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The beginning of life on Earth

It may not be widely known, but life's very existence is directly connected to molybdenum. As one of a handful of essential elements, molybdenum helps the human body – and all other living things – perform key life-supporting processes. Molybdenum even played an important role in the very beginnings of life on Earth, billions of years ago.

Molybdenum is essential for life. It plays a critical role in the production of several enzymes in humans and animals that help to remove toxins and waste products, and it helps cells to produce energy. It is an essential micronutrient for plants, enabling them to extract nitrogen from the air and soil.

Nitrogen is also essential to all life. It is largely present in the air and soil in an inert form that cannot be readily used. Strong chemical bonds hold the nitrogen atoms together in pairs, and they must be broken to release the single atoms used in biological processes. Nitrogen atoms combine with other chemicals to form life-sustaining biological compounds. This conversion process is known as nitrogen fixation.

There are many theories about exactly how life on Earth began and evolved – but a common factor is the presence of molybdenum.

The breath of life

One theory postulates that life started in the seas. The Earth's atmosphere was very different from the oxygen-rich one we breathe today, consisting largely of nitrogen, carbon dioxide and water vapor. The seas were also relatively oxygen-free, although some oxygen would have been produced from the first photosynthesis by early forms of bacteria called cyanobacteria, living in the shallow seas. These early organisms used abundant soluble iron present in the seas to 'fix' nitrogen for growth.

As these organisms grew, photosynthesis led to the oxygenation of the shallow seas, which turned the iron insoluble and inhibited further nitrogen fixation. A period of stagnation began in the development of the earth's atmosphere that scientists refer to as the "boring billion" years from 1.85 to 0.85 billion years ago.

The 'boring' period ended with a sudden growth in organic life and the increasing oxygenation of the Earth's atmosphere. Scientists have argued that a dramatic increase in the amount of soluble molybdenum in the sea at the end of the "boring billion" years led to the development of the molybdenum-containing enzyme *nitrogenase*. A powerful nitrogen-fixing enzyme, nitrogenase greatly increased the amount of available nitrogen, leading to faster growth. As organisms grew, their increased photosynthesis produced more oxygen, creating the oxygen-rich atmosphere that has supported life ever since.

Rock of ages

Another theory asserts that life began not in the sea, but on land. In a paper published in 2015, a team from the University of Washington found evidence of nitrogen fixation in some of the ›

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Palm oil storage tanks in Holland made of LDX 2101®
stainless steel. © Loders Croklaan

oldest rocks on Earth. Stüeken and her co-authors chemically analyzed more than 50 rock samples from what is now southern Africa and Australia. The results were consistent with a pattern caused by nitrogen-fixing by microbes using nitrogenase. Because some of the rocks are more than three billion years old, researchers have suggested that early life may have existed as a single-celled layer of oxygen-producing slime. This oxygen would have reacted with molybdenum in rock, turning it into a soluble form much more suitable for nitrogen-fixing. Thus, it is possible this process could have contributed to the increase in available molybdenum in the sea, "kick-starting" large-scale marine photosynthesis.

A stabilizing influence

There is yet another, more intriguing, theory surrounding the beginnings of life on Earth – one that suggests terrestrial life actually began on Mars! And according to Professor Steve Benner, who presented his theory in 2013, molybdenum proves it.

The idea of panspermia, the transfer of life between planets, is not new. However, Professor Benner's work takes the idea a stage further by looking at the availability of boron and molybdenum oxides. He states that simply adding energy to the organic compounds present on the early Earth would have only resulted in a tarlike 'gloop', not the beginnings of life. This problem has puzzled scientists for many years.

Benner proposed that borate and molybdate acted as catalysts to produce the correct formation of RNA, the precursor to DNA. RNA is widely accepted by scientists to be the first genetic molecule to form and be capable of self-replication. His theory postulates that borate and molybdate stabilized and rearranged the sugar molecules in carbon compounds to make ribose – the 'r' in RNA. Crucially, however, he asserts this could only happen when the boron and molybdenum were themselves stabilized – in their oxidized forms. Because there was very little oxygen on

Life on earth would not be possible without molybdenum. © shutterstock/sdecoret

Earth three billion years ago, Benner concludes that this must have taken place somewhere else – somewhere with plenty of oxygen, like Mars.

Another aspect supporting this theory is that the early Earth was awash with water, which would have both prevented boron from developing in the necessary quantities and attacked RNA as soon as it was formed, posing the second problem for theories arguing that life began on Earth.

By contrast, scientists believe that the surface of Mars three billion years ago had very little surface water, but abundant oxygen. The theory proposes that life began in the more welcoming cradle of the Martian surface before being transported to Earth by a meteorite, where it continued to flourish. By providing plausible explanations for key questions that have shaped debate on the terrestrial origins of life, Benner's theory has gained many followers and looks set to become firmly established as another possible explanation of how life began.

Molybdenum's essential role in sustaining modern life is well documented and understood. There will always be a discussion about the origins of life, and of course scientific discoveries are adding to our understanding continually. However, molybdenum is an essential factor in all the current major theories regarding life's origins and evolution, so it seems likely that it was just as important to life billions of years ago as it is today. (AH)

Molding plastics with molybdenum

Molybdenum-alloyed mold steels are a key component of plastic injection-molding machines. They must be easy to machine into complex geometries that mirror the finished molding, resist deformation and wear under the stress and abrasion of the process, and be able to maintain a high surface polish for long production runs. Molybdenum is a vital alloying element in meeting these requirements.

Plastic objects are ubiquitous today. They can be small and simple, like disposable bottle caps, or large and highly engineered, like multi-component aircraft parts. They are found in a multitude of sizes, forms, colors, and applications. Of the many molding processes available for their manufacture, the most widely used and versatile is injection-molding. As its name implies, this process injects molten plastic into a mold, usually made of steel. Molybdenum-alloyed steels are the mold material of choice because of their strength and durability at elevated temperatures. They represent an important market for molybdenum.

