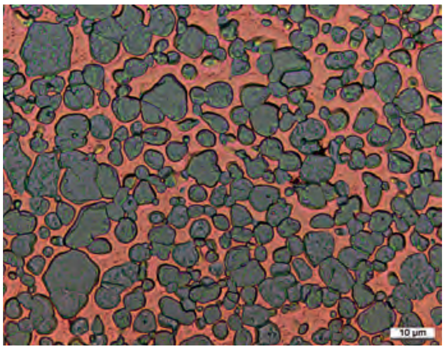
They expand at much higher rates than silicon and would pull the device apart during operation causing premature failure. (see table)

An added benefit of molybdenum is an elastic modulus nearly twice that of steel, which enables it to provide a rigid support for the semiconductor, limiting the possibility of damage due to physical abuse. This unique set of properties has made molybdenum indispensable to the power semiconductor industry.

Molybdenum and copper: an even more powerful combination

Semiconductor designs evolve rapidly, and power devices now use sophisticated integrated circuits built on specialty ceramic substrates. These devices produce more highly concentrated regions of heat, causing greater challenges for the package designer. Furthermore, ceramic substrates expand more than silicon. Pure molybdenum metal has some disadvantage in these designs because its CTE is lower than that of the ceramic substrates.

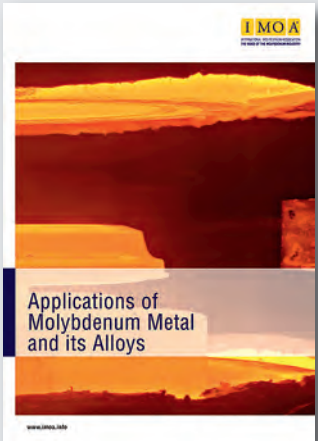
Overcoming this disadvantage requires an engineered composite: By creating a molybdenum skeleton whose voids are filled with copper (see photo), materials engineers have produced a heat sink with higher thermal and electrical conductivity than pure molybdenum, along with the higher CTE required.



Composite molybdenum-copper materials further enhance the already excellent properties of molybdenum metal heat sinks. © Plansee SE

A world of applications

Power semiconductors are everywhere. Electric power generation, whether from fossil fuel, nuclear, solar or wind energy, requires high-power semiconductor devices to manage and distribute the power they create. These devices rely on molybdenum heat sinks, as do all kinds of industrial motors, electric trains and buses, and diesel-electric locomotives. Hybrid vehicles use molybdenum-copper composites in their power management and distribution systems. Even the lowly electric hair dryer needs tiny molybdenum heat sinks to operate reliably. Molybdenum helps to ensure dependable, affordable electrical power wherever it is used. (JS)



IMOA has recently published an updated version of the brochure entitled 'Application of Molybdenum Metal and its Alloys'.
This new edition covers the production of molybdenum metal and its physical, mechanical and chemical properties and explains how they make the metal and its alloys the materials of choice in a wide range of applications.
The brochure is available for download at www.imoa.info/media_centre/downloads

Stainless steel fish scale façade

Molybdenum-containing ferritic stainless steel plays an important role in sustainable construction at the new headquarters of the U. S. Army Corps of Engineers in Seattle, Washington. The material was utilized in the innovative façade, which helped the building win many awards for its cost- and energy-saving features.

One of the U. S. Government's responses to the world's recent economic crisis was the 2009 American Recovery and Reinvestment Act (ARRA), which injected billions of dollars into the U.S. economy. Much of this money was directed to build a more energy-efficient and sustainable infrastructure. The U.S. Army Corps of Engineers (USACE) was one beneficiary of this program. The Corps needed a new headquarters with more space to serve the ever-expanding requirements of the Northwest United States. The new Federal Center South building, constructed with ARRA funding, is an example of the U.S. General Services Administration's (GSA's) Design Excellence Program. The new 19,400 m^2 building occupies a waterfront site in Seattle, WA, on the tidal Duwamish River. Sellen Construction and ZGF Architects LLC delivered it in 2012 as a GSA design-build project.

