The coupled Pickling Line and Tandem Mill installed at Yıldız Demir Çelik, Turkey, is the most advanced PLTCM, allowing unmatched ease-of-operation and product quality.

The Turboflo® pickling line with energy-saving patented technology and preceded by a powerful scale breaker improves efficiency and flexibility.

The Danieli Wean United 6-high tandem mill features original Danieli OSRT control for superior strip flatness and Danieli Automation mathematical models. Final strip thickness of 0.20 mm and widths up to 1,550 mm are achieved for DP600, DP1000, IF and HSLA automotive products.

Ultra-low hysteresis HAGC, X-Dry for 20x greater strip drying capacity, and D-Rec automatic eccentricity compensation algorithm are featured too.

Strip thickness tolerance down to ± 0.6%, head/tail off-gauge length lower than four meters, and strip flatness less than 6IU are achieved.

One week after commissioning the newly supplied PLTCM already was producing at more than 60% nominal capacity, and after 2 weeks 20,000 tons were produced in first quality, for almost all contractual steel grades.
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We are strongly committed to assist our clients with the necessary remote support and will remain available via today’s modern communication channels. Additionally the John Cockerill Industry Metals staff maintains its site activities where contextually feasible.

We would like to thank you for your trust, understanding and collaboration and to assure you of our solidarity with you, your staff and all your relatives.
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Foreword

I am extremely grateful to all the authors and their organisations for sending in articles for publication despite all the difficulties and upheavals to everyone caused by the Covid-19 pandemic.

Data from worldsteel.org shows 2019 crude steel output was 1.84 billion tonnes, a new high. Steel companies acknowledge that they are a significant contributor to world greenhouse gas emissions but they are also part of the solution, as indicated by the many papers published here. There are many steel companies, plant suppliers and research organisations making strenuous efforts to develop new, lower carbon or even carbon-free ironmaking and steelmaking routes. It must be acknowledged that these developments can take many years, or even decades to bring to industrial scale, so CO2 reduction through myriad incremental improvements described is also welcomed. These increments include many energy reduction schemes, which is welcome as less energy means less CO2.

As a result of this ‘green’ surge I have allocated articles into three categories, Sustainability, dealing with the key ‘green’ themes, and Primary Processes and Finishing Processes dealing essentially with plant productivity and quality improvements. All three sections show a determination to further improve steelworks processes, through energy reduction, reduced waste, higher productivity, better ways of working, and with less rework or scrap.

As a closing comment I would say that the Covid-19 pandemic has demonstrated an amazing ability of engineers around the world to work on new virus test equipment at an unprecedented speed. And also for manufacturers not normally in the field of bioengineering from such diverse areas as automotive, vacuum cleaners and aerospace to produce, gain product approval, and deliver, from a standing start, ventilators and personal protective equipment at ‘warp’ speed. Think what could be achieved in steel!

I hope you enjoy this issue.

Production Editor, Annie Cree and Designer, Ray Belletty have produced an excellent, very readable publication, and I thank all the authors and advertisers for their support.

Work on the Millennium Steel America 2020 edition of will be starting soon and I welcome proposals for technical articles.

David Price
Editor
May 2020
REDUCING CO₂ EMISSIONS IS A COMMITMENT WE TAKE SERIOUSLY

At Harsco Environmental, we share growing concerns about the impact climate change is having on our environment. Which is why, as a business partner and knowledge-leader working in close collaboration with the steel industry, our priority is to find innovative solutions to **Reduce, Recycle** and **Reuse** the by-products produced during the steelmaking process.

Our environmental services help our customers repurpose by-products for productive uses and reduce the CO₂ emissions from steel making. The sustainability of our planet for the future is a commitment we take very seriously.

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‘step up’: reducing steel’s carbon footprint

Given that steel produces between 7% and 9% of global CO₂ emissions, the industry is clearly part of the problem. However, it is also part of the solution. Steelmakers around the world are investing large amounts of money in research and development in a diverse suite of technologies that may be described as breakthrough technologies to reduce emissions. To help facilitate improvement via shorter timescale incremental improvements worldsteel has developed step up, a programme designed to lead to reduced carbon emissions by sharing leading practices that drive efficiency gains in both the short and medium term.

