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MolyReview 1/2015

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Stainless rebar keeps traffic flowing

Whether on local streets or major highways, bridges are crucial transportation links – crossing roads, canyons or vast expanses of water. Closing them for repairs causes lengthy delays, time- and fuel-consuming detours and loss of productivity. It is therefore imperative for traffic flow to keep bridges in good condition. Durable molybdenum-containing stainless steel reinforcing bar is increasingly used to extend the service life of new and refurbished bridges, reducing the need for repairs and improving infrastructure investments.

Bridges naturally deteriorate as a consequence of age and heavy use, but climate is also a significant factor. This is particularly true in coastal regions where seawater is present in the atmosphere and in regions with long, snowy winters that require regular use of deicing salts. Both can spell trouble for bridges because both environments contain chlorides which greatly accelerate corrosion of the carbon steel commonly used for bridge components.

In reinforced-concrete bridges, chlorides can migrate over time through pores and cracks in the concrete covering to attack the embedded carbon steel reinforcing bars (rebars). The resulting corrosion product (iron oxide, or rust) needs more space than the original steel and consequently exerts pressure on the surrounding concrete. The pressure causes more cracks in the concrete to form, facilitating more chloride migration to the rebar. This vicious cycle accelerates the rate of deterioration and can threaten structural integrity if left unchecked. Needless to say, a bridge with corroded structural components is extremely dangerous!

North America

In 2002, the U.S. Federal Highway Administration (FHWA) found that of the 583,000 bridges in the U.S., approximately 15% were "structurally deficient" due to corrosion[1]. The report estimated the annual direct cost of corrosion to replace, repair and maintain these bridges at 8.3 billion dollars. Worse yet, it estimated the "indirect cost to the user, such as traffic delays and lost productivity…to be as high as 10 times that of the direct corrosion costs."

The FHWA report led to a large number of bridge replacement and rehabilitation projects across the U.S. In order to overcome the carbon steel rebar corrosion problem, the FHWA and several states approved the use of solid, corrosion-resistant stainless steel rebar, particularly for decks, barrier walls and support piers. As a result, over 100 U.S. bridges have now been built or rehabilitated with stainless steel rebar.

Because Canada experiences winters similar to the U.S. "snow belt" with extensive use of deicing salts and because it has bridges near the Pacific and Atlantic oceans, its infrastructure faces similar challenges. In 2004, the Ministry of Transportation in Canada's most populous province, Ontario (MTO), tested various rebar materials including galvanized and epoxy-coated carbon steel rebar and collected in-service data on their performance. Based on this data and on life cycle cost considerations, the MTO issued a memorandum requiring designers and engineers to use stainless steel rebar for bridges with very high traffic volumes. The reason was that replacement or major rehabilitation of bridges with average daily traffic of 100,000 vehicles ›

1 "Corrosion costs and preventive strategies in the United States," FHWA-RD-01-156 (2002) National Technical Information Service. Springfield, VA. USA.

Publisher:
International Molybdenum Association
454-458 Chiswick High Road
London W4 5TT, United Kingdom
www.imoa.info
info@imoa.info
+44 20 8747 6120

Editor in Chief:
Nicole Kinsman

Managing Editor:
Curtis Kovach

Contributing Writers:
Frank Smith (FS), Thierry Piérard (TP), John Shields (JS), Nancy Baddoo (NB), Robert Bukk (RB)

Layout and Design:
circa drei, Martina Helzel

Stainless steel rebar installation on the Hurdman Bridge in Ottawa. The work is done in stages so that some traffic can continue to flow across the bridge as seen in the background of the picture. © Frank Smith

or more would cause unacceptable traffic disruption[2]. The memorandum recommended Type 316LN austenitic stainless steel with 2–3% molybdenum and 2205 duplex stainless steel with 2.5–3.5% molybdenum as rebar materials.

Since then, scores of bridges on strategic roads and major highways have been replaced or rehabilitated in Ontario using these superior rebar materials. One example is the widening and re-decking of the Hurdman Bridge, which carries traffic on the busy Highway 417 over the Rideau River in the Canadian capital of Ottawa. Since the spring of 2014, new deck and barrier walls have been assembled in stages using 320 tonnes of 2205 duplex stainless steel rebar. Additionally, a large quantity of Type 316 stainless steel tie-wire was used to hold the rebar together prior to pouring the concrete. Because the deck was built in stages, hundreds of stainless steel couplers were needed to connect the rebar in the adjoining deck sections. Amazingly, all this work required only a restriction of traffic flow, rather than a full bridge closure.

A global trend

Stainless steel rebar use for bridges and other concrete structures is not limited to North America, but is growing around the world. In Asia, Hong Kong's Shenzhen Western Corridor Bridge used some 1300 tonnes of 2205 duplex stainless steel in the supports of its 3.8 km roadway. In Morocco, North Africa, the Casablanca Hassan II Mosque was in danger of crumbling into the ocean after only ten years of exposure to the waves. Originally built with carbon steel rebar, it underwent major restorations to replace structural slabs and pillars using high-performance concrete reinforced with 2205 duplex stainless steel (see the July, 2009 issue of MolyReview).

Stainless steel rebar remains strong and ductile in both frigid winter and sweltering summer, and it requires no special coating, cathodic protection or concrete sealer. Although the total construction cost may increase 1–10% when substituting stainless steel for carbon steel, this initial investment buys greatly reduced maintenance costs and greatly increased service life (projected at 75–100 or even 120 years for bridges). Several bridges have been built with a cost increase of only 1–3%. The cost savings achievable over the lifespan of the bridge make stainless steel rebar the obvious choice.

