NICKEL MAGAZINE

THE MAGAZINE DEVOTED TO NICKEL AND ITS APPLICATIONS

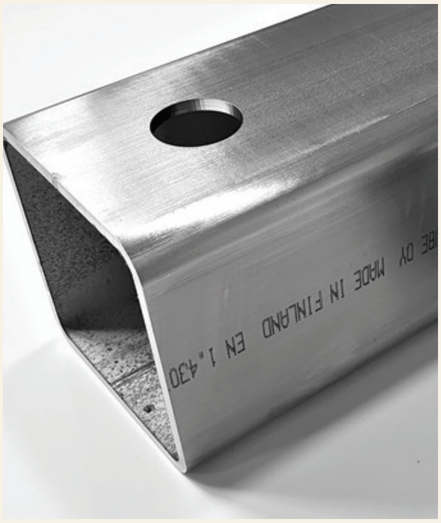
NICKEL, VOL. 35, Nº 2, 2020

Nickel and the next industrial revolution

Artificial Intelligence and sustainable steelmaking

Additive Manufacturing with nickel

Nickel's importance in rocket science



STALATUBE OY

STALATUBE OY

Over four tonnes of stainless steel square and rectangular tubes in three sizes, from 0.5 m to over 2 m long, were supplied by Stalatube to fabricate the balcony frames. The grade of stainless steel chosen was Type 304 (UNS S30400). The tubes were laser cut and perforated to precise tolerances.

CASE STUDY 19
APARTMENT BALCONIES IN LAHTI, FINLAND

The popularity of modular construction is growing. Factory-produced building units are delivered to site and assembled as substantial elements of a building. Undertaking the work off-site leads to savings in time, enhanced quality, decreased material waste, simplified on-site logistics, and less disruption to the surrounding environment.

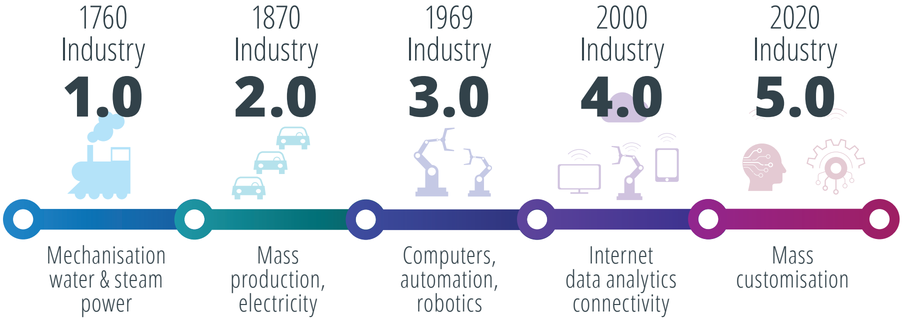
Prefabricated modular balcony systems, both for new build and renovation projects, are an increasingly popular and cost-effective way of expanding the usable space of an apartment, providing a safe and private outdoor space.

Stainless steel is an ideal choice of material for the structural components in both traditional and prefabricated balconies. As well as being aesthetically appealing, it is highly durable and retains its attractive appearance throughout the building's lifetime with minimal maintenance. The high strength-to-weight ratio of stainless steel is another important advantage as it enables the easy and quick installation of the balconies to the building.

Last year, 100 modular balconies were installed in new apartment houses in Lahti, a city in southern Finland. The balconies were prefabricated in the factory – with the handrails, glass and wooden floor grid attached to the structural stainless steel framework, and then delivered to the construction site ready-to-install in one day.

EDITORIAL:
CUSTOMISING THE FUTURE

Today we are on the cusp between Industry 4.0 – the revolution that is digitalisation, the internet of things, connected devices, data analytics – and Industry 5.0, the introduction of Artificial Intelligence (AI) into manufacture. The vision for the latest industrial revolution is mass personalisation and customisation made possible by man and machine – human and Artificial Intelligence – working together.



In this edition of *Nickel* we look at how AI is being investigated and used to make customised nickel-containing steel and alloys, and how it might be used to optimise manufacturing for sustainability. AI is helping industry produce new, accurate, repeatable outcomes. It processes big data that humans cannot and it's already an aid to specification and other intellectual tasks that can dramatically reduce time and cost, and provide novel, better solutions.

But Industry 5.0 is not just about AI. In delivering customisation and personalisation, Additive Manufacturing (AM) is also rapidly developing into mainstream. Nickel-containing alloys are delivering familiar and new properties alike in AM. The combination of AI and AM presents the possibility for more sustainable and bespoke manufacture in the future.