Injection-molded products

Two examples of injection-molded products serve to demonstrate the flexibility and range of the process. The first is high-pressure gas tanks. These are constructed from an inner blow-molded plastic cylinder, wrapped in glass or carbon filament, then covered by an injection-molded plastic shell. These tanks are about 70% lighter than steel tanks with a similar pressure rating, making them ideal for mobile applications such as commercial and private vehicles operating on natural gas or hydrogen. Both traditional combustion engines and fuel cells rely on them for their fuel supply. Even the market for lower-pressure liquefied petroleum gas (LPG) canisters is seeing an increase in the use of composite plastic containers because of their light weight and durability.

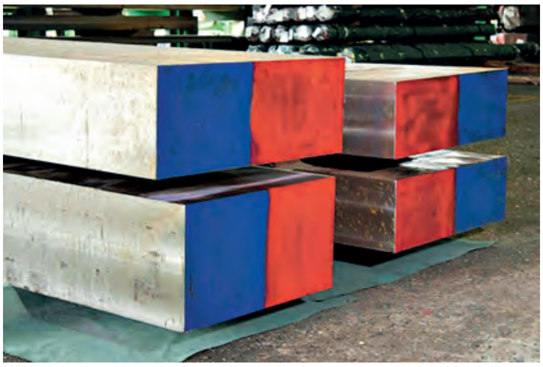
Injection-molded parts range from shoe heels serving massive markets to limited numbers of precision items for medical devices. © iStockphoto/TPopova

A second seemingly mundane, but potentially game-changing product, is a recyclable, BPA-free, transparent, multilayer, injection-molded plastic can that may well replace the traditional metal food can. Its manufacturer calls it the "Klear Can". A major machine manufacturer recently announced the sale of its first Klear Can production system. The design provides the same benefits as airtight metal cans, but in a see-through plastic container that allows consumers to clearly see a can's contents. The product can store shelf-stable foods for up to five years.

The plastic (resin)

Molders can choose from hundreds of different thermoplastic resins, plastics that soften upon heating and become hard after cooling, offering a myriad of properties to the product designer and manufacturer. Common resins include polyvinyl chloride (PVC), polyamides (Nylon), acrylonitrile butadiene styrene (ABS) and polyethylene. Each resin offers a unique set of properties that must be considered with respect to both the resin's performance in the injection-molding machine, e.g. maximum molding temperature, fluidity, corrosivity, and the finished product's performance in its application, e.g. colorability, strength, toughness and surface quality. ›

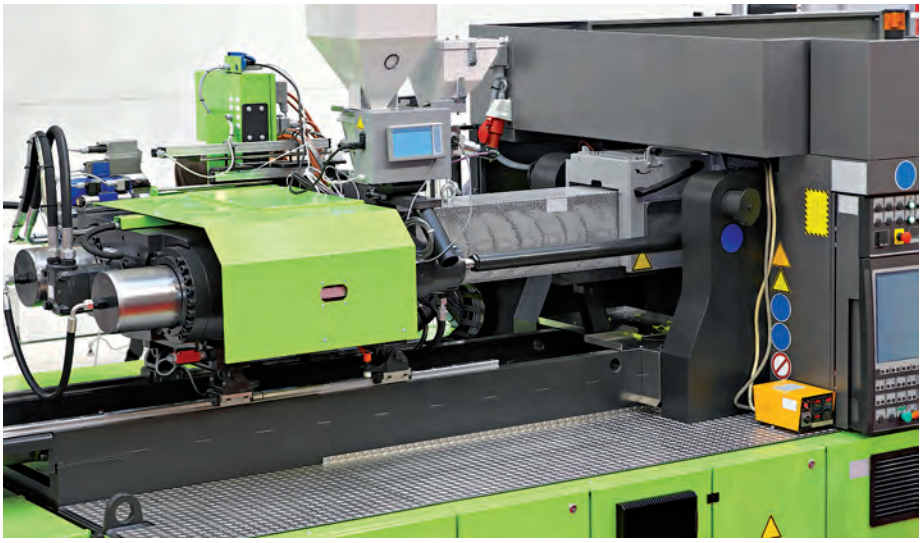
Plastic molding begins with resin pellets and ends with a myriad of simple to complex parts. © iStockphoto/XXLPhoto



The mold is machined out of a block of mold steel produced by a specialty steel producer. © Alloy Tool Steel, Inc.

Injection-molding machines

Injection-molding machines have four major components – motor, injection unit, split injection mold, and clamping unit. Machine size varies greatly depending on the size of the finished product, and is rated according to mold-clamping force. Small units may have only 2 MT of clamping force while very large machines may be rated over 10,000 MT. The basic elements of all machines are similar and quite simple, but they can become very complex when the marketplace requires high quality and high production rates.



Injection-molding machines come in a range of sizes and production speeds, but all have the basic features of a resin delivery and molding system. © iStockphoto/Baloncici

Mold design

The split-injection mold, consisting of a frame and plates, is common to all machines. These highly sophisticated molds require separate channels for introducing the resin and evacuating air, for cooling with either water or oil, and for guiding ejector pins that remove the part from the mold. High-production molds contain cavities for dozens of parts, which adds to the mold's complexity.

Modern mold design employs computer-aided design (CAD) to supplement the mold maker's art. The computer allows the mold maker to design the cooling, venting, and ejection systems while considering shrinkage, warpage, forces, and component deflections. Computer numerically controlled (CNC) machines use the CAD program output to control mold machining, allowing precise dimensional control of finished parts. Electro-discharge machining (EDM) is frequently used when a single mold must produce many small parts. The advantage of EDM is that it can machine a mold after final heat treatment. The mold cavity is often polished after machining to achieve good surface quality on the finished part.