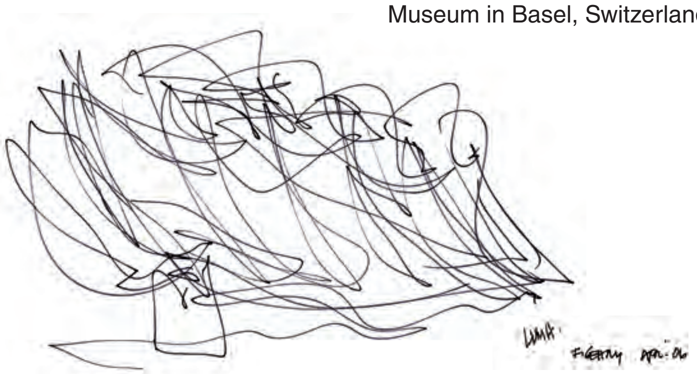
Stainless steel rebar is versatile and useful in many other applications. The added corrosion resistance and excellent durability of molybdenum-containing grades make them strong competitors for any application that demands reliable performance with minimum upkeep. Parking garages, retaining walls, tunnels, airport taxiways, and sea walls are just a few examples of structures that rely on stainless steel rebar. No matter where you go, stainless steel rebar will help to get you there safely, and maybe even on time! (FS)

2 Bridge Office Design Bulletin, "Corrosion protection guidelines for concrete bridge components." Memorandum, January 16, 2004. MTO Bridge Office. St. Catharines, Ontario. Canada.

Duplex rigging for glass sails

Canadian-born California architect Frank Gehry's project for Fondation Louis Vuitton exhibits unprecedented aesthetic innovation and technological sophistication. The spectacular glass sails of the roof appear so light and airy, in large part, thanks to the delicate high-strength molybdenum-containing duplex stainless steel support structure.

With the inauguration of the new Fondation Louis Vuitton museum in October 2014, Paris received what many see as its most recent architectural masterpiece. The museum is located in the Bois de Boulogne – one of the capital's two "green lungs" – on the edge of the most exclusive residential area in Paris. The building was conceived in 2001 when French tycoon Bernard Arnaud, the owner of luxury brands in perfumes, champagnes and haute-couture, met the famous American architect Frank Gehry, winner of the prestigious Pritzker Prize. Gehry's works include the renowned Guggenheim Museum in Bilbao, Spain, the Walt Disney Concert Hall in downtown Los Angeles, and the Vitra Design Museum in Basel, Switzerland.



Frank Gehry's spontaneous preliminary sketch for the museum.
© Gehry Partners, LLP and Frank O. Gehry.

From a spontaneous sketch to a digital model

If one specific characteristic defines Frank Gehry's style, it is undoubtedly his disdain for the straight line! Most of his works show an affinity for fluid forms, curves and counter-curves enhanced with glass walls, or twisted metal sheets placed on undulating facades. Arnaud, in awe of the architect's Bilbao Guggenheim Museum, was eager to present the City of Light with a prestigious showcase for his own contemporary collection, along with commissioned works, guest artists and temporary exhibitions. Gehry's initial sketch for Arnaud used an almost unbroken line, imagining a vessel with billowing transparent sails. He acknowledges the influence of 19th-century iconic parisian glass pavilions ❯

"To reflect our constantly changing world, we wanted to create a building that would evolve according to the time and the light in order to give the impression of something ephemeral and continually changing." Frank Gehry. © Fondation Louis Vuitton/Todd Eberle and conservatories on his design. Once the quick rough sketch was drawn, what remained was to translate the concept into a feasible project.

Gehry created several scale models from the initial sketch and produced a comprehensive digital model from the most advanced. The digital model allowed components of the hyper-complex structure to be defined, detailed and their dimensions to be calculated. The result? A spectacular vessel with twelve monumental glass sails projecting into the sky, supported by an incredible entanglement of steel columns, wooden beams, braces, transoms and tension rods. All these elements are interconnected and supported by a hard-shell structure that contains the museum's enclosed spaces. Composed of white blocks, the shell structure is called the "iceberg."

Aviation technology for a glass vessel

In the beginning, the challenges facing the project teams – designing such highly complex volumes and shapes, solving stability problems, fabricating and connecting the building elements, preparing detailed implementation plans, working out lifting and assembly schedules for every element of such a giant puzzle – were believed to be impossible to overcome. But the architect had already solved these problems. For the Bilbao Guggenheim museum, Gehry Technologies created a software package called Digital Project. Based on Dassault Systems' CATIA software for designing complex aerospace parts, they expanded it into an integrated collaborative platform. All project partners were required to use this tool along with a common 3D model in order to allow close collaboration between R&D, prototyping, fabrication and building phases of the project. This tightly controlled approach produced exceptional project performance that avoided discrepancies or delay,

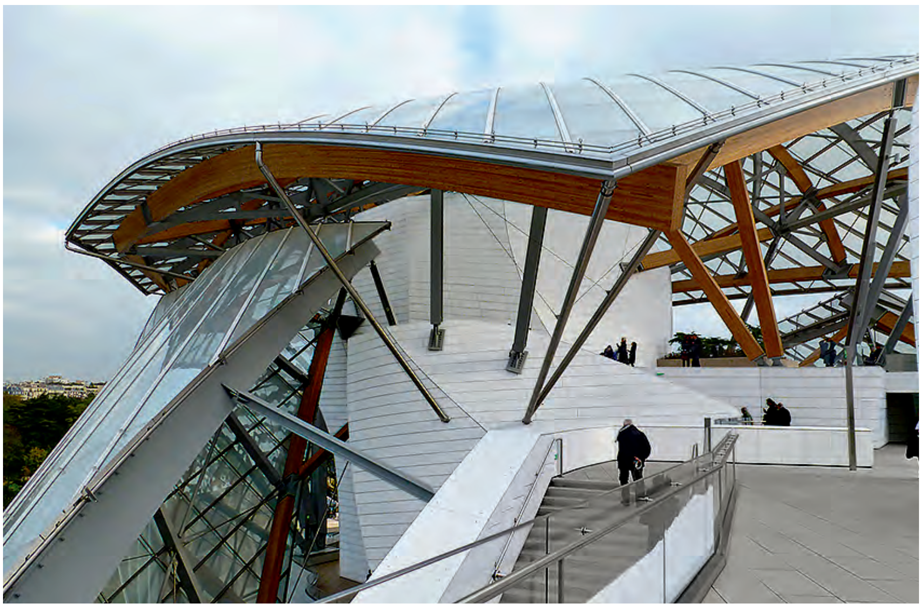
The roof support structure is made of wood, steel and duplex stainless steel components. © Eiffage

from the mounting of coupling parts to the perfect fit of structural elements on site. Partners created and shared more than 190,000 digital files as the project proceeded from 2008 to 2014.