With this edition, *Nickel* is 35 years old! Thanks to our readers and contributors. In an age of massive change, interest in the often unique and astonishing applications for nickel remain as strong as ever. No AI has contributed to this production – yet!

Clare Richardson
Editor, *Nickel* magazine

SPACEX

What could be more futuristic and in need of more sustainability, novel construction and AI than space travel? SpaceX's reusable rockets are set to change the economics of space exploration, with a little help from nickel and Additive Manufacturing.

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Nickel magazine is published by Nickel Institute

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NICKEL NOTABLES

NiPERA turns 40

NiPERA Inc., the independent science division of the Nickel Institute marked its 40th anniversary in July. Since 1980, NiPERA has built its reputation as the leading scientific organisation on nickel-specific human health and environmental research. "Over the past four decades NiPERA scientists have generated an extensive body of scientific work that has enhanced our understanding of the safe use of nickel", says NiPERA's Executive Director, Dr. Adriana Oller. "Thanks to our scientists past and present we have the scientific basis to understand potential health and environmental effects associated with the production, use and disposal of nickel. Nickel has amazing properties and the 40 years of knowledge provided by NiPERA means it can be used with confidence in appropriate applications."
www.nipera.org

NICKEL INSTITUTE

THE 2020 NIPERA TEAM
Dr. Sam Buxton, Dr. Emily Garman, Dr. Kate Heim, Connie Lawson, Dr. Tara Lyons-Darden, Executive Director, Dr. Adriana Oller with former Executive Director, Dr. Hudson Bates, Dr. Adriana Oller, Dr. Chris Schlekat, Dr. Mike Taylor, Dr. Ellie Traudt-Middleton

Meaningful medal

It's both a wearable symbol of support honouring essential and frontline workers and a vital fundraiser for the Breakfast Club of Canada's COVID-19 emergency fund. The Royal Canadian Mint has issued a timely new nickel-plated steel medal that includes a magnet so it can be worn by its recipient. Mint employees donated their time, skills and expertise to create this to help children and families facing food insecurity due to COVID-19. The medal features a heart and maple leaf icon, representing the collective spirit of Canadians "coming together in embrace as we help those in need," according to the Mint. The design also includes a complex array of micro-mirrors with a pulsating light effect around the heart, evoking Canada's "strong heartbeat."

ROYAL CANADIAN MINTZ

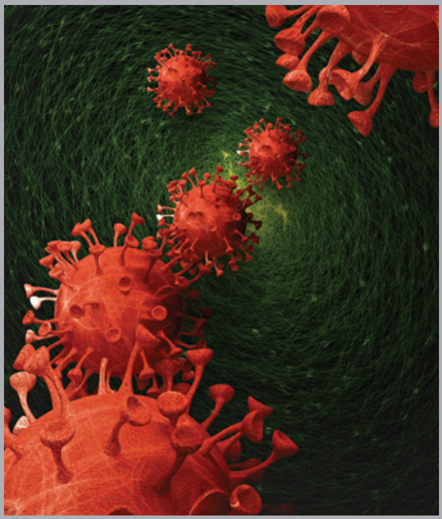
COURTESY OF FORMULA E

Back on track

Formula E geared up for six races over nine days to finish off the 2019/2020 season interrupted by the global pandemic. Suspended in March due to COVID-19, the team of Formula E worked hard to bring racing back while putting "the health and safety of our community first" said Formula E CEO Jamie Reigle. Only essential staff and competitors were on-site. Though there were no live audiences, the nine-day festival featured three track layouts, "presenting a new challenge and creating the conditions for an unpredictable and drama-filled climax to our season," said Reigle. Twelve teams competed at the iconic Berlin-Tempelhof. All batteries in the cars were the same design and supplied by McLaren Applied Technology using the Japanese manufactured muRata high power NCA (Nickel-Cobalt-Aluminum) cells that have increased speeds to 299 kph and doubled the range, so races can now be completed in one car.

COVID-trapping air filter

Addressing the threat that airborne transmission of SARS-CoV-2 can be spread through air conditioning systems, researchers from the University of Houston, in collaboration with others, have designed a filter that traps the virus responsible for COVID-19, killing it instantly. The filter, made from commercially available nickel foam, heated to 200 °C, or about 392 °F, killed 99.8% of the novel SARS-CoV-2 in one pass. This heated air disinfection system paves the way for preventing transmission in closed environments. The research team have advised a phased roll-out of the device beginning with high-priority venues, where essential workers are at elevated risk of exposure, particularly schools, hospitals and health care facilities, as well as public transit environs such as airplanes. They also foresee future uses in airports, office buildings, and cruise ships to stop the spread of COVID-19.