Mold materials

The design engineer must consider various factors when selecting a material. Foremost is the mold's required life. Other factors include the temperature needed to process the resin and the surface finish required in the end product. Various steels, copper and aluminum alloys, rubber, and even epoxy are used as mold materials; the last two typically finding use for short runs or prototype production. Steel is by far the most common mold material, and is favored for its durability and high-quality products.

The mold material must be machinable and capable of producing the required surface finish. It must have strength to withstand clamping forces and wear resistance for long production runs. Steel alloys must be hardenable in relatively thick sections while delivering good toughness and dimensional stability during heat treatment. These requirements make molybdenum-containing tool steels the perfect choice.

Two of the most widely used steel grades, AISI P20 (UNS T51620) and AISI H13 (UNS T20813), have nominal molybdenum contents of 0.42% Mo and 1.3% Mo, respectively. These two alloys have spawned a large number of compositional variants to customize them for specific applications; most retain Mo in their composition. One major mold steel supplier offers fourteen variants, with molybdenum contents up to 3.6%.

The most important material property, particularly for high-end parts, may be good polishability that assures a blemish-free surface. Blemishes are almost always caused by non-metallic inclusions that create discontinuities on the surface of the final part, often resulting in rejection. Special melting techniques such as vacuum arc remelting (VAR) and electroslag remelting (ESR) can minimize inclusions, and are typically offered at a premium price.

Outlook for plastics and the molybdenum industry

The global plastics industry is huge and growing. In the United States, it is the third largest manufacturing industry. The injection-molding segment alone is expected to grow at a CAGR of 4.2% through 2022, driven in part by exciting new products such as gas storage and transport tanks and the Klear Can highlighted here. The ever-increasing demand for larger components having more sophisticated design and better performance continually requires more injection-molding equipment and tooling. Molybdenum, as it has throughout its history, will help to provide the right steel for these new products because it brings strength, stability, durability, and high-surface quality to the steels used in injection-molding. (CK)

Stainless steel stops leaks

Repair sleeves are found in the tool box of virtually every water utility. They allow quick repair of leaking water pipes without replacing them. Often fabricated from molybdenum-grade Type 316 stainless steel, they reduce water wastage and are yet another way that molybdenum helps sustain Earth's resources.

In 97 CE, Emperor Nerva Augustus appointed Sextus Julius Frontinus *curator acquarum* (water commissioner) of the city of Rome. The city was founded over 800 years before, and by then had a highly-refined water system. Nine aqueducts carried water to the city from the Tiber River and other sources, and wells within the city supplied additional water. Archaeologists estimate these sources delivered between 500,000 and 1 million cubic meters of water each day. A system of clay tile, lead pipes, and free-flow channels interconnected with tanks, basins, and reservoirs, distributed water to the city which at its height reached over 1 million people. As a comparison, Tokyo's water authority today serves some 12.5 million people delivering just over 4 million cubic meters per day.

According to his treatise *De aquaeductu urbis Romae*, Frontinus was concerned with a potential shortage of water for a variety of reasons. They included periods of drought, city growth, the demands of Rome's many fountains and baths, leaky old pipes and, most importantly, the loss of taxes by theft. The problems of water loss and potential shortages remain the same today as Rome is facing a drought and reportedly is losing 44% of its water to leakage and theft. Of course these issues concern not only this ancient city but municipalities around the world.

Water loss in municipal distribution systems

The American Water Works Association (AWWA) sets a standard for leakage in new pipes, which applies at the time of installation and testing. The allowable leakage is based on the pipe diameter and length, the number of joints, and the water pressure. As time passes, the ground moves, pipes deflect and corrode, and gaskets deteriorate, all of which increase leakage. Many municipalities have programs to manage pipe leakage and replacement. Pipes are typically considered for replacement after 30 to 50 years of service. However, the best management plans can be turned upside-down by Mother Nature. While pipes with low corrosion rates in stable soil have been known to last more than 100 years with little or no leakage, pipes in less stable conditions might need replacement after only 25 years of service.

Older systems are typically plagued with higher water losses. For example, Washington, DC, which has a 100-year-old water system, loses some 35% of its water on the way to customers. Meanwhile, its neighbor to the south, the growing and affluent Fairfax County, loses less than 3% of its water because the pipes are quite new and the county has the resources to support a strong maintenance program.

United States municipal water systems are estimated to have about 1.6 million kilometers of distribution piping. There is a need to repair, replace or newly install some 21,000 kilometers of pipe each year. Most of this is in diameters of 100–500 millimeters, used for smaller mains and distribution piping.

The "Repair Sleeve" maintenance solution

When a leak occurs, it is not easy to replace a length of pipe because the pipe is buried and it is tied into a pressurized water distribution network. A cost-effective solution is to repair the portion of pipe where the leak is located.

Stainless steel has long played an important role in repairing leaking pipes without having to replace a section or dig up an entire length of pipe. The method employs a "collar" fastened around

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Type 316 stainless steel repair clamps are used to stop pipe leaks without replacing lengths of pipe. © JCM Industries, Inc.

A leak in a water main can lose a large amount of water in a short time.
© iStockphoto/Giorez

the leaking pipe instead of welding or threading a replacement section. It is like a Band-Aid® wrapped around one's finger. Here, a 304 or 316 stainless steel band with an attached rubber gasket is fastened around the pipe, over the damage. Tightening the clamp, or sleeve, applies more sealing pressure on the exterior of the pipe than is on the interior, stopping the leak.

These sleeves are widely used and are readily available for almost any pipe size, although mostly for pipes greater than 300 millimeters in diameter. They can also be used to add branching tees and to make general repairs. They have even been used to add a tee to reinforced concrete pipe; here the device strengthens the pipe that has had its reinforcing bar cut to make the tap. One municipality has used them with concrete pipe having diameters as large as 1200 millimeters. The overriding advantages of repair sleeves are their ready availability, low cost, durability and cost-effective installation.

