NICKEL

THE MAGAZINE DEVOTED TO NICKEL AND ITS APPLICATIONS

Nickel in automobiles: more than ever before

Nickel in space: the power to operate

Rethinking plating: solution for a cleaner, more efficient industry

March 2013 Vol. 28, Nº 1

ENDURING: A lifetime roof for a Singapore sports club

The History of Stainless Steel – Part 3

The First Commercial Stainless Steels

By the end of the first decade of the 1900s, the properties of chromium and chromium-nickel steels were beginning to be better understood and this, in turn, led to the independent development of stainless steels by metallurgists working in several countries.

At the Krupp works in Germany, Eduard Maurer and Benno Strauss were testing many alloys for a high-temperature application and quickly discovered that stainless steels with greater than 20% chromium had exceptional resistance to corrosion. They then developed the austenitic alloy V2A which had 20% Cr and 7% Ni. The composition is quite close to the 18-8 or AISI 304 (UNS S30400) grade which remains the most-produced stainless steel alloy to this day. V2A had exceptional corrosion resistance in many different environments and was found to be especially useful in nitric acid. The most commonly used alloy for nitric acid today is still the low-carbon version of this alloy, 304L (S30403). The V2A alloy received a German patent in 1912. Early applications appear to be mostly industrial in nature.

At the same time, Maurer and Strauss patented a nickel-containing, hardenable stainless steel they called V1M, a martensitic alloy which contained about 14% Cr and 2% Ni. The addition of nickel improves both the toughness of the alloy in the hardened condition and its corrosion resistance. Several of today's martensitic grades contain a nickel addition, including alloys such as AISI 414 (S41400), 422 (S42200) and 431 (S43100). There are also martensitic types that contain nickel so as to improve weldability, such as 410NiMo (S41500) and the family of super-martensitic grades used primarily in the offshore oil and gas industry.

Articles made from both these alloys were exhibited in the German pavilion at the Baltic Exhibition in Malmö, Sweden in 1914. Unfortunately, the First World War began in the summer of that same year, making it necessary to divert steel production to military applications for the duration of the four-year conflict.

Over in Sheffield, England, Harry Brearley, a self-taught metallurgist, began investigating chromium-iron alloys for improved wear resistance in rifle barrels. While that experiment did not achieve its initial goal, Brearley was struck by the fact that the higher chromium alloys required far more aggressive etchants to reveal their microstructure. He also noticed that these alloys did not rust when exposed to humidity. In 1913, he made his first commercial cast of a martensitic stainless steel, containing 12.8% chromium and 0.24% carbon.

Brearley was careful to use a proper heat treatment to obtain the best properties. He also understood that attaining the right forging temperature ensured that the material could be shaped readily and satisfactorily.

One application where Brearley's alloy had great potential was cutlery and it is largely thanks to his stubbornness that the first knife blanks were forged in 1914. Various cutlers in Sheffield began to order Brearley's stainless alloy, but, again, the war interfered with its commercialization. Most of that type of steel, including a version with slightly higher chromium content, went to the war effort (chiefly for valves in airplane engines). No patent was ever filed in Great Britain for this steel. The first patent was granted in Canada in 1915, followed by one in the United States in the following year.

Brearley's initial preference was that this metal be called "rustless steel." However, the manager at the R.F. Mosley cutlery factory, Ernest Stuart, preferred the name "stainless." After testing the knife alloy in vinegar, he is reported to have said: "This steel stains less." The name quickly caught on. Brearley is often credited as the discoverer of stainless steel and he was certainly responsible for introducing stainless steel to the public.

In the next issue, we will look at the early development of stainless steels in the United States.

Eduard Mauer

Benno Strauss

Harry Brearley

Early Cutlery

NICKEL

The Magazine Devoted to Nickel and its Applications

Nickel Magazine is published by the Nickel Institute

Dr. Kevin Bradley, President
Stephanie Dunn, Editor
sdunn@nickelinstitute.org

Constructive Communications, Design

The Nickel Institute can be contacted at:
Eighth Floor
Avenue des Arts 13-14
Brussels 1210, Belgium
Tel. 32 2 290 3200
brussels@nickelinstitute.org

ISSN 0829-8351

Printed on recycled paper in Canada.

Cover:
Photo Composition: Constructive Communications
iStock Photo: © Uyen Le
Roof Image: Millennium Tiles

TABLE OF CONTENTS

RISING PHOTO: CRAIG WHITE, URBANTORONTO.CA

SMALL AND VITAL

Often it's the small things, or the hidden things, that nickel in its various forms and utilizing its various properties allows us to do, and do reliably, consistently, efficiently and safely.

Examples can be found on or under the skin of a motor vehicle. There you will find literally hundreds of small uses of nickel that ensure reliable ignition (see the article on spark plugs on page 16); more complete combustion and reduced emissions (see the article on compressor wheels on page 15); and highly reflective surfaces, aesthetic detailing, and more environmental-friendly outcome at the end of the life of the automobile because of the replacement of cadmium with nickel on fasteners (see pages 8 and 9 for the many places where small amounts of nickel are making big differences).

Many of these items involve placing a layer of one material (or multiple layers of multiple materials, depending on the desired properties of the end product) on another and nickel has exceptional properties that allow this multi-layer technology. Plating, or surface technology, has had to overcome environmental and safety challenges. The last two decades have seen enormous changes in how the industry operates, and, as you will read on pages 4 and 5, extraordinary efforts are being made in China. While industrial efficiencies can be expected to increase at the plating parks, so too will the environmental benefits to the air and water and thus to the quality of life for workers and their families.

In this issue we continue to commemorate stainless steel's century of service with an article about some of the first commercial uses in Europe. And on pages 6 and 7, you will see a very modern usage – an electrochemically coloured stainless steel roof atop a swimming complex in Singapore. The aesthetic theme continues on page 10 where we highlight artist – and poet – Zhang Huan's extraordinary new sculpture "Rising", already a landmark of downtown Toronto.

There is more in this issue for you to explore just as the roving space lab Curiosity is exploring the surface of Mars (see pages 12 and 13). In future issues we will explore these and other developments still further, always with our eye on the small things, the hidden things, the vital things made possible by nickel.

Stephanie Dunn
Editor, Nickel Magazine

Electroplating parks in China:

A strong current for growth

With the rapid development of manufacturing in China, the demand for electroplating in that country continues to rise. There are now about 15,000 electroplating enterprises in China that have annual sales revenues exceeding 20 million renminbi (RMB), over US$3 million, per year. Indeed, the electroplating industry has become a pillar of China's overall economy while rapidly changing to meet today's strict environmental requirements.