A structure where "everything moves so that nothing moves"

The building comprises three major parts. The primary inner-core structure (the iceberg) contains the museum's attractive public and circulation spaces, gallery spaces and service rooms. The stacked boxes of the iceberg are clad with approximately 19,000 white Ductal® panels made from ultra-high performance fiber-reinforced concrete, whose unique curvatures require them to be individually molded. While circulating throughout the iceberg, visitors have access to several outdoor terraces that offer sumptuous and breathtaking views of Paris. From these terraces they can take in the iconic "Old Lady" (Eiffel Tower) and the La Défense business district with its skyline of slender skyscrapers.

The secondary structure, fixed on the building and rising in all directions, supports the amazing glass sails that billow in the Paris sky. It comprises steel columns and wooden beam "tripods" that support a monumental network of long-span laminated larch wood beams and carbon steel trusses. From 3 to 35 m long and variously angled, these elements gently swirl underneath ›

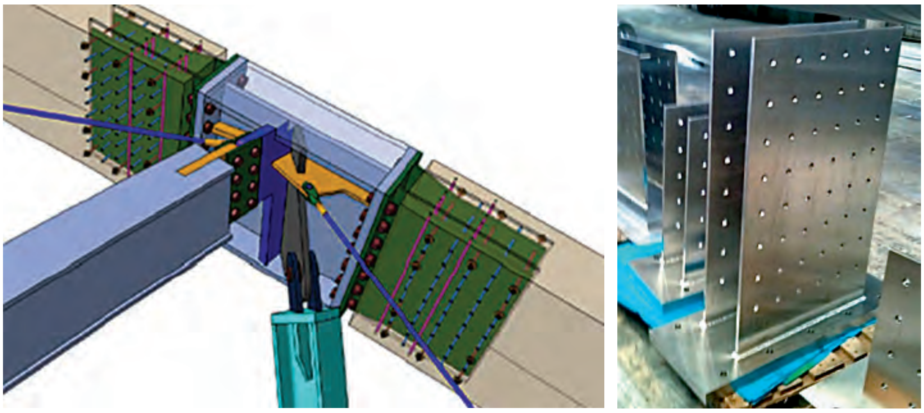


Fixed to the building inner-core, the "iceberg," wood and steel "tripods" support the isostatic suspension frame of the glass sails. © Effitext

The glass panels are supported by a light duplex stainless steel grid. Duplex stainless steel, a flexible building material, can be shaped to the needs of the designer without requiring any protective paint.

the sails. The wooden beams are fitted with 540 duplex stainless steel inserts to ensure firm connections. Connecting all these elements requires 430 unique, geometrically complex nodes made from 100-mm thick carbon steel/duplex stainless steel hybrid plates. The nodes link the wooden and metal elements, ensure the structure's stability, and permit the normal movement of every element in the massive, complex assembly, "making it possible that everything moves so that nothing moves!" as one engineer observed.

The freestanding tertiary structure includes the twelve curved-glass sails wrapped around and above the iceberg and the impressive duplex stainless steel grid that supports them. Three sails act as umbrellas for the building while the other nine sweep around it, creating the appearance of a "ghost ship" sailing above the treetops of the Bois de Boulogne. The sails weigh between 200 and 350 tonnes each and span up to 30 m. Their individual surface areas range from 500 m^2 to 3,500 m^2, and total 13,500 m^2. The sails contain a total of 3,584 curved-glass panels with different thicknesses. The individual 1.5 m x 3 m panels were hot-formed to unique curvatures that depend upon their locations on the sails. This innovative technique, originally developed by the automotive industry, avoided the need for expensive custom molds for each panel.



Duplex stainless steel inserts connect wooden beams and steel columns. © Eiffage

Duplex, the metal of choice to rig the glass sails

Satisfying the complex array of constraints imposed by this unusual work of art and its suspension frame was no small task. The materials solution was somewhat unconventional – 2205 duplex stainless steel containing 2.5%–3.5% Mo instead of the more commonly specified Type 316L stainless steel that would have had sufficient corrosion resistance to withstand the atmospheric conditions in Paris. The duplex grade is much more corrosion resistant and is primarily intended for more corrosive environments, for example in chemical processing or offshore oil drilling. However, it was selected here because its minimum yield strength is more than twice as high as that of Type 316L. The yield strength advantage translates to a 30 percent reduction in the structure's weight. With cantilevered trusses and beams spanning up to 30 m there was no choice: duplex stainless steel had to be used to make it work. The higher strength and corrosion resistance are actually leading to a general shift among architects from Type 316L to 2205, especially for prestigious structures and for more corrosive locations. Maintenance costs and aesthetics were also important factors in the material choice. Although parts and elements that can be easily accessed for cleaning are made of painted carbon steel, the light suspended grids that are difficult to reach are duplex stainless steel.

The glass sails required approximately 25,000 different parts. The nodes, which articulate the main suspension frame and the duplex grid, are an assembly of 120 mm-thick duplex plates to which 9,000 duplex stainless steel mounting "ears" are welded. Gutters of 220 mm ❯

Stainless steel pipes for reliable and sustainable rainwater management

Gutters on the roofing, acting as downspouts, collect rainwater from the 13,500 m^2 glass surfaces and discharge it into the pool at the foot of the building. Before being used to clean external surfaces, the water is filtered and purified to remove contaminants or micro-organisms that could be deposited on the glass. All glass sails will be manually cleaned twice a year from suspended cradles, using mechanized brushes. Rainwater will also feed the museum non-drinkable water network.

Protection of art works was an important criterion for the choice of the indoor piping materials. In rooms where leaks could damage exhibits, pipes are made of welded Type 316L stainless steel and sound-insulated with glass-wool sleeves. This approach was chosen over traditional PVC piping with solvent-cemented connections that were deemed less reliable. For some indoor water piping, stainless steel and aluminum pipes are connected with flanges.