SWEDISH METAL
SUSTAINABLE STEELMAKING THROUGH ARTIFICIAL INTELLIGENCE

SANDVIK

The Swedish Metal project is looking at practical applications of Artificial Intelligence in steelmaking.

When looking at key milestones in industrial development, one might wonder how Industry 5.0 could possibly be relevant to steelmaking. Considering the massive loads, high temperatures and aggressive chemicals used, it is fair to question whether it is too harsh an environment for a high-tech concept such as machine learning to be effective.

Integration of machine learning
The reality is that minerals and metal manufacturing infrastructure has been interfacing with operators through computer systems for decades. It was only a matter of time before machine learning algorithms were integrated into that interface and start to make sense – in a much more efficient way than human beings – of the possible links between inputs (e.g. raw materials, time and temperature) and outputs (steel product quality, greenhouse gases and waste such as slag).

Joining forces

For almost two years now, Swedish carbon steelmaker SSAB and Sandvik, producer of many grades of nickel-containing stainless steels, have joined forces with the University of Skövde. Each partner is approaching the project from their own perspective. Sandvik is aiming to optimise the use of internal scrap to decrease the quantity of virgin alloys needed and reduce the risk of composition errors. SSAB is focusing on optimising converter time and temperature in order to lower emission and energy consumption.

These objectives reflect the ambition to make steel production more sustainable, both from an input point of view (raw materials and energy usage) as well as from an output perspective, in terms of residue and emissions. Furthermore, a role can be envisaged for Artificial Intelligence (AI) where machine learning supports operator decisions in the steelmaking process. This could narrow the gap between the final results achieved by experienced operators compared to novices. Simulations and iterations of such decisions are tested with input from operators and used to strengthen the machine learning tool.

The cradle-to-gate pathway of steel products consists of a number of steps, such as the upstream phase which includes melting and casting of steels, and hot forging. Downstream of these production steps, the steel products are heat treated, often cold rolled and finished. So why would both the steelmakers select the same area of the process to test Artificial Intelligence?

The reasons are manifold:

- The upstream part of steel production is a fairly deterministic process. A number of input variables consistently leads to a somewhat predictable output. There is nothing random about that process. However, deterministic is not tantamount to simple. First of all, there are many variables at play. Secondly, there is an amount of uncertainty at the input side (for example, the average chemical composition of scrap piles) which AI can help make sense of to achieve the desired output.
- The quality of the final product is largely determined by what happens at the liquid stage. So investing in machine learning enhances the output in terms of quality.
- Raw materials and energy largely contribute to the cost of steelmaking. So it makes sense to invest in improvement programs at this level.
- Finally, as SSAB indicates, the steelmaking process for carbon steel is one that is well documented in process automation and control circles. Modelling is available and datasets are plentiful, especially for fairly standardised products such as carbon steel.

Great upside

About halfway through the project now, both steelmakers and the team at Skövde University affirm that the extent to which computer scientists and metallurgists have been able to learn from each other has been a great upside.

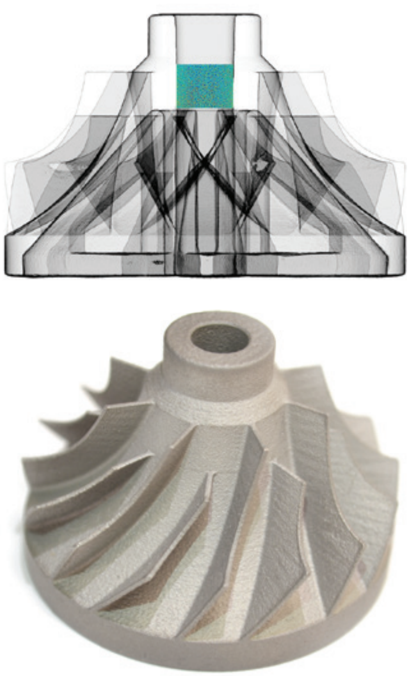
While different segments of the steel industry use different models and datasets and are likely to require bespoke modelling, there is a shared belief that AI can make steelmaking more efficient.

Even if it is not plug-and-play, Industry 5.0 AI concepts look promising for the steel industry and the production of many other nickel-containing products. It's a brave new world. Ni

A role can be envisaged for Artificial Intelligence where machine learning supports operator decisions in the steelmaking process. This could narrow the gap between the final results achieved by experienced operators compared to novices.