Most of China's electroplating is done in large industrial parks, which are zoned and planned for industrial development. More than 30 such parks have been completed to date. The Yamen Electroplating Industrial Base in Jiangmen City, Guangdong Province, is the largest, with a planned floor area of 130 hectares.

The start-up zone has a floor area of 40.5 hectares, with a planned gross investment of about 2 billion RMB, or about US$320 million, and an electroplating surface production capacity of over 2 million metres^2 per year. Construction has so far consisted chiefly of waste water treatment works and other facilities for protecting the environment.

To date, gross investment in the Yamen Electroplating Industrial Base exceeds 1.5 billion RMB (US$240 million), including construction funds of about 1 billion RMB (US$160 million) and contributions totaling 500 million RMB (US$80 million) from resident enterprises. Electroplating work areas constitute more than 300,000 m^2 and much of the park's infrastructure is in place. In excess of 60 electroplating enterprises have signed contracts to enter the park and half of those are already in production.

Pollution control remains a priority.

In 2007, a census of pollution sources showed that the emission of heavy metal pollutants from the metal product industry was 20 times that of the national average. Recent years have seen a rise in the number of accidents related to heavy metal leakage. However, in 2009, the national environmental protection authority increased its overall control of heavy metal pollution. The Ministry of Environmental Protection, together with other ministries and commissions, set forth its Guiding Opinions on Strengthening the Prevention and Control of Heavy Metal Pollution. This report, in conjunction with a five-year plan for the prevention and control of such pollution, called for effective controls to be in place by 2015. These include the following:

- The surface treatment and thermal processing industry should practise park management and centralized pollution control.

"The workers benefit too, as they will be working in a safer, cleaner and more controlled environment..."

- The electroplating industry in the Pearl River Delta in Guangdong should carry out construction under a unified planning system, as well as practise park management and centralized pollution control.
- With the exception of designated industrial bases with complete pollution control facilities, no electroplating enterprise should be set up elsewhere, and existing enterprises should be required to meet emission limits for heavy metals.

The Yamen park, which offers support services and pollutant treatment facilities to resident enterprises, has an environmental protection investment of about 400 million RMB (US$65 million).

Wastewater is cleaned and supplied to the various electroplating enterprises for reuse. As well, the park has exhaust air treatment facilities which are well-suited to the technical characteristics of electroplating. This ensures that the air quality in the park meets national standards and contributes to a favourable working environment.

The types of electroplating being carried out include black nickel, pearl nickel, hard chrome, gold imitation, and French gold and bronze. With the entry of new enterprises, the number of types will also increase. A specialized technical team for electroplating will be established in the park to provide technical support for upgrading.

The continued rise of manufacturing in China is expected to result in various improvements to electroplating parks. Industry concentration will be improved, greater pollution controls will be established, wastewater will be treated centrally and land resources used more intensively by optimizing industrial layout and work flows, and allowing a full range of electroplating processes to be delivered from a single park. It also allows for greater efficiencies in processing from adopting more advanced technologies, which leads to greater energy efficiency and less waste. The workers benefit too, as they will be working in a safer, cleaner and more controlled environment and exposed to advanced technologies and equipment sooner than would have otherwise been the case. All of which shows that the electroplating industry is taking the sustainable path of energy conservation, pollution reduction, and optimum efficiency. Ni

△ *Top and Above: Part of the wastewater treatment works of the Yamen electroplating park.*

▽ *Below: Chart at the Yamen electroplating park indicating the flow of the wastewater treatment facilities.*

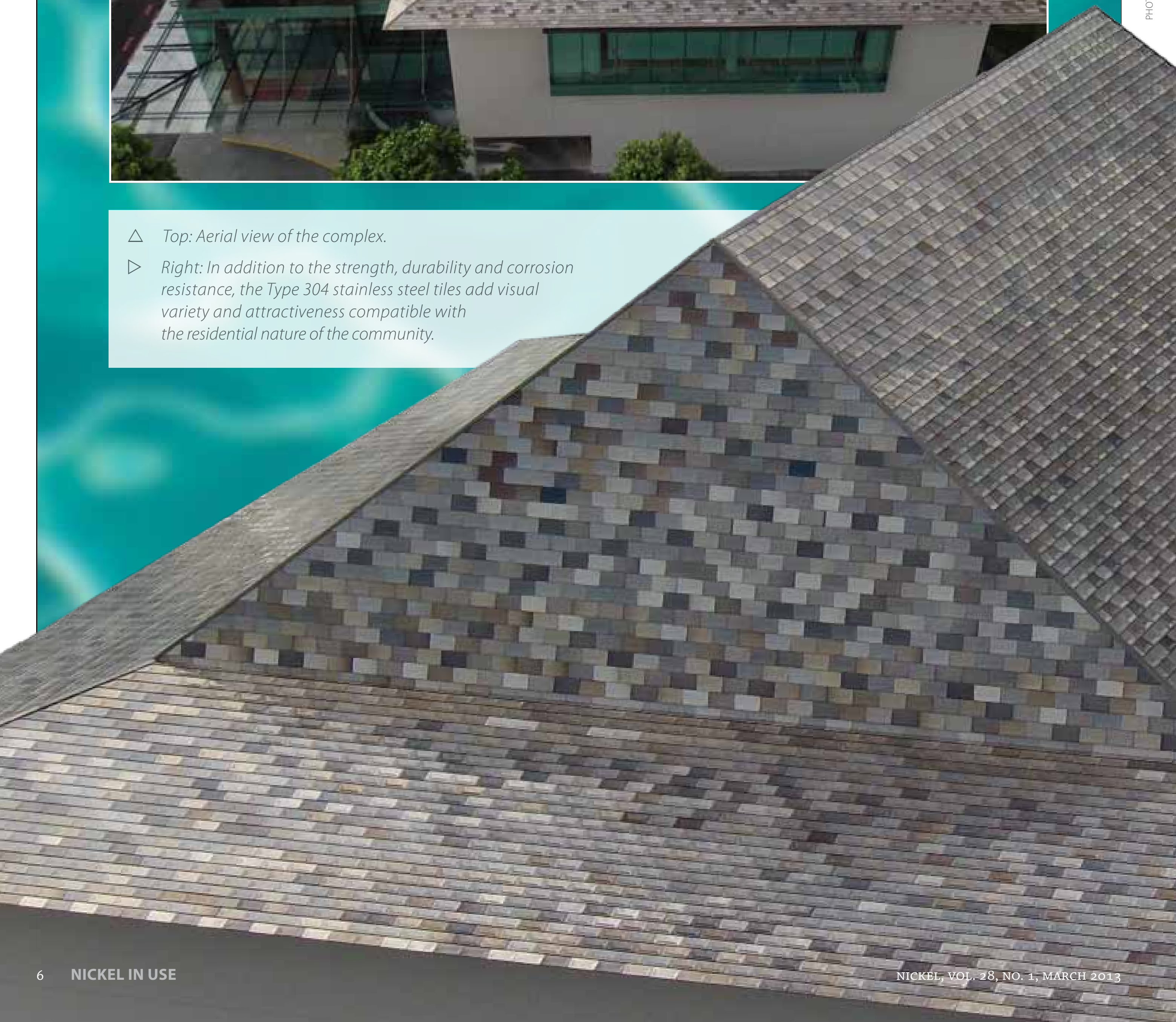
PHOTOS: BEIJING SURFACE ENGINEERING ASSOCIATION