Straight or curved, duplex gutters are fitted with fixing "ears" and mounting plates. © Gérard Tordjman diameter, 20 mm thick duplex stainless steel, help to stiffen the support grid, recover rainwater on the periphery of the roofing, and drain it to downpipes on the front or inside the iceberg (see box on p. 7). They are welded to duplex stainless steel mounting plates, that are fitted with "ears" and other hanging and fixing devices. The support grids include duplex tubular transoms (90 and 80 mm diameter, 8 mm thick) that are up to 12 m long and connect to duplex stainless steel mullions that support the glass panes. Added to these elements are braces, tension rods and thousands of bolts, all of them in duplex stainless steel as well. Finally, duplex stainless steel is used for the rails for suspended cleaning cradles and hundreds of securing fasteners (tie-down rings, pigtail hooks) spread on the tripods and the steel grids.

Eiffage, the main contractor for the large sails, worked closely with the supplier of the fabricated duplex stainless steel parts ThyssenKrupp Materials France (TKMF). Fabrication of the various components demanded attention to detail and precision. In order to avoid deformation due to heating and to comply with the tight flatness tolerances, TKMF acquired specialized high-pressure water-jet equipment to cut the components. The cutting process is so slow that it required two years of continuous day and night shifts on the new machine to prepare all pieces. Because of the great variation in dimensions and curvature, the roofing components had to be milled on five-axis machines. The variety of these parts was so great that engineers considered two identical parts to constitute a series! At the end, all duplex stainless steel was finished with a 220-grit directional polish to add to the overall brightness of the building, meeting Gehry's aesthetic requirements. To avoid risk of corrosion that could damage grid components, engineers verified the microstructure of all parts metallographically. Very few on-site welds were needed since 99 percent of the secondary- and tertiary-structure joints are bolted. They aligned perfectly during construction thanks to the close coordination among all involved parties.

In this era where buildings are no longer simple square boxes, and architects are constantly pushing the limits of what is physically feasible, stainless steel doesn't just make these audacious shapes possible but makes them beautiful. (TP)

With its glass sails and the water features throughout, the new museum resembles a ship sailing above the Bois the Boulogne. © Fondation Louis Vuitton/Todd Eberle

An impressive architectural success by the numbers

- 15,000 tonnes of steel are present in the whole of the building structures, which is twice the amount in the Eiffel Tower!
- 2,000 tonnes of carbon steel are used in the suspended frame of the secondary structure.
- 1,500 tonnes of high-strength duplex stainless steel support the majestic glass sails.
- 3,430 glass panes, individually hot-formed in different thicknesses to various curvatures, cover the 13,500 m^2 of surface area contained in the 12 sails.
- 430 unique, geometrically complex nodes link all wooden and metal elements.
- 540 duplex inserts connect wooden beams and carbon steel columns.
- 10 km of duplex stainless steel curved mullions have been manufactured and welded.
- 5 km of stainless steel transoms adjust with millimeter accuracy.
- 2 km of stainless steel gutters contribute to the stiffening of the support grid.

Lighting the way to a greener future

LEDs are revolutionizing lighting technology. They are more sustainable than traditional lighting sources because they use much less energy and last much longer. At the same time, lighting can be used in completely new ways. Molybdenum plays a key role in making the sapphire substrate of LED devices and is also important as a heat sink in these lights.

In Stockholm, Sweden on December 10, 2014, Isamu Akasaki and Hiroshi Amano of Japan, and Shuji Nakamura of the United States each received a share of the 2015 Nobel Prize in Physics from King Carl XVI Gustav of Sweden. Their accomplishment: the first high-brightness blue light-emitting diode (LED). Akasaki and Amano, working together, and Nakamura, working independently, produced blue LEDs in 1992 using different approaches. Their achievement, the culmination of years of research by many scientists around the world, made possible a bright future in energy-efficient lighting devices. Green and red LEDs have been available for many years, but only the advent of the blue LED enabled the blending of the three colors to produce white light. The researchers' work solved the problem and opened the door to the future.

Reflecting upon the Nobel award in an email statement, Frances Saunders, president of the Institute of Physics, a worldwide scientific organization based in London, said, "This is physics research that is having a direct impact on the grandest of scales, helping protect our environment, as well as turning up in our everyday electronic gadgets."

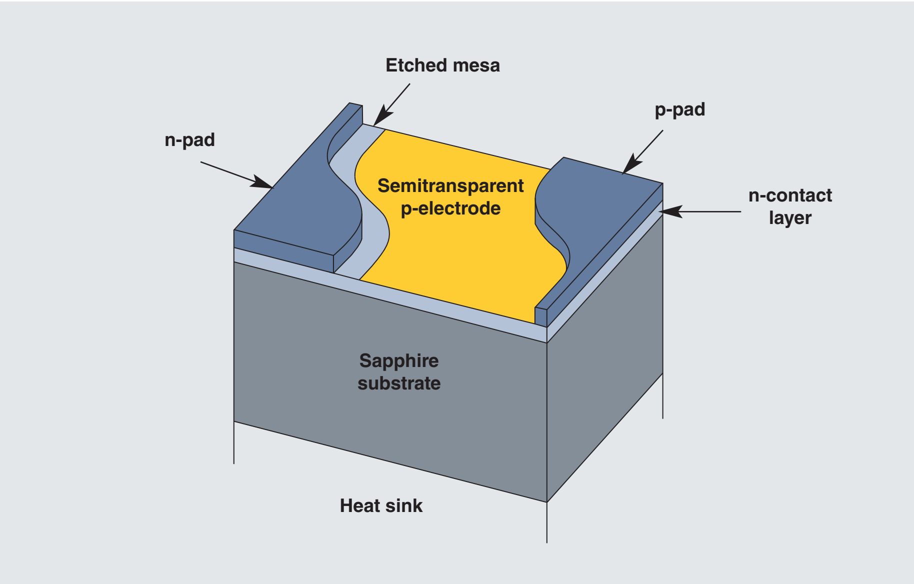
LED light and society

LED lighting is an extraordinary advance over current illumination technologies because it is much more eco-friendly. For a given amount of electrical power, LED bulbs produce four times the light of fluorescent lamps and nearly 20 times the light of an incandescent lamp. This energy efficiency is important because lighting is estimated to be responsible for 20%–30% of the world's electrical power consumption. Moreover, LED lights do not have the problem of mercury disposal associated with fluorescent lamps.