INDUSTRY 5.0

METAL ADDITIVE MANUFACTURING AND NICKEL



BRYAN HO-ON

EXPANSE MICROTECHNOLOGIES

Figure 1
5cm diameter impeller in stainless steel alloy 17-4PH (UNS S17400)

While we are still in the midst of Industry 4.0 (smart manufacturing via integration of Artificial Intelligence, cloud computing, just-in-time manufacturing and internet of things), the term Industry 5.0 or its Japanese variant Society 5.0, is gradually gaining in popularity. The basic principle behind the fourth industrial revolution recognises that by linking production equipment, intelligent monitoring and control devices, as well as real-time, internet-based connection to customers, manufacturers are creating smart networks throughout the supply and value chains.

In the upcoming stage of this development, the return of direct human involvement is envisioned to provide the next level of sophistication, responsiveness and relevance to meet the evolving human needs – hence the term Society 5.0. Closer integration of the production systems and participation of humans in their operation and guidance merges the high-speed accuracy of industrial automation with the cognitive, critical and intuitive creative skills of humans. The concept of Society 5.0 has been promoted by the Japanese government since about 2015 – an idea which places the society as a whole at the centre of technology development, rather than the industry. Giving technology the role of a catalyst and a driver, Society 5.0 aims at the general welfare of the members of the society and strives toward building a super-intelligent society-technology ecosystem. Society 5.0 takes Industry 4.0 and places the human being at its centre.

How do these developments impact the production and use of metals, and nickel in particular?
Let's look at this topic with a brief overview of the latest trends in manufacturing technology, with particular emphasis on Additive Manufacturing (AM, or 3D printing) with metals (Metal AM).

Metal AM is a rapidly growing field catalysing a revolution in modern manufacturing. The most common approach involves the use of metal powders as feedstock material and laser sintering to assemble, layer-by-layer, 3D objects. The laser process involves heating particles to the melting point of the given metal (~1,500 °C for nickel-containing steels) to fuse or "weld" the particles, and careful selection of the laser beam control parameters (power, laser beam spot size, beam scanning pattern among many others) to produce a fully dense object, such as in *Figure 1.* Various other approaches involve different energy delivery methods, including electron beam, ultrasound, kinetic energy (cold spray), electric/plasma arc, and extrusion or material jetting of metal-polymer composites (such as metal powder-containing filaments), followed by conventional debinding and sintering processes. *Figure 2* is a high-level, stage-of-development map (industrialisation vs. technology maturity index), showing that the most advanced deposition processes on both scales are the laser beam powder-bed fusion (LB-PBF), powder laser deposition (also known as powder-fed, or Directed Energy Deposition process), electron beam, electric/plasma arc and wire-based electron beam deposition processes. Filament FDM (fused deposition modeling with metal powder-containing filaments) and binder jetting are rapidly approaching the same mature territory.

Figure 3 shows a more detailed list of the various Metal AM techniques. Judging by the number of players, laser beam powder bed fusion is clearly the dominant approach in Metal AM today.

Forming 3D objects layer-by-layer is not a foreign concept in the nickel industry. This is exactly how carbonyl nickel and ferronickel pellets are made, utilising chemical vapor deposition from iron pentacarbonyl, $Fe(CO)_5$ and nickel tetracarbonyl, $Ni(CO)_4$, discovered by Ludwig Mond in late 1800's. *Figure 4* shows a cross-section image of a ferronickel pellet, revealing alternating layered structure of Ni- and Fe-rich layers. The individual layers form a regular pattern. The pellets are at a uniform temperature and the deposition of each layer takes place on all pellet surfaces simultaneously within the reactor. Owing to the differences in nickel and iron carbonyl properties, the decomposition of each takes place preferentially within certain reactor space, resulting in the segregation of

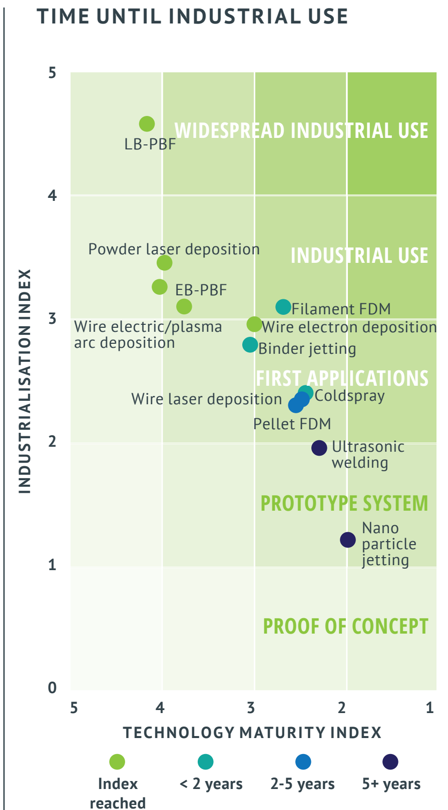


Figure 2 Technology and industrial maturity index of different Metal AM technologies