ARTIST'S CONCEPT: YAMEN ELECTROPLATING INDUSTRIAL BASE

Ni

POOL BACKGROUND: ISTOCK PHOTO © UYEN LE

PHOTOS: MILLENNIUM TILES



△ *Top: Aerial view of the complex.*

▷ *Right: In addition to the strength, durability and corrosion resistance, the Type 304 stainless steel tiles add visual variety and attractiveness compatible with the residential nature of the community.*

FIRST CLASS COVER

Situated on Singapore's idyllic East Coast, the Chinese Swimming Club has a 90-year history of excellence in sports – not just swimming but water polo, basketball, tennis, squash and badminton as well.

Now the club has something else to boast about: a dazzling roof consisting entirely of electrochemically coloured tiles made from nickel-containing stainless steel.

Millennium Tiles of Elkhorn, Wisconsin, U.S.A., designed the mosaic-like roof. Singapore receives considerable rainfall (2,340 mm per year on average), so the company chose Type 304 (UNS S30400) stainless steel which performs well in boldly exposed applications.

The tiles are available in a full range of high-performance custom colours. The colouring process draws upon the chemistry of the stainless steel itself to create multi-faceted hues that will never fade with sun exposure, or peel or chip. This process actually enhances the corrosion resistance of the stainless steel.

Visible light is separated – prism-like – into different wavelengths, resulting in different colours within the oxide surface. The oxide is impervious to ultraviolet damage from the sun. The colour changes with light conditions as they occur throughout the day, reflecting the natural environment. There are slight colour variations in the tiles, similar to those found in organic products. As Walter Hauk founder and president of Millennium Tiles, explains: "These variations give the tiles a natural appearance as well as remarkable aesthetic beauty."

...the company chose Type 304 stainless steel which performs well in boldly exposed applications

The process is electrochemical in nature and uses oxidizing acids at elevated temperatures, enhancing the naturally occurring chromium oxide of stainless steel which is in the neighborhood of 200-400 nanometers thick. The oxide reflects incoming light to create a rainbow effect, with no pigment added, and is referred to as "light interference colour".

"We can obtain colours of wheat, bronze, and slate, as well as blue, purple, peacock, and green, all of which are highly appealing to designers and architects. The underlying finish of the stainless surface determines the appearance."

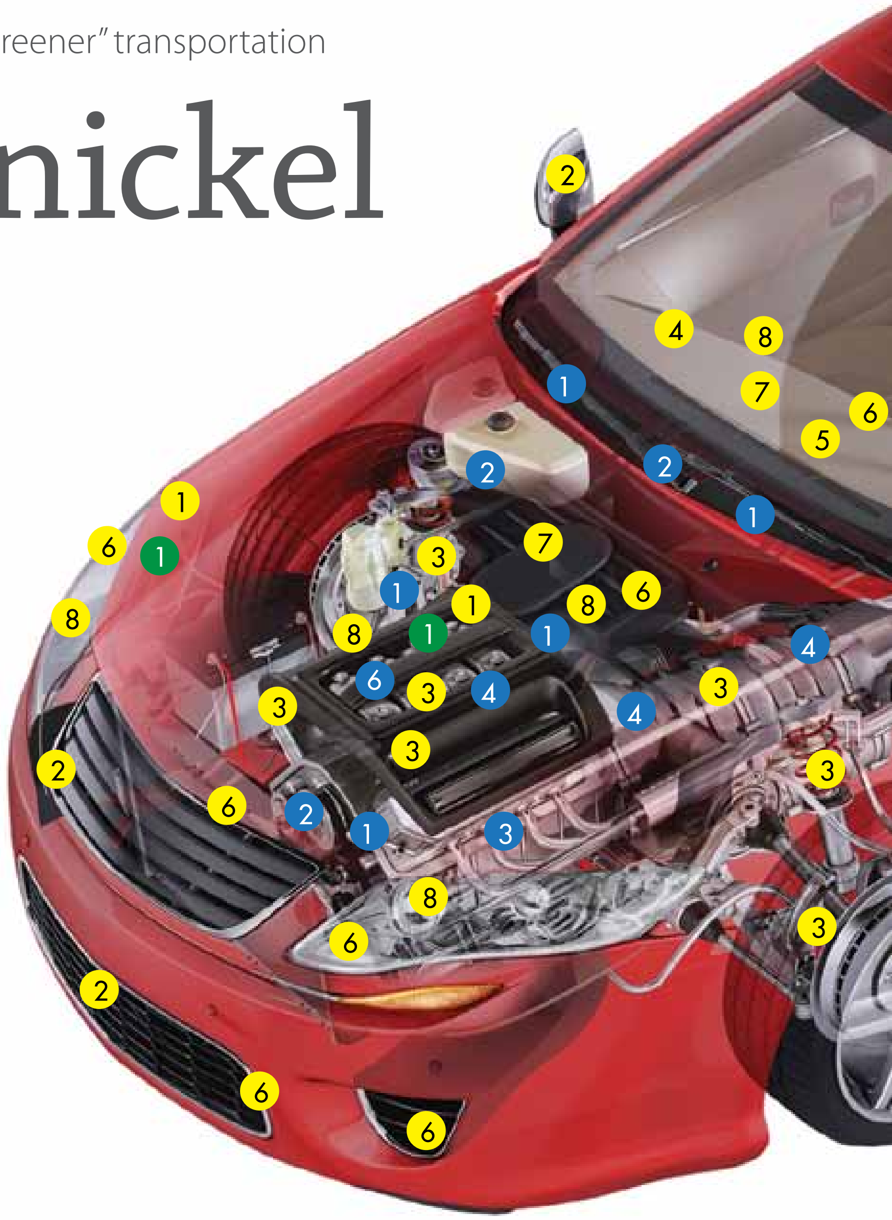
Type 304 nickel-bearing stainless steel was chosen, chiefly for its ability to resist corrosion, an especially important aspect in the maritime environment of Singapore. The high amount of rain there prevents the chlorides from building up on the metal surface, reducing the risk of pitting. Ferritic grades cannot compete with 304 unless they have molybdenum added, but even then, ferritic grades lack the superior forming characteristics of the nickel-alloyed grades.