"Mock" installation of a custom-fabricated Type 316 stainless steel repair sleeve. The technicians are practicing the underwater installation on a piece of pipe in the dry. © Charleston Commissioners of Public Works

Molybdenum completes the seal

The sleeve's metal component is almost always stainless steel, most commonly Type 304 because it is compatible with many soils. However, when soil corrosion is a concern, molybdenum-containing Type 316 is specified because it is very resistant to both general corrosion and pitting. Recently, some manufacturers are even offering molybdenum-containing 2205 duplex stainless steel as a superior alternative to Type 316. Duplex 2205 has more than double the strength and is resistant to stress-corrosion cracking and general corrosion. High strength is important because the outer metal sleeve is subjected to considerable stress as it is tightened to seal the rubber sleeve.

Technicians are reviewing the steps required to install the sleeve correctly. © Charleston Commissioners of Public Works

Adaptability for special needs

Some manufacturers provide engineering and fabrication services for custom-made sleeves for critical applications. One supplier, for example, undertook a very difficult underwater repair of a failed 610 millimeter diameter HDPE plastic pipe for the city of Charleston, SC. This 4.8-bar water main failed at a fusion joint on the harbor bed under 7.5 meters of water.

Initially, the Charleston Commissioners of Public Works made a repair using a stock Type 304 sleeve and coated carbon steel restrainer. However, for a permanent solution, the authority desired a more robust sleeve that would support high stresses on the pipe and assure good long-term performance. They asked the fabricator to engineer and build a new sleeve to completely encapsulate the repair sleeve, and to build a restrainer to relieve stresses on the extending plastic pipe. In addition to designing and fabricating the new Type 316 sleeve, the project specification included a dry run to test the anticipated difficult installation under 7.5 meters of water. The new sleeve was installed in 2004 and has performed very well, with no problems reported to date.

Stainless steel repair sleeves have been used for decades to repair municipal water pipes at the point of leakage. As water scarcity becomes more pronounced, water authorities increase their efforts to reduce water loss. Simultaneously, the need for repairs increases with the aging water infrastructure and the lack of funding for wholesale replacement. Repair sleeves will therefore become even more important in the future. (CK)

Strong sustainable storage tanks

Duplex stainless steel storage tanks are increasingly being used due to their long, low-maintenance service life. Surprisingly, they can also reduce initial costs for tank owners. The higher strength of duplex grades permits thinner walls requiring less steel. Because costly protective coatings or cathodic protection are not necessary, they can compete on installed cost with carbon steel tanks.

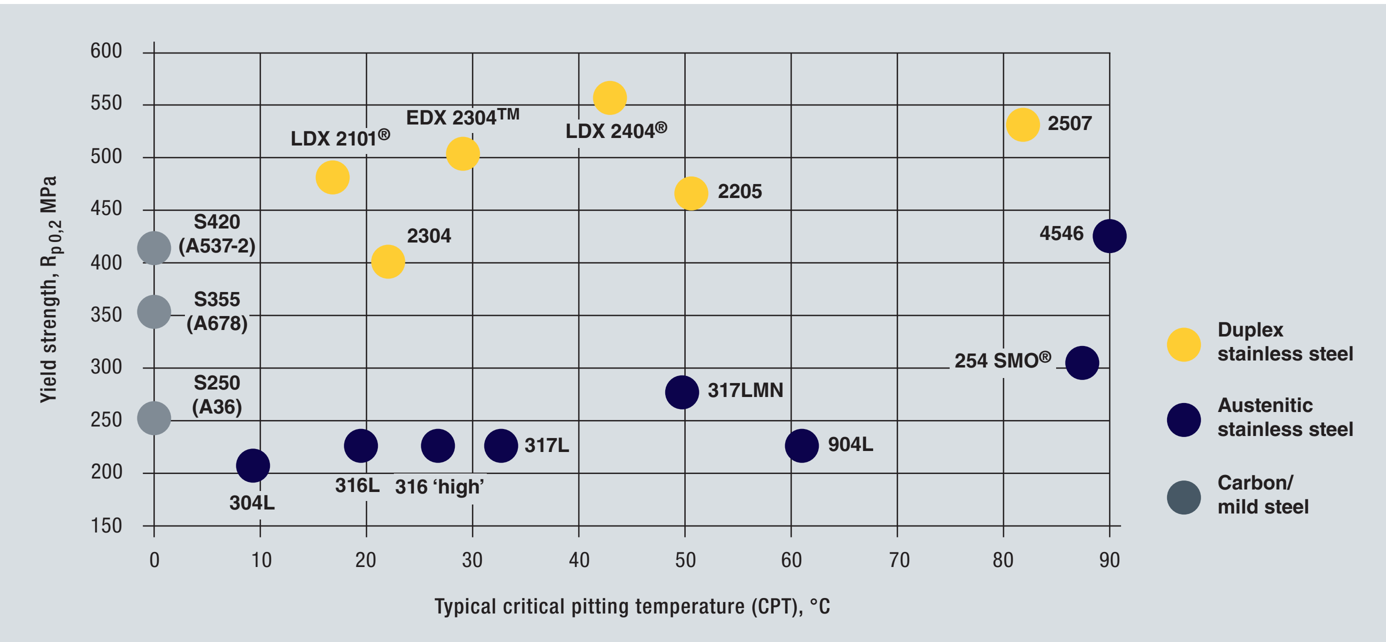
Storage tanks range in size from home water heaters to industrial tanks containing millions of liters of petrochemicals. They can be stationary or mobile, and hold solids (powder, grain), liquids (water, milk, food products, petrochemicals, inorganic chemicals, liquefied gases), or gases (biogas, inert gas, reactive gases). Some even transport live fish! Usually made from carbon steel, concrete, plastics, or corrosion-resistant alloys, they are widely used around the world.