The high efficiency of LEDs and their ability to operate at low voltages has led to the miniature flashlights, key fob lights, and mobile phone lights that we are all so familiar with. Perhaps more importantly, they have fostered creative solutions for lighting areas that lack traditional electrical generation and distribution systems. For example, programs in Africa to replace polluting oil lamps have distributed millions of solar-powered LED lamps in remote areas. Durability is another great advantage of LED lamps. Their operating life is ten times that of fluorescent lamps and 100 times that of incandescent lamps.

Manufacturing the LED

The science of LED lamps is not the only revolutionary thing about them. They require manufacturing technology that is entirely different from traditional lamps. While the traditional incandescent lamp relies on heating a tungsten wire filament and the fluorescent lamp requires excitation of a gas-filled tube to activate fluorescent coatings on the tube, LED lighting is a semiconductor-based technology. A new way of making lights was needed and molybdenum plays an important role in that technology. ›



Schematic of a planar LED chip, illustrating the active region (yellow) and sapphire substrate (gray). Light is emitted through the semitransparent electrode of the active region. Source: STR Group: Modeling Solutions for Crystal Growth and Devices (www.str-soft.com)

Molybdenum metal crucibles for sapphire production. © Plansee

LEDs require a substrate on which to build the device. Substrates are made from high-purity single-crystal sapphire (Al_2O_3), because of its excellent thermal conductivity and thermal expansion match with the semiconductor layers to be built on it. To manufacture the required single-crystal material, sapphire is melted at temperatures above 2,000°C in molybdenum crucibles and allowed to solidify over a period of 15–20 days under carefully controlled conditions to form a solid single-crystal "boule." Boules are produced in a number of sizes, with a recently announced furnace claiming a capability of 500-mm diameter, 300-kg boules. Molybdenum's excellent high-temperature strength and its resistance to attack by molten sapphire are the primary reasons it finds use in this application. The high purity of molybdenum metal (99.97% is typical) assures contaminant-free sapphire with the best properties.

Growing the sapphire substrate

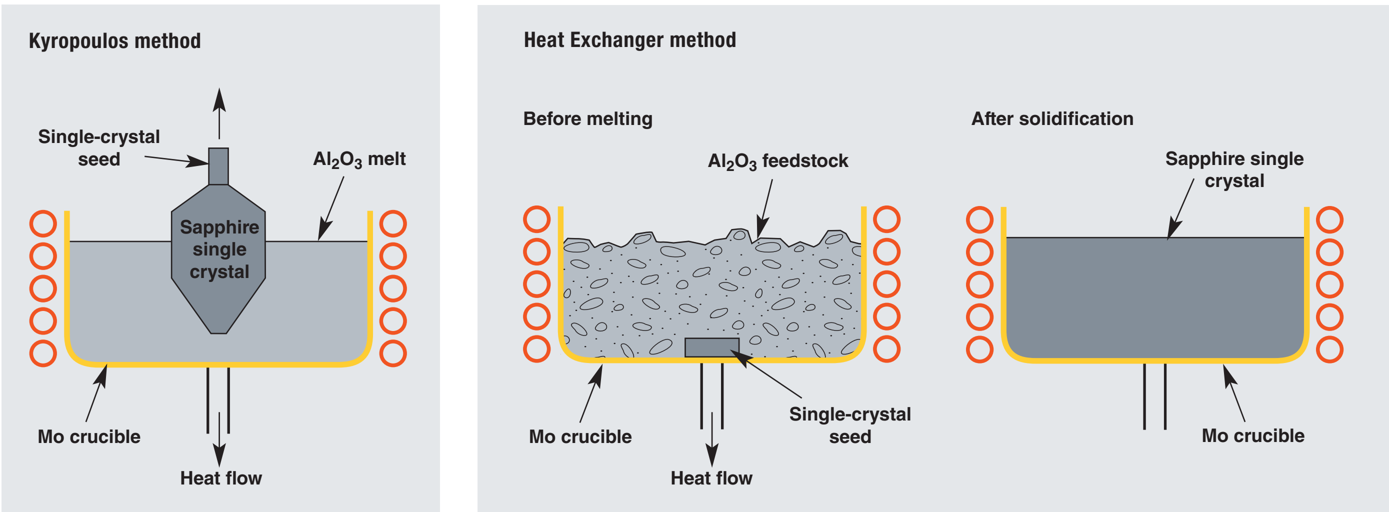
Most LED substrates are grown using one of two methods: the Kyropoulos method and the Heat Exchanger method. In the Kyropoulos method, a molybdenum crucible is filled with pure alumina (Al_2O_3) powder and melted. A cooled single-crystal sapphire seed with a desired orientation is brought into contact with the melt surface. By careful control of the melt temperature distribution a large sapphire single crystal grows from that seed. The crystal is slowly rotated and withdrawn from the melt as it grows.

The Heat Exchanger method places the seed, instead, at the bottom of the molybdenum crucible where it is cooled to prevent melting. The raw material is a mixture of alumina powder and 'crackle' (chunks of high-purity alumina recycled from previous runs). The furnace charge of raw material is then melted and allowed to cool under carefully controlled conditions. Eventually, all the melt solidifies as a sapphire single crystal grown from the original seed. In this method, the crucible is used only once, and is broken away from the finished boule.

In addition to the molybdenum crucibles used in these two processes, molybdenum heat shield assemblies help control the temperature distribution within the furnace. This critical function is necessary to manufacture single crystals of the required uniformity, since the growth process is dependent on temperature changes during the furnace run.