The stainless tiles weigh only 4.5 kilograms per square metre (0.9 pounds per square-foot), allowing for easy installation. By comparison, asphalt shingles weigh over three times as much, and ceramic or concrete tiles are as much as 16 times heavier. The Millennium Tiles units have passed wind tests using speeds of up to 250 kilometres per hour (155 mph).

"The colour will last the life of the stainless steel since UV light cannot modify the colour," says Hauk, adding that the earliest examples of the process application are facades in the late 1970s and 1980s which show no deterioration to this day. Ni

Enabling more durable, efficient and "greener" transportation

Driving nickel



Nickel is used in thousands of different applications, but often you don't see it and probably don't even know it's there. There is, for example, some nickel in every one of the 80 million motor vehicles that were assembled in 2011, which included 60 million automobiles and 20 million trucks of all types.

The image on these pages shows where nickel can be found in most automobiles. Not all will use nickel or nickel-containing alloys for every application, but the reasons for the choice of nickel are predictable and important: durability, performance and aesthetics.

Not represented here are electric and hybrid vehicles, which have many of the same nickel end-uses in addition to the essential roles nickel plays in batteries, both nickel-metal hydride and in many of the emerging lithium ion ones for automotive applications.

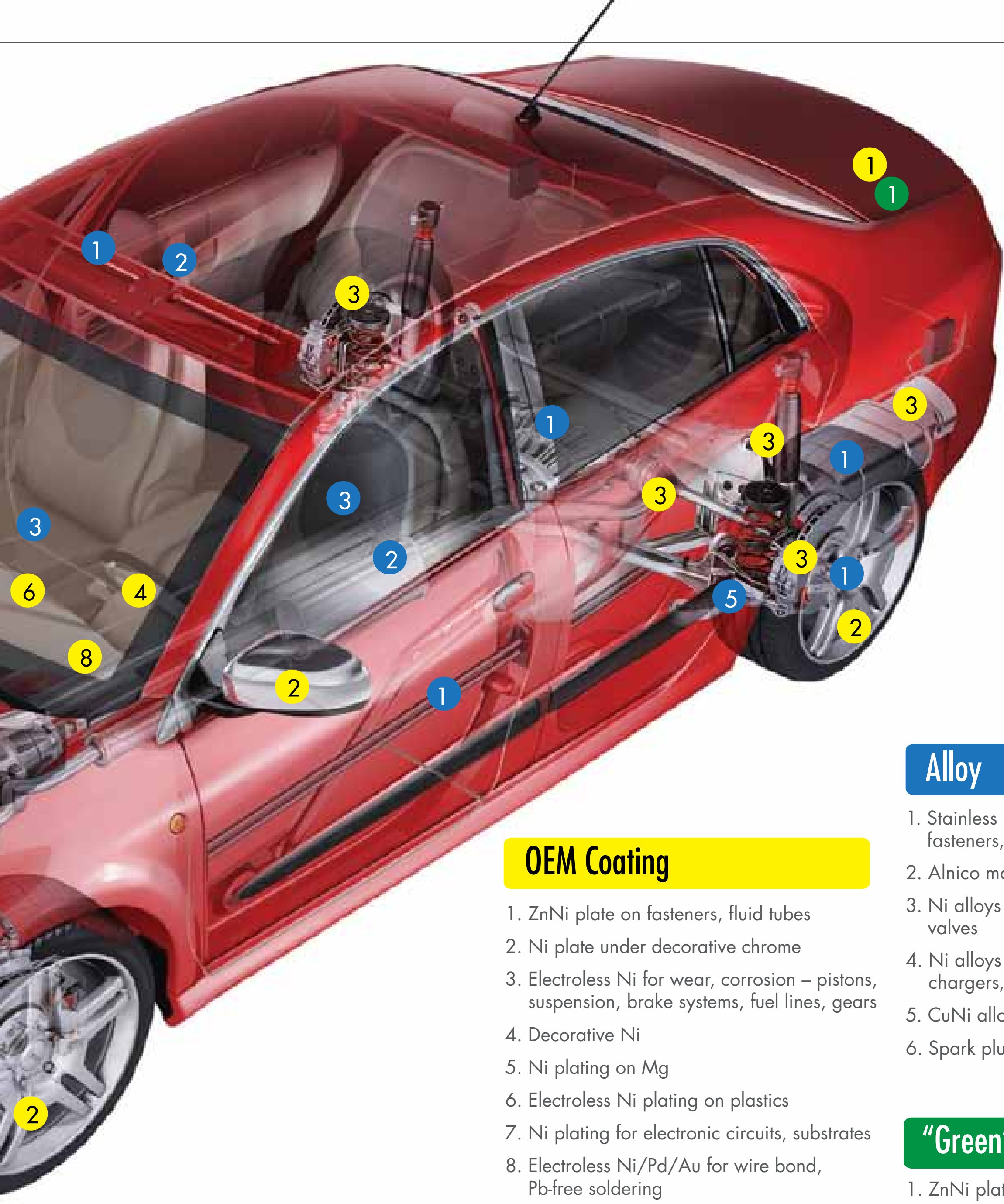
Coatings and alloys for durability

Some driving environments are more challenging than others, but in all, the exhaust system is exposed to the moisture present in the slightly acidic combustion exhaust gases. When parts of the exhaust system fail, it is usually because they have "rotted" from the inside as a result of corrosion. In recent decades, stainless steel has become the near standard material for exhaust system parts. While it is true that the ferritic stainless steel Type 409 (UNS S40900) and variants with only 11% chromium and no nickel are currently dominant, the higher-quality systems for the most demanding environments make use of nickel-containing austenitic grades such as Type 304 (S30400).

> There is some nickel in every one of the 80 million motor vehicles that were assembled (2011)

The ability of nickel to provide hard, wear-resistant surfaces in hot, aggressive atmospheres is why it shows up in pistons, cylinder liners, turbo-chargers and brake systems. And while nickel (and sometimes chromium) may be there primarily for wear resistance, there is often the additional benefit of increased fuel efficiency as closer engineering tolerances can be achieved and maintained over the operating life of parts.