Carbon steel tanks dominate the chemical and petrochemical storage business because generally such products are not very corrosive. Even so, moisture and environmental corrosion are still of concern. Therefore, coatings, impressed currents, or sacrificial electrodes must be used for protection. Austenitic stainless steel tanks, made from Type 304 or Type 316 stainless steel, are corrosion resistant, so can be used as an alternative. However, they require thicker walls because of their lower strength, which means higher weight and higher material cost, making them somewhat more expensive.

Thanks to their high strength, duplex stainless steel tanks can be less expensive to build than either austenitic stainless steel or carbon steel tanks. The cost advantage is even more pronounced when the whole life-cycle costs are considered. Tank designers most often specify lean duplex steels with 0.3 to 0.5% molybdenum, but select higher-molybdenum grades for more corrosive environments.

The strength advantage

Structural design codes such as EN 14015 (Europe) and API 650 (United States) now incorporate duplex stainless steels. This permitts designers to build thinner-walled tanks. The figure below shows the yield strength and pitting corrosion resistance of several carbon and stainless steels. Duplex stainless steels have a great strength advantage over both austenitic stainless steels and carbon steels. As designers and end users learn of these advantages, they increasingly specify, build, and commission duplex stainless steel tanks. ›



Yield strength and corrosion resistance of a wide range of stainless steels. Carbon steels are added for comparison of their strength only on the 0°C line. Source: Outokumpu

Benefits beyond strength

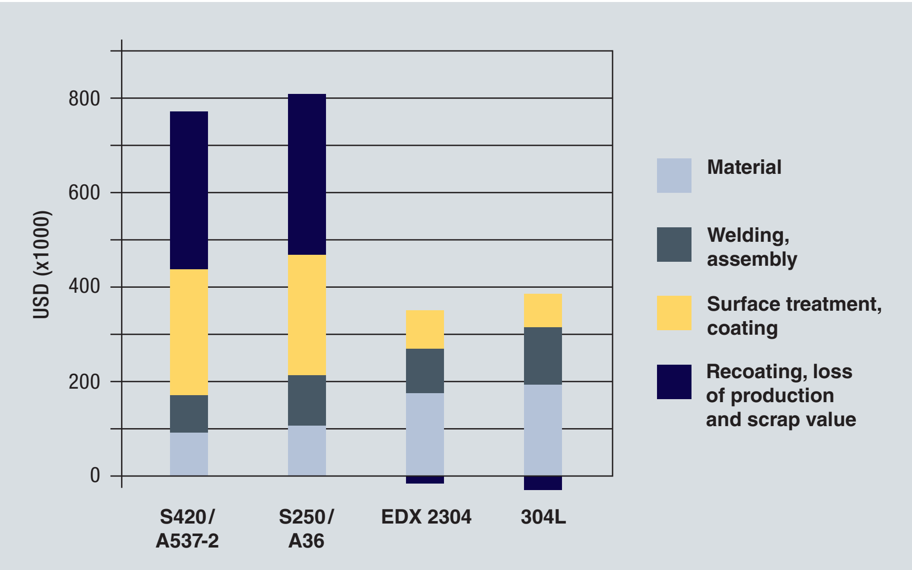
Name	UNS No.	EN No.	C	N	Cr	Ni	Mo
304L	S30403	1.4307	0.03	0.06	18.5	9	–
316L	S31603	1.4404	0.03	0.06	17	11	2.2
LDX 2101	S32101	1.4162	0.03	0.22	21.5	1.5	0.3
2304	S32304	1.4362	0.02	0.10	23	4.8	0.3
EDX 2304	S32304	1.4362	0.02	0.18	23.8	4.3	0.5
LDX 2404	S82441	1.4662	0.02	0.27	24	3.6	1.6
2205	S31803	1.4462	0.02	0.17	22	5.7	3.1

Typical chemical composition in weight percent of stainless steels considered for storage tank applications.

Construction cost – Corrosion-control measures add substantial cost to carbon steel tank construction. Designs must incorporate a 'corrosion allowance', an extra wall thickness beyond what is needed for structural strength, to accommodate any metal loss due to corrosion. Carbon steel tanks also require internal and external coatings to prevent corrosion and often additional anodic or cathodic protection. These elements make a coated carbon steel tank more expensive to build than a duplex stainless steel tank, especially if the tank is built for corrosive contents. The figure summarizing a 30-year life-cycle cost analysis clearly shows that the duplex stainless steel tank is less expensive to build than the alternatives.

Operating cost and life-cycle cost – The same image illustrates the long-term cost advantage of duplex stainless steel. A carbon steel tank must be recoated every five to ten years to keep it protected. Cathodic and anodic protection adds further operating costs for electricity and equipment maintenance for the former as well as electrode replacement for the latter. Duplex stainless steel will require little attention beyond cleaning, increasing tank availability and productivity. A properly specified duplex stainless steel tank will operate practically forever. Even if it is retired for reasons other than deterioration, its higher scrap value further reduces the life-cycle cost.

Environmental benefits – Duplex stainless steels are produced with a significant portion of recycled material, partially eliminating the need for energy-intensive mining and refining steps. This conserves resources and reduces overall energy consumption. Stainless steel tanks also eliminate volatile organic compounds associated with coating processes. Their corrosion resistance greatly reduces the risk of tank failure and the potential for associated spills and damage to life and environment. When decommissioned, duplex stainless steel tanks will be recycled.