Author: Rizwan Janjua
World Steel Association

In December 2015, governments around the world signed the Paris Agreement, which commits countries to keeping global average temperature rises to below 2°C and pursue efforts to keep the increase below 1.5°C. The importance of achieving this, and steel’s role in ensuring we achieve this, cannot be overstated.

Decarbonisation of the global economy will be a steel-intensive process in everything from installing the wind turbines and solar panels that will generate renewable energy, to building the mass transit systems that will reduce the environmental impact of the transport sector. However, the steel industry is energy-intensive, and CO₂ emissions are an inherent part of current steelmaking processes. Although the amount of carbon released per tonne of steel made has been falling as steelmakers drive efficiencies in their operations, the volume of steel produced means that the industry currently accounts for between 7% and 9% of total global carbon emissions.

We recognise that while we are clearly a big part of the problem, we are also a part of the solution and have a responsibility to do everything we can to support global mitigation efforts. This article describes the key direction of the steel industry in response to global warming. There are two aspects: development and implementation of breakthrough technologies and incremental improvements to existing technologies.

BREAKTHROUGH TECHNOLOGIES

Steelmakers around the world are investing large amounts of money in research and development in a diverse suite of technologies.

The development of a hydrogen economy is one of the steel industry’s most exciting prospects. Using hydrogen as a reducing agent to reduce iron ore and circumvent the need for preparation and use of coking coal could make carbon-neutral steelmaking possible. Swedish steelmaker SSAB’s HYBRIT project aims to introduce ‘fossil-free’ steel into the market as early as 2026 by reducing iron ore with hydrogen created from the electrolysis of water using renewably generated electricity.

Sweden is able to make use of its abundant renewable energy resources, but local circumstances mean that it may not be appropriate for all steelmakers to take this route. The UAE’s Emirates Steel, working with Masdar, the national renewable energy company, has developed commercial scale carbon capture and utilisation projects that make use of the Abu Dhabi Nation Oil Company’s mature oilfields to sequester around 800,000 tonnes of CO₂ annually.

Radically redesigning existing technologies is another option. The HIsarna facility at Tata Steel Europe’s Ijmuiden plant liquifies iron ore in a high-temperature cyclone before injecting powdered coal. This process removes a number of pre-processing steps and allows for less stringent raw material quality conditions to produce the same high quality steel.

Unfortunately, the widespread commercial viability of these technologies is not likely to come about until around the middle of this century. To maintain a good reputation in the eyes of our customers and of society at large the steel industry needs to act and be seen to act on its responsibilities in the meantime, especially as demand for our products increases. This is where step up comes in.

INCREMENTAL IMPROVEMENTS – STEP UP

step up is our programme for helping steel companies make ever more incremental process improvements by sharing leading practices that drive efficiency gains in the short and medium term, and subsequently lead to reduced carbon emissions. The membership of worldsteel represents more than 80% of global crude steel production and includes steelmakers operating in every continent and...
in very different local circumstances, so the potential for different industry players to learn from one another is enormous.

worldsteel has developed a clear four-stage efficiency review process covering raw material quality, process yield, energy efficiency, and process reliability that is intended to support improvements in plant operations to efficiency levels commensurate with the steel industry’s top performers.

BENCHMARKING

To determine where a site is positioned in a list of global performers, worldsteel maintains benchmarking systems that collect data on CO₂ emissions and energy use at steel plants [1]. The data report overall emissions intensity for the production of steel at a particular site, irrespective of the products being made. We have developed a methodology, now published as an International Standards Organisation (ISO) standard ISO 14404. There are three versions, one for a production site...
with a blast furnace, one for a production site with an electric arc furnace, and one for a site with an electric arc furnace with a coal or gas-based direct reduced iron (DRI) facility. The data collection methodology and standard is designed to ensure that sites reporting emissions use the same boundaries and parameters. Once a site's position in the system is determined, worldsteel can work with plant management to determine where efficiencies in the four areas of the step up review can be made (see Figure 1).

RAW MATERIAL QUALITY
The quality of raw materials, particularly iron ore and coking coal, has a direct impact on CO2 emissions, but unfortunately availability of good quality materials is becoming more problematic. Measures such as beneficiation of ore and coal at the source or increasing scrap use in the basic oxygen furnace are just a few of the measures that can significantly improve operational performance.