Design and style are an integral part of the automotive industry and the success of certain models in the marketplace. Here designers make selective use of nickel's ability to adhere strongly to different material substrates



OEM Coating

1. ZnNi plate on fasteners, fluid tubes
2. Ni plate under decorative chrome
3. Electroless Ni for wear, corrosion – pistons, suspension, brake systems, fuel lines, gears
4. Decorative Ni
5. Ni plating on Mg
6. Electroless Ni plating on plastics
7. Ni plating for electronic circuits, substrates
8. Electroless Ni/Pd/Au for wire bond, Pb-free soldering

Alloy

1. Stainless steels – mufflers, catalyst, wiper, fasteners, clamps, springs, etc
2. Alnico magnets – generators, motors
3. Ni alloys – heating elements, exhaust valves
4. Ni alloys – pistons, cylinder liners, turbochargers, gears
5. CuNi alloys – brake fluid lines
6. Spark plug alloys

"Green" Coating

1. ZnNi plated fasteners

while having an attractive appearance. Nickel can also be the substrate for decorative finishing layers such as chrome.

Wide variety of other applications

Nickel is also used in a host of other applications, depending on the vehicle manufacturer and type of engine. These include: spark plugs, diesel valves, catalyst supports, thermostats, turbocharger wheels and castings, gears, drive shafts, airbag components, fuel and brake lines and many others.

Changing material specifications

Concerns about materials that may pose a risk to human health or the environment have resulted in a move away from cadmium and lead (in other than automotive lead-acid batteries), at least in some jurisdictions, and this shift is gradually becoming standard for manufacturers in the global market. Nickel, often combined with tin, zinc and other metals, provides lead-free solder and cadmium-free alternatives. The amount of nickel used per automobile for these applications is obviously small, but when there are hundreds of millions of parts going into tens of millions of motor vehicles every year, the amount of nickel working to make them more durable, efficient, environmentally acceptable and attractive to the eye becomes significant.

Automotive Nickel Coatings and Alloys schematic originally produced by the National Association for Surface Finishing (NASF) and the Nickel Institute. Ni

CAR PHOTO SHUTTERSTOCK

PHOTOS: CRAIG WHITE, URBANTORONTO.CA

△ *Above left and right:* Rising *detail. The polished stainless-steel sculpture is comprised of countless doves, the international symbol of world peace, and a twisted tree branch that resembles the body of a dragon.*

△ *Above: Artist Zhang Huan and his interpreter at the unveiling of* Rising.

Sculptor of stainless steel '**Rises**' to the occasion

When the Art Gallery of Ontario in Toronto, Canada, exhibited the incense-ash paintings and carved wooden doors of renowned Chinese artist Zhang Huan last spring, the event coincided with the unveiling of a permanent public sculpture by the same artist – not inside the Gallery but outdoors and a few blocks south in Toronto's financial district.

Rising, as the sculpture is known, was designed as "a philosophical reflection of the world around us," according to the description on Zhang's web site. Consisting entirely of mirror-polished stainless steel (Type 316, UNS S31600), the work depicts innumerable doves in flight, the symbol of world peace, and a twisted tree branch that resembles the body of a dragon. "The sculpture suggests the fragile conditions facing our planet," says Zhang, who is also famous as a performance artist. "I sought to convey the message that humans can exist in harmony with nature, and that our cities will become better places in which to live if and when this delicate balance is achieved.

"Through the monster-shaped tree, I'm advocating the protection of ecology as well as the harmonious relationship between humans and nature. . . . My wish is for beautiful city life to be shared by mankind and nature."

The sculpture, which graces the entrance to the newly opened Shangri-La Hotel and Living Shangri-La Condominium residences, is 10 metres high by 19 metres long and weighs about 22 tonnes.

At its base is a luminous reflecting pool, which adds to an already-complex design.

Zhang chose nickel-containing Type 316 stainless steel chiefly for its unmatched ability to reflect light, according to Yolanda, one of Zhang's assistants at the Shanghai studio where he is based. The Sculpture was shipped to Toronto in five containers and assembled on-site. Among his other reasons for choosing stainless are hardness, weld-ability, ease of cleaning, and corrosion resistance (the last being especially important given that Toronto's streets and sidewalks are heavily salted in the winter). Zhang has a history of working with stainless steel. In 2010, for instance, he sculpted a pair of stainless panda bears for the World Expo in Shanghai.

Rising was two years in the making. During the unveiling ceremony last May, Zhang recited a prose poem he wrote for the occasion. It was in the first person, as if the sculpture itself were addressing the assembled dignitaries and other guests. The English translation goes:

"My name is *Rising.* I was born a beast but am leaving Earth and rising up to the sky to the mythical dream-world of beauty and harmony. This dream world is Toronto, where I know I shall live for a long time."

What better testament to the beauty and durability of nickel-containing stainless steel? Ni

Up, up and away

Nickel-chromium alloy to power cost-effective space flight

If the full potential of space technology is to be realized, the cost of getting into orbit will have to be reduced, and the key to doing so could be a hybrid rocket engine that could power an aircraft beyond the stratosphere.

At its heart is a nickel alloy.

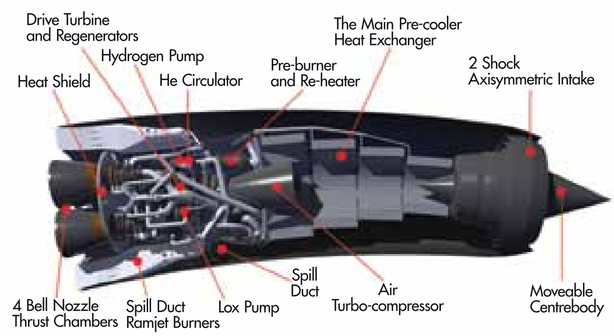
The SABRE engine is being developed by Reaction Engines Limited at the Culham Science Centre, near Oxford, England. It can operate in two modes: air-breathing and as a conventional rocket engine. This dual approach considerably reduces the weight of oxidant that needs to be carried by the aircraft and eliminates the need for massive single-use booster rockets.

For people like Richard Varvill, technical director at Reaction Engines, a single-stage propulsion system for orbiting the earth is the ultimate next step in space flight design. "Currently the cost of access to space is in the order of $150 million (US) per flight," he says. "We aim to reduce that by a factor of at least 10, and hopefully to around $10 million."

But as Varvill explains, operating an air-breathing rocket engine is fraught with technical difficulties: "The air needs to be compressed to around 140 bar pressure before injection into the engine's combustion chambers, The act of compression raises the air temperature to several thousand degrees Celsius, a temperature that would melt engine components in an instant."