30-year life-cycle cost (LCC) for a 20 meter diameter, 20 meter tall tank containing liquid with the density of water operating at 20 °C and designed to API 650. The duplex stainless steel EDX 2304 is compared to two carbon steels on the left and Type 304L stainless steel. It has the lowest installed cost and much lower LCC than the carbon steels. Source: Outokumpu

Versatility – Unlike carbon steel, stainless steel resists many corrosive chemicals. It is compatible with foods and beverages, and is easily cleaned and sanitized. This versatility is particularly important for owners and operators of tank shipping containers and chemical tank ships whose cargo is frequently changing. The greater corrosion resistance (and flexibility) of a Type 316L austenitic stainless steel with 2% or 2205 duplex stainless steel with 3% molybdenum can therefore almost always justify its higher cost in mobile applications. Versatility can be important for land tanks as well. Building one tank is certainly cheaper than building two tanks, and the ability to handle multiple products is a clear advantage to owners and operators of third-party storage terminals.

Multiple duplex stainless grades with a range of corrosion resistance and costs provide users with a variety of options. The chart of critical pitting temperature ❯

A biogas tank made of LDX 2404 in Germany. © Börger GmbH

(CPT) vs. strength in chloride environments emphasizes this fact. Similar data are available for many corrosive solutions, which allows the tank owner to select the optimal material for a given environment.

Real-life installations

Although duplex stainless steels are relatively new to tank construction, some duplex tanks have been in use for many years. An early example is a 2205 duplex stainless steel phosphoric acid storage tank built in 1989 in Sweden. The tank was used continuously until it was shut down just a few years ago due to problems, not with the tank, but with its retaining embankment.

The same 2205 grade was used when one of Spain's largest brewers replaced an old, severely corroded carbon steel storage tank in 2015. The duplex alloy's 460-MPa yield strength allowed a 25% weight saving compared to carbon steel. The duplex grade is highly resistant to both general corrosion and stress-corrosion cracking and has a very high PREN (Pitting Resistance Equivalent Number) value of 35. Its availability as wide plate and sheet lowered construction costs by minimizing welding time and filler metal consumption. Based on this initial experience with duplex stainless steel, the company intends to use it for future needs.

A 2205 stainless steel tank at a brewery in Spain. © Outokumpu

In Germany, a tank builder selected LDX 2404 duplex stainless steel with 1.6% molybdenum for a biogas tank instead of a standard grade because of its higher strength and good corrosion resistance. This choice reduced material weight up to 25%, and associated costs. The bolted tank can be dismantled and moved, so less weight also means lower moving costs.

EDX 2304 is a version of the traditional duplex stainless steel 2304 with higher chromium, molybdenum (0.5% vs. 0.3%) and nitrogen content. The steelmaker developed this grade for the offshore oil and gas industry but it is now used in storage tanks as well. The modified ›

2304 duplex stainless steel tanks at the tank terminal in Bilbao, Spain. © Outokumpu/Acedika

alloy has higher strength and greater corrosion resistance than 2304, and a guaranteed PREN above 28 – an improvement over the original grade's PREN of 26. The first tank using this material was built for a Swedish company, and the second project was built in the Netherlands.

Tanks of the future

Duplex stainless steel offers multiple advantages to owners and operators of storage tanks. Construction costs are often lower than for carbon steel tanks. Operating costs are significantly lower due to nearly zero maintenance. Duplex stainless steel tanks have a practically unlimited life because of their high corrosion resistance. They are easily cleaned and can handle a variety of substances, making them more versatile than carbon steel tanks. If and when end of life arrives they have higher scrap value than traditional tanks. Moreover, their resistance to degradation and material loss during operation, and their higher material value, provide substantial sustainability benefits. They are profitably recycled, require lower energy consumption and reduce the risk of failure-related environmental contamination. These advantages not surprisingly come in large part thanks to molybdenum. Together with the competitive as-installed cost of duplex tanks, they should translate to increasing demand in the future. (ES)

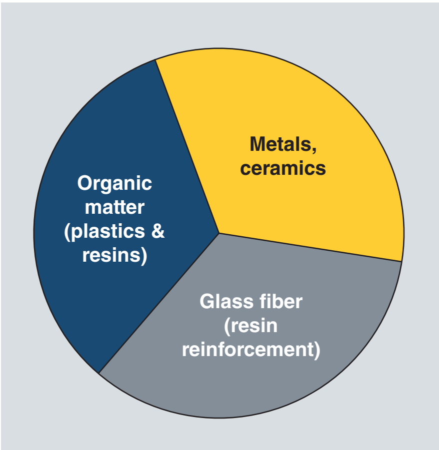
Mining gold with moly

Modern electronic gadgets contain dozens of metals crammed into the smallest possible space. The construction is such that they are nearly impossible to disassemble for recycling. Highly reactive supercritical water can facilitate "mining" of precious-metals from this electronic waste. Because of the corrosive process environment, molybdenum containing nickel alloys are needed for the vats.

It is estimated that there were approximately 7.3 billion mobile device subscriptions active globally as of November 2016, about 3.3 billion of which were for smartphones. These numbers are expected to grow to 8.9 billion and 6.8 billion, respectively, by 2022. Moreover, these estimates do not include unused and unconnected phones that lie around gathering dust. This mountain of electronic waste, or e-waste, contains tiny nuggets of valuable metals that are part of a giant "ore deposit" distributed around the world. Gold, palladium, silver, and copper can all be "mined" by recycling this never-ending stream of e-waste discarded in the quest for ever more efficient and entertaining devices. The recovery of precious and specialty metals contained in electronic equipment has even been given a name – "urban mining." Instead of being deposited in rocks, the metals of interest are contained in the intricate circuitry of silicon devices and are firmly secured to polymer substrates, so extracting them presents a new set of problems.