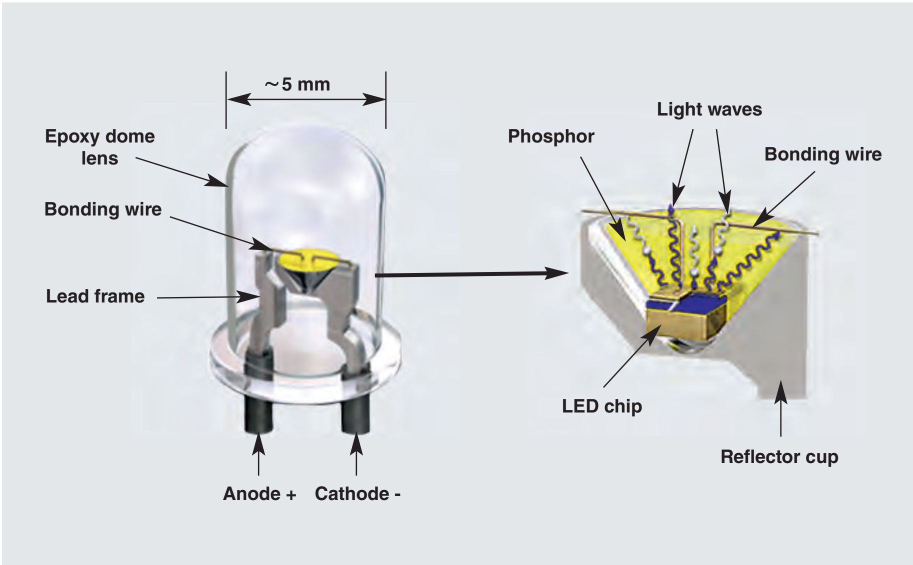
Producing the 'device' also requires molybdenum

After solidification, cylinders are core-drilled from the boule and individual wafers are sliced and polished from the cylinders. The wafers are less than 0.5 mm thick, and have diameters compatible with standard semiconductor processing equipment, where thousands of individual LEDs are produced on each wafer. The LED devices are built on the sapphire substrate, layer by layer, using processes like Metal Organic Chemical Vapor Deposition (MOCVD) or Molecular Beam Epitaxy (MBE). Such processes employ high temperatures ›



Schematic drawings of the Kyropoulos (left) and Heat Exchanger (center and right) techniques of crystal growth. Source: SubsTech (www.SubsTech.com)

Individual LED lamps with epoxy dome dyed to indicate the color of light produced. © iStockphoto.com/JamersonG



Individual LED light bulbs are only about 5 mm in diameter, but the LED chip is even smaller, measuring a fraction of a millimeter in length and width. Source: Molecular Expressions (www.micro.magnet.fsu.edu), National High Magnetic Field Laboratory (www.nationalmaglab.org).

and reactive materials, so molybdenum components are used in the deposition equipment.

Additional metal coatings may be needed for the LEDs to perform properly. Traditional physical vapor deposition (PVD) processes like evaporation are used to metalize the devices. Molybdenum heating coils and boats, which hold the evaporant, are common components used in these processes. Molybdenum's high-temperature strength and stability and its compatibility with evaporants make it a natural choice.

LED devices built on sapphire substrate need a structural base with compatible thermal expansion characteristics and high thermal conductivity to remove heat produced during operation. Here again molybdenum fills the bill, either as pure molybdenum metal or engineered composites of molybdenum and copper. Molybdenum-copper composites also appear in the heat sinks and base plates used for high-power LED lamps.

After the devices are manufactured on the sapphire substrate, the wafer is sectioned to obtain the individual LEDs, which are then assembled into lamps. The figure above emphasizes the size of a typical finished LED bulb. The LED chip, typically a fraction of a mm in planar dimensions, is embedded in a clear epoxy envelope that is only about 5 mm in diameter. Individual bulbs can be used alone (e.g. holiday lighting strings) or in groups (e.g. traffic signals, strip lighting, automotive lights or interior lighting fixtures as seen on the right).

The future

LED lamps have made great inroads in the automotive, commercial, and residential marketplaces worldwide. They have given designers new and creative ways to illuminate buildings and spaces e.g. the "Indemann" on the cover of this issue. The annual growth rate for LED lamps is estimated to be a phenomenal 45%. The U.S. Department of Energy has forecast that 74% of lighting sold will be LED by 2030, and that LEDs have the potential to reduce U.S. lighting energy consumption by almost one-half [1]. The global LED market has been predicted to grow from $4.8 billion in 2012 to $42 billion by 2019. With manufacturing costs continuing to drop thanks to ongoing research, development, and engineering advances, LED lighting will contribute even more to much-needed energy conservation efforts. As markets continue to grow, molybdenum will support that growth at nearly every step in the manufacturing process. (JS)

Commercial LED lamps employ multiple individual bulbs. Semiconductor technology permits great latitude in the way individual devices are arrayed in the lamp. © iStockphoto.com/ludinko

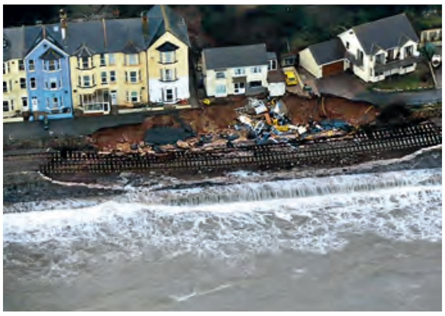
1 www.ssl.energy.gov/tech_reports.html

Reinforcing cliffs and walls

Stainless steel ground and rock anchors keep land from sliding and walls from tumbling. They were used recently to stabilize and reinforce a crucial sea wall in England and an unstable rock face at the site of important antiquities in Greece. Molybdenum provides the added corrosion resistance necessary for a long service life even in the most corrosive environments.

Building a seawall to withstand the biggest waves

On the night of February 4th, 2014, a major storm hit South West England. At the sea-side resort of Dawlish, huge waves crashed against the sea wall which retains the coast-hugging mainline rail link from London to Cornwall. The waves washed out the granite facing blocks and eroded the back fill, leading to failure of a 100 meter length of the wall. The railway was left suspended in mid air and collapsed into the sea, severing this strategically important route into Cornwall.