BASED ON AMPOWER INSIGHTS

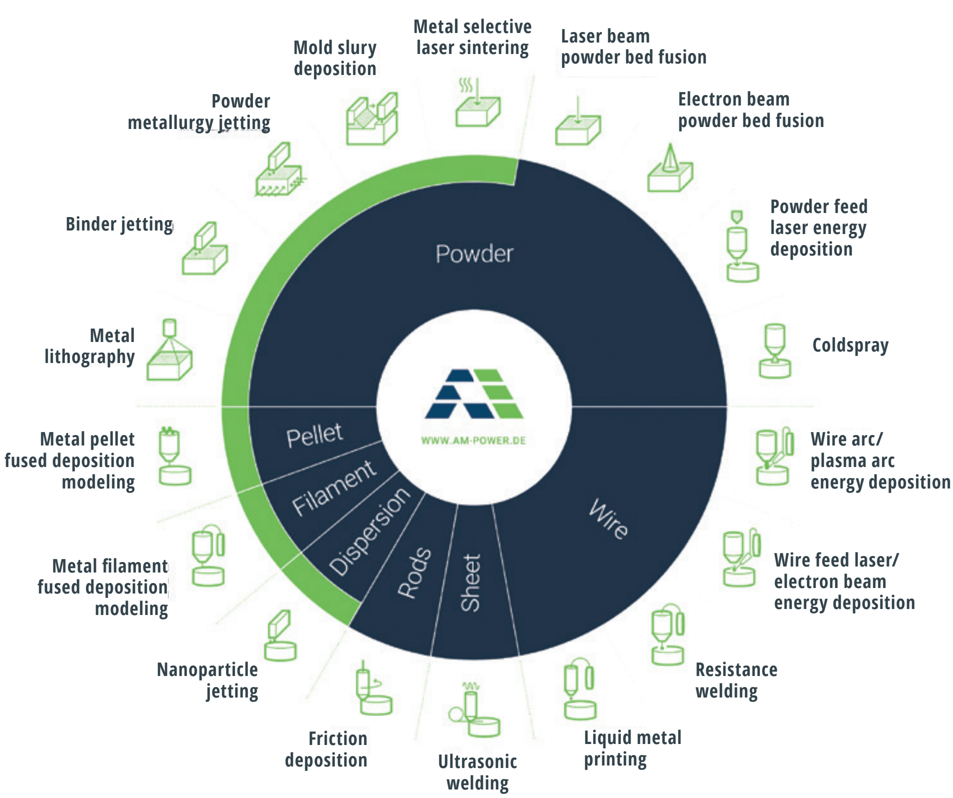


Figure 3
Technology overview Metal Additive Manufacturing
Over 18 different metal 3D printing processes are known. AMPOWER Insights provide an overview and classification of the most important procedures.

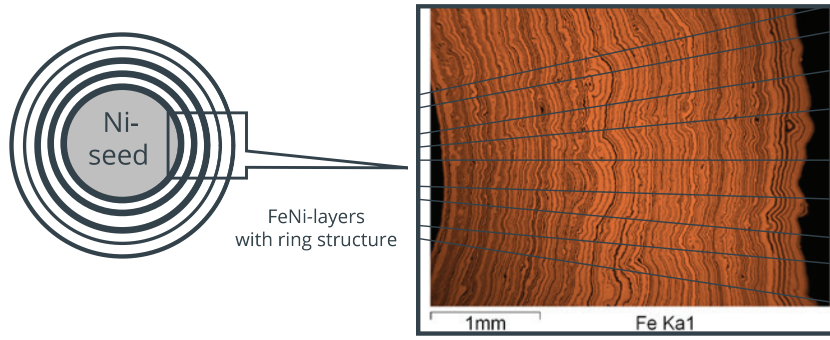
AMPOWER INSIGHTS

3D printed sensors

A typical modern automobile has between 60 and 100 sensors helping the engine run efficiently and the vehicle to operate safely and comfortably. Similarly, sensors have become essential in the manufacturing and process industries, aerospace and health care. For Industry 5.0 to be successful, a huge amount of information on all operating aspects of a system needs to be instantaneously available and analysed, all coming from different kinds of sensors. Additive Manufacturing can help in two ways – sensors themselves can be printed, and sensors can be embedded in parts while being printed. As with standard 3D printed parts, these sensors can be custom designed, produced quickly and cost-effectively in small quantities. Sensors are being printed in many different materials, including nickel-containing stainless steels and nickel alloys. Sizes of sensors can range from sub-micron to very large. Types of sensors that can be printed include strain, pressure, force, flow, vibration and many more. As the need for more sensors increases, more will be produced by 3D printing.