To avoid this dangerous increase in temperature, the SABRE is fitted with novel ultra-lightweight, high-performance heat exchangers in a pre-cooler system, thereby reducing the air temperature to almost the liquid stage. Key to this enabling technology is nickel.

The heat exchangers must pre-cool the air intake to around minus 150°C using cold, gaseous helium at 200 bar pressure. The heat exchangers also have to cope with external air temperatures that might vary from 10°C at sea level to 1,000°C when the aircraft is flying at Mach 5 (five times the speed of sound) or greater.



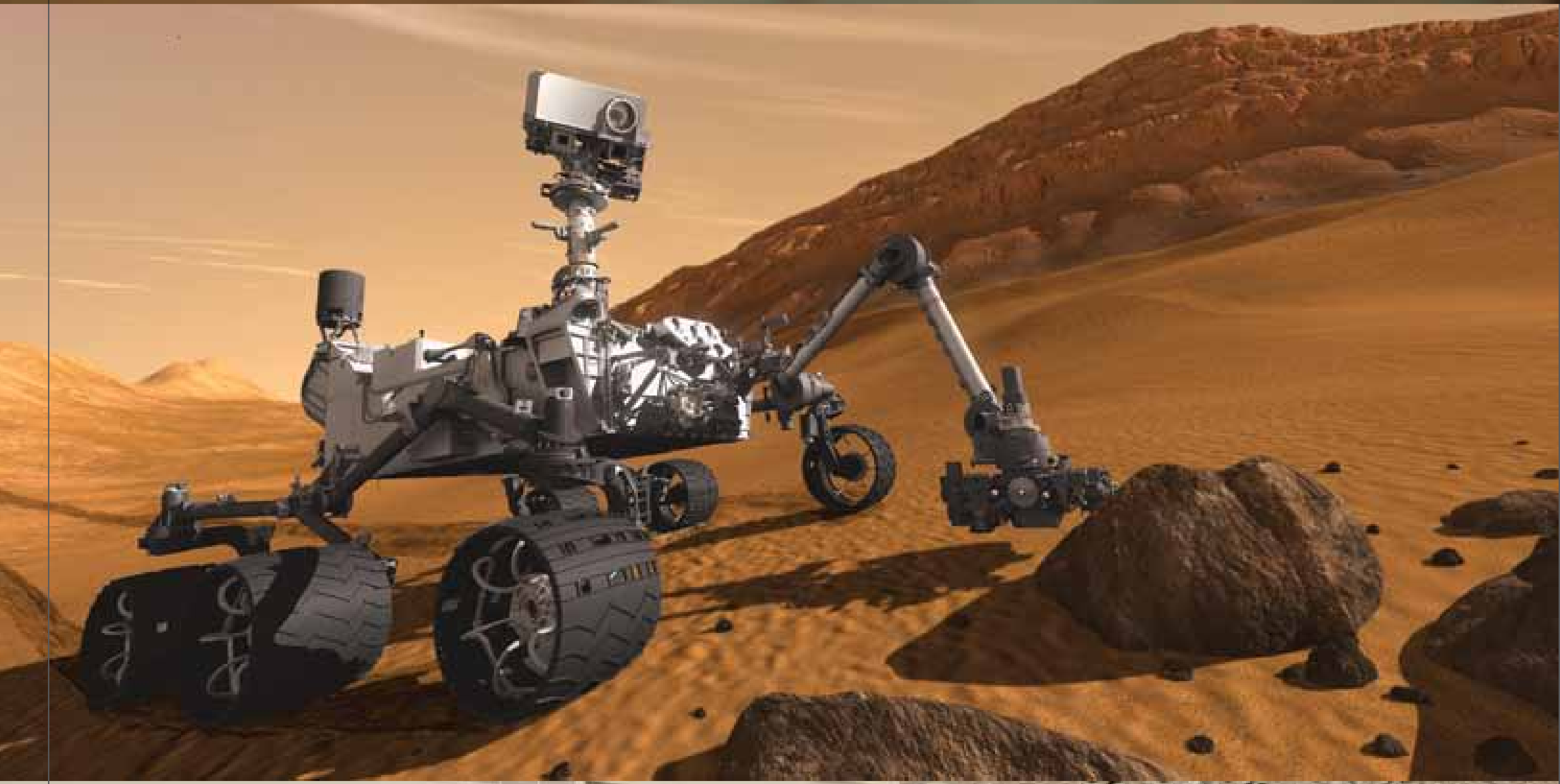
△ *The SABRE engine is essentially a closed cycle rocket engine with an additional pre-cooled turbo-compressor to provide a high pressure air supply to the combustion chamber.*

◁ *The pre-cooler heat exchanger essential to the operation of SABRE is 52% nickel.*

The nickel-chromium superalloy Inconel® 718 (UNS N07718) is used for the tubing in the heat exchangers and plays a critical role in the engine design. "There are many good reasons for using this alloy, which contains about 52% nickel," says Varvill. "This is a high-temperature application and Inconel 718 has high tensile strength and good creep strength, as well as incredibly good resistance to oxidation and corrosion."

The company has built its first complete pre-cooler system, which is being tested at Culham. Meanwhile, the Reaction Engines team is planning the next phase of the development process. "That will include detailed design of the full SABRE engine down to the component level," says Varvill. "We will also construct two or three scaled demonstrators. One will be a ground-based air-breathing demonstration that runs on liquid hydrogen fuel at Culham; the other will be a demonstration rocket engine, to be tested elsewhere in Europe." Ni

The assembly's nickel "hot shoe" conducts the heat of the reaction while the vacuum of space or the cold Martian atmosphere provides the temperature differential needed to produce a current.



△ *Above Left: Curiosity undergoing testing prior to launch.*

△ *Top: Mars Rover Curiosity, Artist's concept.*

△ *Above Right: The nickel-bearing Jake Matijevic rock. Red dots indicate laser targets, the circles show areas examined by the Alpha Particle X-Ray Spectrometer.*

IMAGES: NASA/JPL-CALTECH/MSSS

Curiosity using nickel

to generate power on Mars

Not long after NASA's Curiosity rover began exploring the surface of Mars in August 2012, its Earth-bound controllers used laser and X-ray probes to analyze an odd-coloured rock nicknamed "Jake." Among the array of elements they discovered was one that was helping to power those very instruments: nickel.

Curiosity, the mobile science lab that landed in Gale Crater last summer to search for signs of water and life, is the first spacecraft equipped with a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The device is essentially an onboard power plant that converts heat from decaying nuclear fuel into electricity.