The train track in Dawlish was left suspended in mid-air after storms battered the sea wall in February 2014. © Network Rail

Network Rail, the owner and operator of most of the rail infrastructure in Great Britain, called for urgent repairs to the track and seawall. Houses in the vicinity also required stabilisation because their foundations had been ripped away by the sea. In addition, the Global Crossing Cable, a major communication line laid on the Atlantic seabed connecting New York and London, runs alongside the main railway line and had to be supported. Rebuilding and fortifying the 100-meter breach of the sea wall began immediately and a crew of more than 300 people worked round the clock in order to complete the repairs in time for the Easter holidays – a busy time for that particular train route. One of the challenges facing Network Rail and the various contractors was the continuing stormy weather. There were exceptionally high tides and rough seas, which limited the time that the teams could work on site. Huge waves caused by another severe storm a week later led to further damage to the sea wall.

A critical component of the repair was the use of 160 fully threaded stainless steel anchor bars to tie together 5,000 tonnes of concrete in the construction of the wall. The anchors were part of the Grip-Bar system manufactured by Sheffield-based company Stainless UK. They were 6 meters long, 36 mm and 39 mm in diameter and had 20 mm thick end plates and fixings. Type 316 austenitic stainless steel was selected for the anchors. This grade of stainless steel contains about 2% molybdenum which gives improved pitting and crevice corrosion resistance in chloride-containing environments.

Grip Bar stainless steel tie bars being installed in the base of the new concrete sea wall at Dawlish. © Network Rail

Stabilizing the Acropolis cliff face

Stainless steel anchor bars have also been used to stabilize part of the northern cliff face of the Acropolis in Athens. This was necessary to prevent the cliff from collapsing onto the sacred cave containing the Klepsydra Spring, one of Athens' ancient sources of water. Other ancient sanctuaries which date back to Neolithic times (3500–3000 BC) were also in danger. Landslides were common over the centuries and the cliff collapsed onto the cave in the 1st century AD. Two thousand years later the continuing threat of crumbling of the unstable rock face led to a major renovation project to preserve this World Heritage Site. Type 316 anchors with diameters of 16 mm and lengths of up to 6 meters were fixed into the rock using resin capsules and steel end plates. ❯

The stainless steel anchor bars which stabilize the northern cliff face of the Acropolis and their end plates are very unobtrusive – just barely visible in the foreground of the picture. © Stainless UK

Stainless steel anchor bars

The stainless steel anchors are made by cold drawing which produces high strengths, nearly three times higher than the strength in the annealed (softened) condition (see table). The bars are threaded along their entire length via a cold forging process, forming a custom-made, coarse pitch. The technique results in localized strengthening of the threads and the pitch size facilitates the attachment of fixings. The bars can be cut to length on site without damage. Traditional stainless steel rock anchors are made of reinforcing bars with a fine threaded section of fixed length on one end. The threads are tapped, which does not add to their strength. Comparative testing at the University of Sheffield showed that across a range of grout strengths, the coarse-pitch anchor system had a bond strength, up to the first slip, of at least 2.8 times that of equivalent stainless steel reinforcement bar.

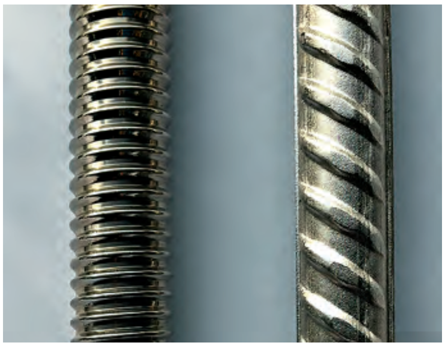
Stainless steel anchor bars are used for soil nails and ground anchors to stabilize soil slopes or to anchor structures in the ground. They also serve as cross ties to strenghten buildings and bridges, as holding down bolts, and to secure coastal defense walls and slabs. Their relatively high ductility also makes them ideal for areas of seismic activity. Compared to carbon steel alternatives where the required additional corrosion protection can lengthen the installation process, stainless steel installation is quick and easy.

Stainless steel is becoming an increasingly popular choice of material for ground and rock anchors. The inherent corrosion resistance, especially of the molybdenum-containing grades, leads to a durable, long-life solution. This helps to protect infrastructure investments in construction, transport and communications. (NB)

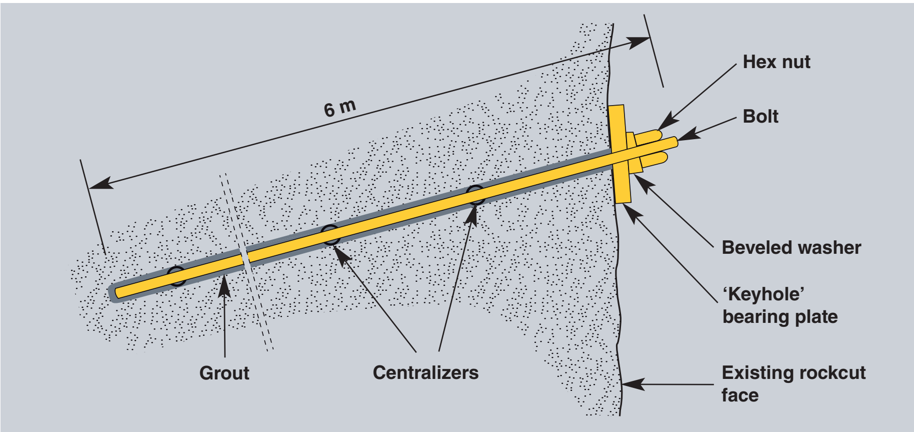
Ground and rock anchors are used to restrain and stabilize tunnels, rock faces, cuttings and slopes as well as provide support to retaining walls. The anchor is under tension and is installed inside a borehole. Its end is generally grouted into deeper sound rock with cementitious or resin grout. The anchor applies a restraining force to the rock face or slope via a plate. **Soil nails** work on a similar principle and are used for slope stabilization. Anchors can be used to stabilize individual blocks or in a grid pattern to improve stability of an entire rock face. They may be temporary or permanent and, dependent on the environment, have varying durability requirements. Design lives exceeding 100 years are not an uncommon requirement for permanent anchors.