The building

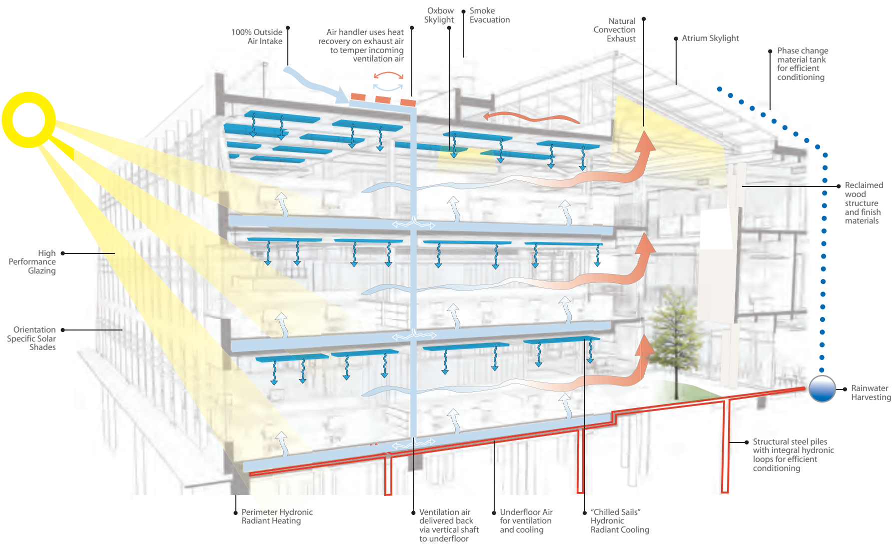
GSA made sustainability a primary requirement in the construction and operation of the building, targeting Leadership in Energy & Environmental Design (LEED) Gold certification. Specifically, the team designed a building that would obtain an Energy Use Intensity (EUI) of 230 MJ/m^2/year or less[1], use 100% filtered outside air, achieve a minimum Energy Star score of 97, and obtain energy performance 30% better than specified in ASHRAE[2] 90.1 2007. These criteria put the building in the top 1% of energy-efficient office buildings in the U.S. without sacrificing comfort, amenities, or design innovation.

The oxbow-shaped design provides an ideal workplace environment for the USACE, emblematic of their mission of "Building Strong". The diagrid structural frame extending around the building perimeter meets the GSA's security requirements for progressive collapse, ensuring that the building will remain intact should one of the column elements be compromised. This is a very important consideration in the earthquake-prone Northwest. The exterior stainless steel shingle cladding also emphasizes "Building Strong" through the reflective power of the shiny silver skin of the building.

Materials of construction

Material reuse, long-term maintenance, and life-cycle cost were three important material selection criteria. The site's corrosive location along a salty waterway and adjacent to a cement plant, was an important additional consideration for the exterior cladding system.

Ferritic Type 444 stainless steel containing 2% molybdenum was selected for the façade. Due to its molybdenum content, Type 444 has better corrosion resistance in the demanding environment than the lower cost Type 304 stainless steel. Its corrosion resistance is similar to that of the better known, but more costly, Type 316 which also contains 2% molybdenum. ❯



Building section showing sustainable systems and integrated strategies. © ZGF Architects LLP

1 Average EUI for an office building in Seattle is 680 MJ/m^2/year, according to the report "Seattle 2011/2012 Building Energy Benchmarking Analysis".
2 ASHRAE, founded in 1894, is a building technology society with more than 54,000 members worldwide.

The stainless steel shingles on the façade shimmer in many shades like fish scales. © Benjamin Benschneider/OTTO

An additional factor in selecting Type 444 was its ability to be readily colored electrochemically to the pewter color required by the architect. Also, Type 444 can be brake formed into a variety of parts for siding and cladding, but requires a more generous bend radius than Type 316.

Stainless cladding design details

In order to support his vision of a nautical theme, the architect helped Millennium Tiles of Elkhorn, WI redesign one of their standard tiles (shingles) into something that looked like a fish scale. The electrochemically colored stainless steel mimics fish scales by varying the reflectivity of the tiles. Being next to a brackish tributary of the Puget Sound, the tiles capture the theme perfectly. Vertical and horizontal sun-shading elements create an additional layer of texture to the façade and provide a relatable human scale to the building. Woods from the Northwest are used liberally in public interior areas; they blend very well with the exterior stainless steel façade.