M2N TECHNOLOGIES

3D printed stainless steel pressure sensor



VALERY CHANI

Figure 4
Layered structure of ferronickel pellets (dark color=Ni-rich, light color=iron-rich)

Ni and Fe-rich layers. One can easily envision selected area deposition if the energy is supplied by a precise laser beam, writing a 3D nickel object (*Figure 5*). The development of such vapor-phase Metal AM techniques is still in a laboratory stage. As of 2020, the dominant metals used in Metal AM are titanium, stainless steel, tool steels, aluminum, and nickel-based superalloys. In addition to the nickel content in stainless steels, the nickel alloys play an important role in aerospace, tools production and other demanding applications, positioning nickel as an important component of high-value, additively printed metal parts. While the total volume of metal powders used as feed materials in Metal AM printers is very small compared to the conventional metal forming techniques (~3,000 tons of all combined metal powders in 2020), the rapid growth of Metal AM is expected to persist and nickel will continue to play a key role in many applications.

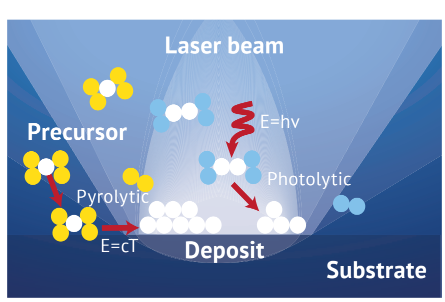


Figure 5 Laser beam guided selective area deposition from vapor phase metal precursor

3D printing of nickel superalloys is a particularly active area of research, owing to the high potential in application areas such as aerospace and tooling.

The rapid growth of Metal AM continues to evolve and has the potential to become one of the most revolutionary technologies in metalworking. Aerospace, usually one of the earliest adopters of novel technologies, has been leading the applications development along with tooling and the medical market segment. Significant challenges that remain include safety (working with metal particulates) and regulations, limited production volumes due to process inefficiencies, equipment size constraints and long build-times, limited availability of economical metal powders, the need to develop best practices, specifications, and standards for acceptance by various industry segments.

Nickel is bound to be one of the dominant participants among this new category of metallic feed materials, driving the development of high-performance parts in the next generation products in a variety of industries. Ni

DOES ARTIFICIAL INTELLIGENCE PROMOTE USE OF NICKEL?

In recent years, Artificial Intelligence (AI) has been introduced into many areas of our lives. Industry is no exception and new alloy development is one industrial application being explored.

Developing a new alloy typically takes a team of researchers around ten years. It requires a high degree of expertise and understanding of the interactions between the various alloying elements to achieve the desired properties as well as the ability to commercially produce it. AI has the potential to significantly shorten that development time and support even inexperienced developers.

Dr. Ikumu Watanabe, Senior Researcher at the National Institute for Materials Science (NIMS) Japan and his team have developed AI-based Alloy Development Support Software which calculates the most suitable chemical composition and manufacturing process to achieve the properties required for nickel-containing and other alloys. The software identifies correlations between multiple properties, structures and production processes, and allows the improvement of the alloy's properties. For example, an alloy may need heat-resistance as well as creep strength and phase stability. In practice, if one property is strengthened, other properties are often sacrificed. Achieving a balance is the challenge for an alloy developer and where AI has the potential to help.

The software does require an enormous amount of data. Its deep-learning AI can gather information and generate diagrams correlating several factors by reading and picking up words related to alloy manufacturing processes, alloy metal structures as well as alloy physical properties. Currently, the software extracts data from the Elsevier database, but it can also be customised and extended to read a company's own technical data and to gather big data available on the internet. At present it only draws qualitative correlations, but in the future, the software aims to handle quantitative data for actual implementation on site.

There are many benefits for end users. For example, if we can improve the heat-resistance property of an existing nickel alloy, we can improve the fuel efficiency of an aircraft or of a thermal power generation plant and CO_2 emissions can be reduced. With the help of AI the potential is there for superior nickel alloys to be launched faster, with accompanying environmental benefits for society. Ni

By inputting properties such elastic modulus, strength, ductility, fatigue limit, weldability and phase stability, the software calculates how to achieve the new alloy's required physical properties.

NICKEL-COPPER ALLOY
IN SPACE

HTTPS://WWW.ENVIRONMENTAL-EXPERT.COM/COMPANIES/KCM-SPECIAL-STEEL-CO-LTD-100088/

It is commonly known that about 70% of all nickel production is used in the production of stainless steel. Stainless steel was independently discovered by a number of researchers in 1912, yet corrosion-resistant nickel-base alloys predate it. In 1906, a nickel-copper (Ni-Cu) alloy, developed by the International Nickel Company (INCO), was patented. This now is comprised of a group of nickel alloys that contain about two-thirds nickel and one-third copper and is known as Monel®.