Mininmum mechanical properties for annealed and cold drawn bar

For bars 10–48 mm diameter	Annealed	Cold drawn
0.2% proof strength	200 MPa	650 MPa
Ultimate tensile strength	500 MPa	750 MPa
Elongation	40%	15%



The cold forged thread of the rock anchor on the left is much stronger and provides much better “grip” than the traditional reinforcing bar profile. © Stainless UK



The 6 meter long rock anchors are inserted in pre-drilled holes where centralizers keep them centered before the grout is injected along the entire length of the anchors. After the grout has cured, the nut on the outside is tightened to put the whole system under tension.

Drilling of the bore hole where a Grip-Bar will be installed to stabilize this old stone bridge. © Stainless UK

Designing a memorial

Pittsburgh has a new memorial made of stainless steel, glass and stone. The work of art is a tribute to the citizenry of Western Pennsylvania. Its building materials are a reflection of the local surroundings and the industries that shaped the region. Thanks to the use of low-maintenance molybdenum-containing stainless steel the area will be graced with a memorial that is both beautiful and lasting.

The stainless steel spires glisten in the sunlight of the new memorial.

In the first half of the 20th century, the steel industry in Western Pennsylvania was the global leader in steel production. During most of this time, the area produced more steel than all of England, France, Germany and Russia combined, hence Pittsburgh's nickname "the Steel City." Steel that was once vital to the advancement of the region and the country is now finding a new purpose in a recently finished memorial.

"The Southwestern Pennsylvania World War II Memorial" was designed by the famous artist Larry Kirkland of Washington, D.C. His works marry materials and shapes not only for their aesthetics, but also for significance to their surroundings and sustainability. For this particular piece, steel and glass were selected for their historical relevance to the region. He chose molybdenum-alloyed stainless steel as the focal point of the memorial, because it combines beauty and sustainability with strength and durability. With its highly-reflective surface, it also presents the desired "contemporary look" that the designer wanted to achieve.

Design and material challenges

The 52 tapered trapezoidal-shaped stainless steel spires (ranging from 4.45 to 8 m in height and 0.6 m by 51 mm width at the base) must bear the weight of 11 glass panels, framed in stainless steel, each weighing 200 kg. They buttress 12 triangular-shaped granite slabs etched with historical content weighing 300 kg each. The spires have 1,890 m of invisible welds and must retain their shape while bearing the weight of the stone and glass. They must also be resistant to corrosive elements introduced by the environment. These challenges are met with the use of 7 gauge 316L molybdenum-alloyed stainless steel.

Maintenance of the memorial

Western Pennsylvania's temperature extremes, coupled with high levels of air pollution, acid rain, and heavy use of de-icing salts during winter months, can have an adverse impact on the integrity of most building materials. This is one reason why public art projects in the area must include in their planning a provision that establishes a maintenance fund. Capital is held in an escrow account and is disbursed for the cleaning and upkeep of the art work over time.

The ability of molybdenum-containing stainless steel to stand up to corrosives allows it to be washed with ordinary tap water from the public supply. Gouges and scratches can easily be cleaned and removed with buffing. These two characteristics alone will aid in keeping maintenance costs in check. Also, because 316L is resistant to corrosives, "a properly designed and maintained memorial such as this could last a very long time," as Dr. Roy J Matway of ATI, Allegheny Ludlum Corporation stated.

A lasting tribute

The artwork stands as a tribute to the citizenry of the area. It is a reminder of their contributions, not only to the past, but the future. Because the designer and specifiers had the foresight to recognize molybdenum-alloyed stainless steel as a key component of the art piece for its strength, durability, aesthetics, and historical significance, this tribute will endure, like the Steel City itself. (RB)

IMOA news

AGM

The venue for IMOA's 26th Annual General Meeting moved East this year to Hangzhou, China. Kindly hosted by Jinduicheng Molybdenum Co Ltd, the event attracted some 180 delegates over the four-day meeting. Outgoing President, Eva Model, noted the increasing level of IMOA's market development activities in China and welcomed guests from China's mining, processing and steel industries. Eva outlined some of the highlights of the past year, including the generation of a new five-year strategic plan. Commenting that IMOA was a well-regarded commodity association, Eva paid tribute to the Secretariat team and thanked the Executive Committee and the wider membership before welcoming new President Carlos Letelier of MOLYMET.

Among the varied presentations was an overview of the Chinese molybdenum market from hosts Jinduicheng, and an analysis of the development of molybdenum-containing stainless steels in China by TISCO.

IMOA hosted a dinner at the Cheng Huangge which was reciprocated on the following evening by hosts Jinduicheng at the 704 Garden Restaurant. On the last day, delegates had the opportunity to tour Hangzhou Steel before departing.

New market development tools launched

IMOA has launched a new monthly e-newsletter, Stainless Solutions, targeted at design and specification professionals in the architecture, building and construction (ABC) sector. The newsletter highlights a different stainless steel issue every month and is sent to over 500 recipients.

Additionally, a comprehensive set of technical resources for the stainless building and construction sector has been compiled into a downloadable library on the IMOA website. Containing over 280 PDFs, the collection is categorized into key areas for ease of reference and contains case studies, technical articles and other resources. Both are featured on the ABC pages under "Molybdenum uses" on the IMOA website.

IMOA's ever-popular duplex fabrication brochure has been revised and updated. The third edition includes a new chapter on weld overlay, new grades and information on the new formable duplex stainless steels. The design of the high-performance austenitic fabrication brochure was recently updated and published in Italian as well as English. Both are available on the IMOA website.

Members imbibe ... the ambiance at Cheng Huangge during the IMOA hosted dinner.

Gear steel study

A newly-developed molybdenum-alloyed carburizing steel has outperformed existing gear steels without increasing alloy cost in a study conducted by the German Institute for Machine Elements (FZG) in Munich, Germany.

The IMOA-sponsored study, conducted in assocation with a German special steel producer, found that hardenability and strength were greatly improved, with the new steel clearly outperforming all reference steel grades. The new steel contains twice the amount of molybdenum compared to standard high-end gear steel.

Dr Nicole Kinsman, Technical Director, said: "This superior performance means that gears made from this new grade could support either higher torque, or for equivalent loads, could be built smaller and lighter. Possible applications include wind turbines, heavy machinery, trucks and cars."