Current recycling processes

Recyclers now use pyrometallurgy, hydrometallurgy, and electrolytic processes to extract metals from e-waste. Pyrometallurgy, which involves heating, is the most common approach because it is relatively energy efficient compared to other current alternatives. This is because the combustible portion of the scrap stream, such as plastics, is a supplemental source of "free" process energy. The modern plants found in Japan, Europe and North America are relatively inexpensive and environmentally efficient compared to competitive processes. Pyrometallurgical processing usually extracts precious metals and elements such as nickel into a metallic copper ›



Electronic circuit boards: three main types of materials

The electronic devices of today are the "urban mines" of tomorrow.
© iStockphoto/xuanhuongho

phase, which is electrorefined to extract copper and separate the remainder for subsequent production of pure gold, silver and other precious metals. Copper electrorefining is highly efficient, requiring only the electric energy of 0.35 kWh per kilogram of copper extracted. Conventional hydrometallurgical techniques (chemical extraction using aqueous acid solutions) are also used to recover precious metals from e-scrap.

Conventional technologies such as those noted above are efficient, have low to moderate energy requirements, and possess good environmental records; but there can always be a better approach around the corner. Any process that lowers cost and reduces environmental risks will generate considerable interest. However, new technologies always require lengthy steps of small-scale laboratory experimentation and larger-scale piloting before they can eventually move to full-scale commercial operation.

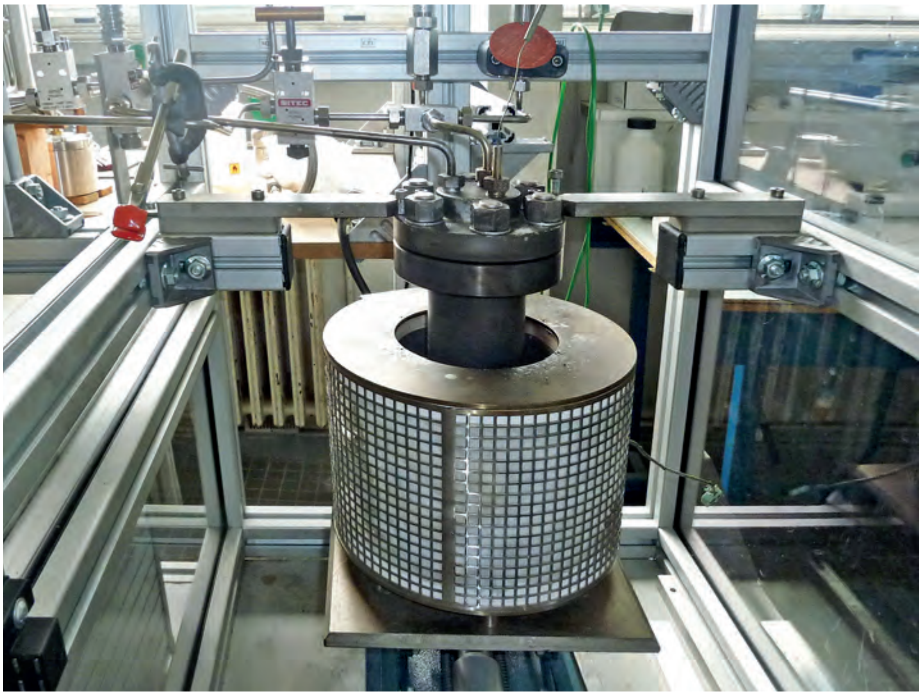
One new innovative process that generates high hopes for more efficient and environmentally friendly technology is well along this arduous development path. It uses a common and seemingly unlikely candidate – water – as a tool to lay bare the treasures of mobile devices and other electronic components.

An ore deposit of continental proportions, by the number

It is difficult to know accurately how much e-waste is produced globally. The EU reports that about 1.1 million tonnes were collected in 2014 from information-technology, telecommunications, and consumer equipment. This number is probably lower than the amount of e-waste actually generated. The reported weight incorporates all parts of the various components in these categories, including the circuit boards and electronic devices that contain valuable metal resources. Using the iPhone as a reference, the BBC estimated in 2016 that one million such smartphones alone would yield 15 tonnes of copper, 340 kg of silver, 34 kg of gold, and 15 kg of palladium. On a weight basis, circuit boards in electronic devices contain 300 times more gold than a typical gold ore and 6–7 times more silver than typical silver ore. These numbers do not include other elements present in iPhones and other electronic equipment, such as nickel, tin, cobalt and tantalum. The figures highlight the potential of "urban mining" to maintain an economical supply of precious and specialty metals.

An abundant and powerful resource, and a new idea

The water used in the process is not water as normally seen in rivers, lakes, and drinking-water systems; it is *supercritical water*. When heated above 374°C under pressures above 221 bars (22.1 GPa, or about 221 times atmospheric pressure), water is in a *supercritical state*. Under these conditions water's gaseous and liquid states cannot be distinguished from one another, and the phase present is an ever-boiling cauldron of many different pieces of the lowly water molecule, H_2O. Supercritical water is a strong oxidizer and a highly-corrosive reactant. It turns carbon-containing matter into gas and dissolves other substances that are insoluble in plain water. Because it reacts with materials that require the use of hazardous chemicals for processing, supercritical water is currently used for the processing of toxic waste such as biomass and chemical weapons stocks.



Prototype reactor for environmentally friendly electronic-waste treatment. © CNRS

A French research team working on the Remetox project deserves credit for the idea to change the focus of supercritical water processing from toxic waste to e-waste. The project's approach is to destroy the polymeric materials of e-waste using supercritical water, without deteriorating or melting the metal components. The team members hail from the French Geological Survey (BRGM), Orléans University, and France's National Center for Scientific Research (CNRS), in association with Terra Nova Development (a company specializing in electronic-waste management). Drawing from knowledge ❯

The recipe: plunge the board into supercritical water and cook it for about 30 minutes. © CNRS

of organic waste treatment processes like gasification and hydrothermal oxidation, the team envisioned plunging electronic circuit boards into supercritical water to extract the contained metals. They designed a laboratory-scale supercritical-water reactor that could operate at 500°C and 250 bars pressure. Their next problem was to choose the best material of construction for their equipment, one that would withstand the aggressive supercritical-water environment.