Stronger than pure nickel, Ni-Cu alloys possess excellent corrosion resistance in a range of non-oxidising acids and alkaline environments, including rapidly flowing seawater. Ni-Cu alloys offer exceptional resistance to hydrofluoric acid in all concentrations up to the boiling point and are resistant to many forms of sulfuric and hydrochloric acids under reducing conditions.

Characteristics

Ni-Cu alloys also possess excellent resistance to oxidation (burning) in high oxygen environments, excellent mechanical properties both at subzero temperatures and up to 550°C (1020°F). Ni-Cu alloys can be fabricated readily by hot- and cold-working, machining, and welding. The most well known variety is alloy 400 (N04400). Alloy 400 can only be hardened by cold working, however, in 1924, the addition of aluminum and titanium produced an age-hardening version with higher strength, known as K-500 (N05500). By means of the precipitation of gamma prime particles, yield strength in excess of 690 MPa, (100 ksi) about three times higher than alloy 400 (N04400) is achieved.

Aerospace

Ni-Cu alloys can be found in tubes, pipes, rods, and wire for various aerospace applications. The natural resistance of Ni-Cu alloys to burning in oxygen, excellent properties at subzero temperatures, and the high strength of K-500 has made this alloy an important contributor in the fabrication of turbopumps for the oxidiser side of the oxygen-rich liquefied-fuel rocket engines, such as the Blue Origin BE-4.

Blue Origin has taken advantage of 3D Additive Manufacturing to make many of the key components of its Ox Boost Pump (OBP). The housing is a single printed aluminum part and all of the stages of the hydraulic turbine are printed from K-500. This

Far left: The housing of the Blue Origin BE-4 Ox Boost Pump is a single printed aluminum part and all of the stages of the hydraulic turbine are printed from K-500.

Left: A mechanic inspects the Ox Boost pump.

Below left: The Ox Boost Pump can be seen in the bottom quarter of the image.

Below: Blue Origin New Glenn Rocket

manufacturing approach allows the integration of complex internal flow passages in the housing that would be much more difficult to make using conventional methods. The turbine nozzles and rotors are also 3D printed and require minimum machining to achieve the required fits.

Even today, Ni-Cu alloys developed more than a century ago are essential in demanding leading-edge applications.

ASK AN EXPERT

FAQ FROM THE NICKEL INSTITUTE TECHNICAL ADVICE LINE

Geir Moe P.Eng. is the Technical Inquiry Service Coordinator at the Nickel Institute. Along with other material specialists situated around the world, Geir helps end-users and specifiers of nickel-containing materials seeking technical support. The team is on hand to provide technical advice free of charge on a wide range of applications such as stainless steel, nickel alloys and nickel plating to enable nickel to be used with confidence.
https://inquiries.nickelinstitute.org/

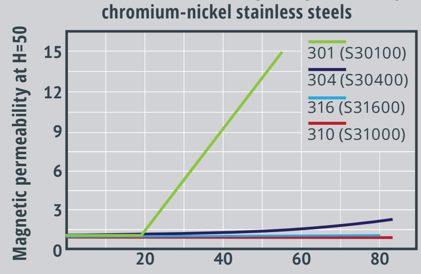
Q: Why do nickel-containing austenitic stainless steels, such as 304, sometimes possess magnetic properties?

A: Above approximately 727 °C, steel possesses a non-magnetic microstructure called austenite. Below this temperature steel possesses a magnetic structure called ferrite. The addition of sufficient nickel makes austenite stable at room temperature. This is why austenitic stainless steels such as 304 are non-magnetic. However, the austenite in 304 (S30400) and particularly 301 (S30100) is metastable. This means when plastically deformed (cold worked) some of this austenite can undergo a transformation into yet another magnetic microstructure, called strain-induced martensite which includes an increase in tensile strength. The greater the amount of plastic deformation the more martensite is formed and thus more magnetic attraction and higher strength.

In most instances this magnetic attraction is of no consequence. In fact the attendant increase in tensile strength is beneficial in the production of components such as seat belt retractors in cars, wire and strip springs and even surgical needles. However, in some applications it can cause problems for equipment that can be affected by small amounts of magnetic attraction, such as Magnetic Resonance Imaging (MRI) machines. In these cases, grades that possess stable austenite with higher nickel contents are employed.