The fuel, plutonium-238, generates about 125 watts of electric power, enough to run the robotic rover's instruments, computers, and communications and mechanical systems. An additional 2,000 watts of thermal energy keep these systems at the required operating temperature, both in space and on the planet's surface.

A thermoelectric couple – two dissimilar conductive metals – transforms the heat from the plutonium's natural decay into an electric current. The assembly's nickel "hot shoe" conducts the heat of the reaction while the vacuum of space or the cold Martian atmosphere provides the temperature differential needed to produce a current.

"The MMRTG has no moving parts, so it is very robust," says Larry Trager, general manager of the Rocketdyne division, which developed the power plant in partnership with the U.S. Department of Energy. He adds that the system "can operate in the most extreme environment."

The generator is the eighth in a line of nuclear power sources used to operate American spacecraft. Earlier versions were used on satellites, Apollo missions, and deep space probes, including the Voyager craft, which remains operational more than three decades after its launch in 1977.

The units enable spacecraft to operate in deep space and on planet surfaces where the sun's rays are too weak to be harnessed with solar panels. Dust in the Martian atmosphere also accumulates on solar panels, reducing their effectiveness and longevity.

This flexibility was essential to the Curiosity mission. The compact car-sized rover was designed before its destination was determined and the MMRTG ensured it could operate at latitudes where shorter days and long Martian winters limit exposure to sunlight.

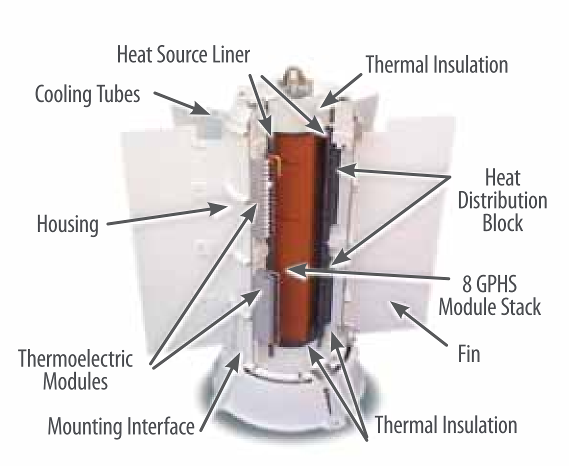


IMAGE: NASA

△ *Labeled cutaway view showing the major components of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG).*

The cylinder-shaped MMRTG is compact. Just 66 cm long and 64 cm in diameter, it accounts for only 43 kg of the rover's 900-kg weight.

Stainless steel and other nickel-containing alloys were used in the rover's construction. Some tubing in the MMRTG is fashioned from 304L (S30403) and 316L (S31603) stainless steel, and nuts and bolts made from the nickel-chromium alloy Inconel® 718 (N07718) connect many of the rover's structural aluminum components. Alloy 718 is able to withstand temperatures up to 650° Celsius while maintaining its high strength.

In addition, nickel plate holds the reference sample of basaltic rock which is used to calibrate the APXS (Alpha Particle X-ray Spectrometer), the instrument which performs the chemical analysis of the Martian rocks.

The rover has performed so well since touchdown in August that NASA has extended its projected two-year mission. The MMRTG is rated for at least 14 years of service, though Curiosity could be poking and prodding at the Martian surface even longer.

"We've already decided . . . we'll continue to operate Curiosity as long as it is scientifically viable," according to John Grunsfeld, NASA's associate administrator for science. Nickel and nickel alloys are part of key components that will keep Curiosity functioning in this extremely harsh environment. Ni

ISTOCK PHOTO © HEIDI KRISTENSEN

Re-inventing the wheel

Electroless nickel coatings boost the efficiency of automotive engines

PHOTO: COLLINI GROUP

ISTOCK PHOTO © LEE PETTET

△ *Above left: Compressor wheel with a nickel-phosphorus coating that allows engines to be efficient and low-emission for 500,000 km or more.*

In recent years designers of gasoline and diesel engines have made great strides in improving automotive fuel economy. Today's engines are much more fuel efficient than those that were manufactured only a few years ago. At the same time that their performance has increased, harmful exhaust emissions from such engines have fallen dramatically. All of which is good news since improving overall engine performance in relation to fuel economy is crucial to reducing greenhouse gas emissions and conserving fossil fuel stocks.

One recent innovation is the small aluminum alloy "compressor wheel" which is installed in the exhaust gas recirculation system of engines to increase operating efficiency. The wheel is connected to a shaft linked with a titanium turbine driven by the exhaust gas at 800°C (1470°F) and must rotate at 250,000 rpm.

The key to the performance of the compressor wheel is the 30-micrometer-thick electroless nickel-phosphorus alloy protective coating developed by the Collini Group of Hohenems, Austria. The performance requirements for the wheel are nothing less than remarkable. It must function in the heat of the exhaust system at 250°C (480°F), which means its lifespan must be equal to that of the entire engine system. Over that lifetime, it must provide excellent resistance to corrosion by exhaust gasses, protection against solid particles, together with oleophobic characteristics to prevent carbon "coking."

The basic component is manufactured from an aluminum alloy, and the coating technology used must not exceed 250°C (480°F); otherwise the aluminum alloy substrate will recrystallize, causing a reduction in mechanical strength and thus damage to the wheel. Electroless nickel was selected since not only does it resist the extremely rigorous working conditions but also because the solutions used in the coating process work at a temperature of approximately 90°C (195°F) - far below the danger level for base metal recrystallization. Ni

UNS details

Chemical compositions (in percent by weight) of the alloys and stainless steels mentioned in this issue of *Nickel*.