A superalloy derived from nuclear technologies

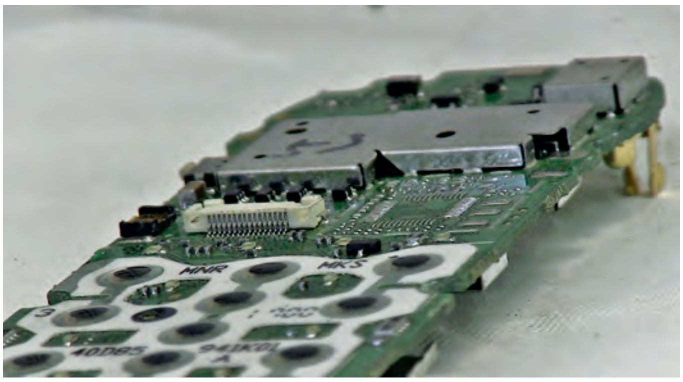
Experience acquired in supercritical-water reactors for biomass processing, toxic waste treatment, and nuclear power generation guided the material choices for the vat, valves and metallic seals. These crucial components must resist stress-corrosion cracking and retain their strength at high temperatures. The team chose the nickel-base superalloy Inconel® Alloy 718 containing 3 percent molybdenum to meet these requirements. The alloy possesses excellent strength, toughness, and stress-corrosion-cracking resistance, and has a decades-long history of reliable performance in safety-critical nuclear-reactor components like fuel-assembly support grids.

The Remotox team's laboratory-scale results have been impressive. When electronic circuit boards are immersed in supercritical water for a few hours the water decomposes their polymer resins, leaving behind a crumbly residue. On the other hand, the circuit boards' metal components and glass fiber reinforcement remain intact. These various materials can then be separated by a sorting step and directed to appropriate recycling processes.

A modest but highly promising industrial goal

The project now operates experimental vats with capacities of 0.3 and 2 liters. A 10-liter vat designed to handle relatively small quantities of electronic scrap is scheduled to begin operating in 2020. This next development phase will employ a semi-continuous closed cycle that feeds batches of circuit boards to the reactor while maintaining supercritical conditions. Treatment times will range from 30 minutes to a few hours, depending upon the quantity of material contained in the batch. The gases produced by the reaction – mostly methane – will be recovered and fed back into the loop to reduce energy consumption and process cost. The commercial process envisioned by the team aims to handle the components of about 1 million phones annually.

One million phones seems like a large number, but it is actually quite modest considering that global smartphone sales for 2016 alone are estimated to be nearly 1.5 billion. Even so, Orléans University's moly-containing vats may be a first step towards a new technology to treat electronic waste. (TP)



Electronic circuit board before treatment. © CNRS

Resin and fiberglass crumble and turn into ashes while precious metal components remain intact and can be sorted. © CNRS

IMOA news

China Molybdenum Application and Promotion Group founded

China is the largest molybdenum producing country, and during 2016 IMOA worked with suppliers on market development. IMOA proposed the China Molybdenum Application and Promotion Group (CMAPG) last autumn. In April this year, the Group was officially founded by JDC, CMOC, Climax Molybdenum China and IMOA. The Group admitted the CSSEA (China Special Steel Enterprises Association) and CSSC (China Stainless Steel Council) to its membership during the first meeting and is now also in talks with the China Molybdenum Association (CMoA).

The Group aims to fund selected market development projects, the first being a moly-steel forum to be held in 2018. The forum will focus on the additional strength and toughness achieved with the addition of molybdenum in alloy steels. Further details will be announced in a MolyNews e-bulletin once they have been finalized.

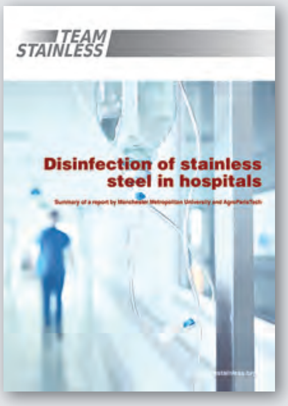
Team Stainless publishes new disinfection study

Thanks to its unique properties, stainless steel is used widely in many applications throughout hospitals and healthcare facilities. Team Stainless commissioned Manchester Metropolitan University and AgroParisTech to devise and conduct a study to examine the effectiveness of disinfection on stainless steel in hospital environments.

Unlike previous studies, which have only tested the effectiveness of disinfection on new stainless steel, this study was specifically designed to test both new and artificially-aged surfaces. A fouling and cleaning protocol was first designed to replicate the aging effects of multiple cleaning cycles in normal use.

New and aged samples of AISI 304 and AISI 316, the two grades of stainless steel usually found in clinical environments, with various finishes were contaminated with the bacteria most commonly associated with healthcare acquired infections. The samples were then cleaned using a proprietary disinfectant and analysed for the presence of bacteria.

The study demonstrated that standard cleaning and disinfection effectively sanitised all tested samples, regardless of surface finish or simulated age. This confirms that stainless steel continues to be suitable for use in hospital environments. A summary brochure, “Disinfection of stainless steel surfaces in hospitals”, will shortly be available to download from the IMOA and Team Stainless websites.



New Team Stainless brochure on disinfection of stainless steel in hospitals.

New moly video to hit our screens soon

Video is fast becoming the medium of choice for internet users, with sites such as YouTube streaming an incredible one billion hours of content daily. Statistics now suggest that four times as many web users prefer video to text.

In keeping with this trend, IMOA is developing a short video introducing molybdenum to complement other online information on its website and in social media. It will provide an introduction to molybdenum’s wide-ranging properties, applications, essentiality and contribution to sustainable development. The video is in final production and is planned for launch at the IMOA AGM this year.