Visit: inquiries.nickelinstitute.org

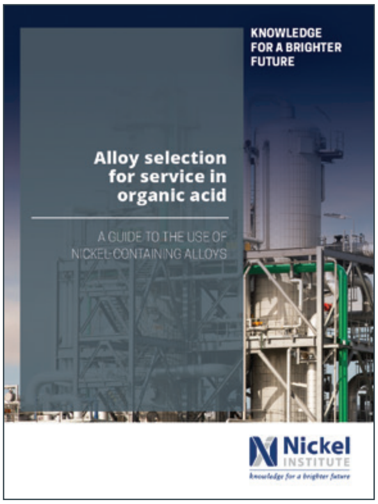
Effect of cold work on the magnetic permeability of chromium-nickel stainless steels



NEW PUBLICATION

Alloy selection for service in organic acid (10063) reviews the corrosive effect of organic acids, such as formic, acetic and fatty acids, at all concentrations. The corrosive action of organic acids is complicated because these acids are not handled in isolation but rather as process mixtures with inorganic acids, organic solvents and salts. Organic acids rank among the most important chemicals in industry today. They are the building block for many compounds, ranging from drugs and pharmaceuticals, such as aspirin, to plastics and fibres. This fully revised technical publication from the Nickel Institute provides a useful guide for materials engineers.

Available to download free from www.nickelinstitute.org



NEW LIFE CYCLE ASSESSMENT FOR NICKEL

The latest nickel life cycle assessment data (reference year 2017) for nickel metal, ferronickel and nickel sulphate are now available. The report provides a robust and transparent overview of the inputs (energy, process chemicals or water) and outputs (emissions to water, air or waste) of the nickel production process. Nine Nickel Institute member companies and twenty four production sites around the world contributed.

"The study represents 52% of global nickel metal production, 47% of ferronickel production and 15% of nickel sulphate production" explains the Nickel Institute's Dr. Mark Mistry who led the project. "It is compiled to ISO standards and has been independently critically reviewed. This is the third update of life cycle data for nickel. It shows the commitment of Nickel Institute member companies to provide customers and end users with high quality information."

Download summary infographics from the Nickel Institute website. The full report is available upon request. *communications@nickelinstitute.org*

UNS DETAILS

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

UNS	Al	C	Cr	Cu	Fe	Mn	Mo	Nb	N	Ni	P	S	Si	Ti
S17400 p. 8	-	0.07 max.	15.0-17.5	3.00-5.00	bal.	1.00 max.	-	0.15-0.45	-	3.00-5.00	0.040 max.	0.030 max.	1.00 max.	-
S30100 p. 14	-	0.15 max.	16.0-18.0	-	bal.	2.00 max.	-	-	0.10 max.	6.0-8.0	0.045 max.	0.030 max.	1.00 max.	-
S30400 p. 2, 14	-	0.08 max	18.0-20.0	-	bal.	2.00 max.	-	-	-	8.0-10.5	0.045 max	0.030 max	1.00 max	-
S31600 p. 14	-	0.08 max.	16.0-18.0	-	bal.	2.00 max.	-	-	-	10.0-14.0	0.045 max.	0.030 max.	1.00 max.	-
N04400 p. 11	-	0.3 max.	-	bal.	2.50 max.	2.00 max.	-	-	-	63.0-70.0	-	0.024 max.	0.50 max.	-
N05500 p. 11	2.30-3.15	0.25 max.	-	bal.	2.00 max.	1.50 max.	-	-	-	63.0-70.0	-	0.01 max.	0.50 max.	0.35-0.85

SPACEX

Two-thirds of the Falcon Heavy rocket – the two boosters – make a pas de deux *return to the Kennedy Space Center in February 2018. Of the 30 attempts at landing on a sea platform, twenty-five have been successful. With experience, failures have become the exception, not the rule.*

THE END OF DISPOSABLE ROCKETS

No, it hasn't happened yet but the brave beginning is over. Launch-and-recover is in the process of being made ordinary: SpaceX has over 50 recoveries of the first stage of Falcon 9 rockets, and three first stages have been launched five times. The rapidly and economically reusable module for taking humans to space – the SpaceX Crew Dragon – returned triumphantly on 2 August, 2020. No longer with that 'new space capsule smell', the craft will be used again, perhaps with the soot washed off.

It's been dramatic but the focus has been more on the tubes, not the ten Merlin engines (nine for the first stage, one for the second). Each time a first stage lands, it lands with its nine Merlin engines intact, ready to be refueled and re-used. The goal is ten launches before refurbishment and re-entry into service.

The ultimate service life is not known but the approximately 1125 kg of nickel-containing alloys will ultimately be recovered and recycled…except for whatever goes to museums as evidence of human ingenuity and ambition. Ni