Average costs but better sustainability result

Owners, developers and architects sometimes dismiss stainless steel cladding because they think it too expensive. However, according to the GSA, the Federal Center South building was constructed for $2,900/m^2, which includes the warehouse demolition and the build-out, and is about average for prime office space in the region. This is all the more remarkable when the building's high performance is considered. The requirement for a building with a 50-year minimum lifespan and mechanical equipment that lasts at least 20 years inspired and drove the design process. Because GSA is a long-term property owner, payback calculations have a longer timeline than for a conventional office building. This allowed the design to include a broader range of sustainability enhancing systems.

Building energy use intensity turned out to be only about 170 MJ/m^2/year and the resulting energy performance is 40% better than that of an ASHRAE standard building. Carbon dioxide emissions are expected to be lower than the standard by a similar amount. To add to its impressive credentials, its energy bill should be approximately $200,000/year less than comparable new office buildings.

Federal Center South Building 1202 has won many awards, including the Engineering News-Record Best Project award: 2013, ENR Best Projects: Government/Public Buildings. The awards are a testament to the success of the building, which now provides a productive, green and light-filled workspace for the Corps of Engineers, cost savings for the American taxpayer, and a more sustainable future for all. (TW)

IMOA news

A quarter century of achievement

Salt Lake City in Utah, U.S. was the venue for IMOA's 25th AGM in September 2013, attracting 173 delegates from 70 companies. Hosted for the first time and with great flair by Kennecott, the 2013 AGM marked almost a quarter of a century since the Association's founding. It provided a perfect opportunity to look back on the organisation's considerable achievements and to thank the member companies and individuals who have helped to turn IMOA into the industry-leading association it has become.

President Eva Model opened the meeting by contrasting the organisation today with its beginnings, when it was founded by six companies in 1989. Since then, IMOA has steadily grown its membership, rising to 31 members by the first AGM and now representing 68 members from 20 different countries. She paid tribute to the work done by Sandra Carey in Health, Safety & Environment and Nicole Kinsman in Market Development respectively, emphasising the importance of sound regulation and market development to the worldwide industry. Further, she pointed to the sustainability and enhanced communication initiatives that have also supported IMOA's five-year strategic plan.

Eva gently reminded members that the Association has a complement of just five staff, and that the considerable achievements of the past quarter century would not have been possible without the unstinting support of committee members, consultants and the wider membership, whom she thanked for their help and support.

She emphasised the continuing need for a trade association with a strong, credible voice in an evolving world before high-lighting the forthcoming presentations, including 'Advancing Sustainable Development Through Technology' and 'Bingham Canyon Mine – Sustainable Over Time' from hosts Kennecott.

The first of two dinners, hosted by Rio Tinto, took place at the Natural History Museum of Utah in the Rio Tinto Center, a stunning and sustainable building nestled in the foothills of the Wasatch mountain range. After a tour of the exhibits and an address by host and IMOA President Eva Model, members dined overlooking the Salt Lake valley.

IMOA hosted a second dinner at the Stein Erikson lodge in Deer Park. Secretary-General Tim Outteridge welcomed members and gave thanks to the current and former Presidents who have shaped the development of IMOA over the years. A 25th anniversary dinner, held earlier in the week, was attended by every President since 1992.

Tim also used the occasion to pay tribute to Tom Millenseifer, acknowledged by his peers as one of the world's leading authorities on molybdenum and rhenium. He had been a stalwart supporter of IMOA since its early days, serving on the HSE Committee for many years, but had recently announced his retirement.

After the formal AGM drew to a close, many members took up Kennecott's invitation of a tour of its new Molybdenum Autoclave Process (MAP) facility. MAP is a fully integrated plant producing molybdenum and rhenium with a number of environmental benefits.

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1 Past presidents Juergen Leibbrandt, Dick De Cesare and Ulrich Krynitz (from left) celebrating at Deer Valley.
2 IMOA members dine overlooking the Salt Lake Valley at the Natural History Museum of Utah at the Rio Tinto Center.
3 Tom Millenseifer, who announced his retirement after more than 50 years in the industry.