UNS No.	Al	B	C	Cb	Co	Cr	Cu	Fe	Mn	Mo	Ni	P	S	Si	Ti	V	W
N06600 p. 15	-	-	0.15 max.	-	-	14.00-17.00	0.50 max.	6.00-10.00	1.00 max.	-	72.0-min	-	0.015 max.	0.50 max.	-	-	-
N06601 p. 15	1.0-1.7	-	0.1 max.	-	1.0 max.	21.0-25.0	1.0 max.	rem.	1.0 max.	-	58.0-63.0	-	0.015 max.	0.50 max.	-	-	-
N07718 p. 11, 13	0.20-0.80	0.006 max.	0.08 max.	4.75-5.50	1.00 max.	17.0-21.0	0.30 max.	rem.	0.35 max.	2.80-3.30	50.0-55.0	0.015 max.	0.015 max.	0.35 max.	0.65-1.15	-	-
S30400 p.2,7,8,13	-	-	0.08 max.	-	-	18.00-20.00	-	-	2.00 max.	-	8.00-10.50	0.045 max.	0.030 max.	1.00 max.	-	-	-
S30403 p.2	-	-	0.030 max.	-	-	18.00-20.00	-	-	2.00 max.	-	8.00-12.00	0.045 max.	0.030 max.	1.00 max.	-	-	-
S31600 p.10,15	-	-	0.08 max.	-	-	16.00-18.00	-	-	2.00 max.	2.00-3.00	10.00-14.00	0.045 max.	0.030 max.	1.00 max.	-	-	-
S31603 p.2	-	-	0.030 max.	-	-	16.00-18.00	-	-	2.00 max.	2.00-3.00	10.00-14.00	0.045 max.	0.030 max.	1.00 max.	-	-	-
S40900 p. 8	-	-	0.08 max.	-	-	10.50-11.75	-	-	1.00 max.	-	0.5-max.	0.045 max.	0.045 max.	1.00 max.	6xC-0.75	-	-
S41400 p. 2	-	-	0.15 max.	-	-	11.50-13.50	-	-	1.00 max.	-	1.25-2.50	0.040 max.	0.030 max.	1.00 max.	-	-	-
S41500 p.5	-	-	0.05 max.	-	-	11.5-14.0	-	-	0.50-1.00	0.50-1.00	3.50-5.50	0.030 max.	0.030 max.	0.60 max.	-	-	-
S42200 p. 2	-	-	0.20-0.25	-	-	11.00-12.5	0.50 max.	-	1.00 max.	0.75-1.25	0.50-1.00	0.040 max.	0.030 max.	0.75 max.	-	0.15-0.30	0.75-1.25
S43100 p. 2	-	-	0.20 max.	-	-	15.00-17.00	-	-	1.00 max.	-	1.25-2.50	0.040 max.	0.030 max.	1.00 max.	-	-	-

Nickel for memory:
Essential for digital storage and retrieval

A digital storage and retrieval device is as vital to a computer as a heart is to a human being and nickel makes two essential contributions.

All computers need a way to store and retrieve data, the most common type being a hard disk drive (HDD). Most HDDs today contain multiple stacked disks. Yet most computer users are unaware that one of the vital elements in the hard disk, a truly impressive piece of engineering, is a layer of electroless nickel.

Most such disks are manufactured from an aluminium alloy due to that alloy's light weight and rigidity, and to the ease with which it machines to perfect flatness. However aluminium cannot be polished to the high level needed and requires a coating.

The coating in question consists of high-phosphorus electroless nickel which is applied to the surface of the aluminium alloy disk. It is the only coating that can be used in this application. Electroless nickel enables the essential flatness to be maintained since deposit thickness is perfectly uniform. The coating must be extremely hard to allow polishing to the required finish, a maximum roughness of about 4 Angstroms. This high standard of precision is required since the separation between the disk and the read/write head can be as small as 2 nanometres. Another reason for using high phosphorous electroless nickel is that it is non-ferromagnetic.

The next step involves applying a very thin, soft magnetic under-layer by a Physical Vapour Deposition (PVD) technique, often called "sputtering", performed in a high vacuum. This layer is made from an alloy typically containing nickel, cobalt and iron. Some disks will have 2 layers of this material separated by a layer of ruthenium only 4 atoms thick.

Several data storage layers come next, typically a cobalt, chromium and platinum alloy, applied by the PVD technique. Again they are often separated by a thin layer of ruthenium. This is followed by a protective overcoat.

Annual global production of hard disks containing electroless nickel and nickel-containing magnetic under-layer is estimated at 300 to 500 million units and new uses are emerging in automotive control systems and other manufacturing sectors. Hard drive disks remain highly competitive with other storage devices such as flash (or Solid State) drives used in smaller devices such as cameras, since the price per gigabyte of storage is considerably lower.

▷ *The hard disk drive is a truly impressive piece of engineering, using both electroless nickel and a nickel alloy deposited by PVD.*

PHOTO © SEAGATE

Keeping the spark alive:
Nickel alloys for spark plug ignition

△ *Nickel alloys provide the strength of both electrodes as well as the optimal substrate for surface finishes of iridium and platinum.*

Designers of internal combustion engines big and small – from the compact four-cylinder motor under the car's hood to room-sized power plants – require reliable spark plugs to keep their creations running smoothly. And spark plug manufacturers in turn rely on nickel alloys to build reliable, durable electrodes to keep their plugs firing dependably.

"Nickel alloys are the default materials for electrodes in the spark plug ignition world," says Richard Keller, director of product engineering for ignition at Federal-Mogul Corp., maker of the well-known Champion® brand. "Life would be almost impossible without it as a choice for electrodes."

A spark plug has two electrodes: a central one which protrudes from the bottom of the plug and an L-shaped ground electrode which forms the narrow gap where the spark is produced.

Federal-Mogul, which is based in Southfield, Michigan, U.S.A., uses high-nickel alloys for most of its electrodes, including Alloy 600 (N06600) and 601 (N06601), as well as its own specialty nickel-chromium alloys that contain 80-97% nickel. While a small number of plugs use electrodes made of Type 316 (S31600) stainless steel, the high-nickel and nickel-chromium offer "the best balance of performance and cost," says Keller.

The electrodes must withstand high temperatures for long periods while producing a consistent spark, and also resist oxidation and chemical exposure. A major challenge is ensuring the electrodes resist "spark erosion," that is, the loss of metal that can gradually widen the gap between electrodes and affect an engine's performance.

Maintaining the specified spark gap is "absolutely critical" to prevent misfires or shutdowns, Keller says, particularly when the engine powers a pump or generator. Service interruptions can be costly. When customers buy a plug rated to last 4,000 hours, "that's exactly what they expect," he notes. "In our business, failure to meet or exceed an intended service interval is about as bad as it gets."

To strengthen an electrode's resistance to erosion, alloys of durable precious metals such as platinum and iridium are added to the sparking surface of most plugs. Not only does the weldability of nickel alloys ensure the precious metal surface stays bonded to the electrode, nickel is also the metal of choice to combine with platinum.

"Nickel and platinum work exceedingly well together," Keller notes. Nickel may account for anywhere from 10% to almost a third of a platinum alloy used on plug tips.

Nickel also plays a key role in the manufacture of industrial and high-performance racing plugs. While zinc plating protects automotive plugs from corrosion, plugs designed for these demanding applications are typically made by using a special process. Nickel-plated steel is used for the body of these plugs because the nickel can withstand the high-temperature crimping process.

Federal-Mogul produces spark plugs for buses, cars and trucks as well as for industrial applications such as turbine engines, power plants and pipeline pumping stations. Ni

SPARKPLUG IMAGE: FEDERAL-MOGUL CORP.