This last point is crucial. The dynamics of the industry are such that we estimate the availability of scrap is set to increase to around 1.3 billion tonnes annually by 2050, largely as the steel produced for the infrastructure and building construction projects in China in the early part of this century reaches the end of its first life. As such, we can expect the steel industry to increasingly replace natural resources with steel scrap, thereby conserving raw materials, energy, and reducing CO2 emissions.

In the long term this is likely to encourage a shift to EAF production, although it is important to stress that there will still not be enough scrap alone to meet demand for steel for the foreseeable future.

The shift to more EAF production and increased scrap use in BOF production will see the steel industry move to an increasingly circular rather than linear economic model, one in which CO2 emissions and the extractive burden on nature is reduced.

PROCESS YIELD
Yield improvement means using fewer resources, which means less energy and processing time, resulting in fewer emissions for the same input. Identifying the potential for yield improvement can positively influence other key performance indicators (KPIs), such as process control, quality control and general planning. The step up review compares yield across the entire facility, starting from ironmaking through to steelmaking and on to rolling and finishing for integrated sites.

ENERGY EFFICIENCY
Energy efficiency is an area in which the steel industry has made considerable improvements over the last few decades, to the extent that the best performers have approached the absolute limits of what is possible with current technologies.

Bringing the whole industry up to the standard of these best performers can involve implementing a number of tested and proven improvement measures including energy recovery from solid and gas streams, coke dry-quenching, cogeneration units, and self-sufficiency in less carbon-intensive electricity production.

PROCESS RELIABILITY
Improving a steelmaking plant’s maintenance ensures process reliability, reduces losses in quality and process time, thereby reducing energy use per tonne of steel. Here, the step up review is based on identifying operational Overall Equipment Effectiveness (OEE). Plant management can compare the links in their facility’s production chain (continuous casters, hot rolling mills, coating lines, etc.) to identify the potential for reducing their unscheduled losses and benefit from the extra uptime for running at high speed, quality and throughput rate without associated unnecessary emissions.

CONCLUSION
step up was tested across nine sites around the world in 2019 and will be rolled out more comprehensively over the coming years.

The steel industry is making headway in responding to the carbon challenge, but there remains much to do. Fortunately, both the steel industry and steel as a product, already play an important role in driving the sustainability that signatories of the Paris Agreement expect. Our step up programme and the range of initiatives that steelmakers around the world are developing will ensure we don’t disappoint them.

A more comprehensive article containing greater technical and financial detail will be published in Millennium Steel in a subsequent issue. MS

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From liquid steel to rolling: concepts and applications for higher efficiency and zero waste

Green technologies are those that reduce emissions, waste by-products and resource consumption; increased process efficiency directly results in decreasing energy consumption and resource utilisation. Danieli has a long record of environmental achievements and process developments; concepts and examples are described.

Author: Rolando Paolone
Danieli SpA

DEFINING SUSTAINABILITY FOR METAL PRODUCTION
In metals production ‘green’ technologies are those that reduce emissions, waste by-products and resource consumption. Resources represent costs and so reducing the intake of raw materials and energy provides economic advantages to metals producers, but it also has benefits in terms of emissions reduction: greenhouse gases (CO₂), liquid (dirty water), and solid emissions (slag/dust).

There are also maintenance advantages, as reducing resource consumption will limit intervention, and extending the lifetime of old equipment reduces the requirement for new resources.

Personnel training and risk-analysis will limit failures or accidents, which represent costs both in terms of materials and of human beings.

Plant start-ups and shut-downs are studied in order to minimise consumption and equipment wear, to abate costs and to cut emissions and resource waste because often these are a consequence of very un-optimised paths.

DEVELOPING ‘GREEN’ PRODUCTION PROCESSES
From conceptual modelling to the prototype, the design of new equipment increasingly relies on computational modelling. Computer fluid dynamics (CFD) is used to explore new configurations, design of experiments (DoE) reduces the number of experiments required, statistical tools transform sparse data into information, and predictive models convert observations into know-how.

Environmental constraints can be implemented in these models like any other process parameters. For example, the Acou-Stack process was optimised by means of detailed CFD modelling.

Increased process efficiency directly supports decreasing energy and resources. Machine-learning tools using databases of failures, procedures or maintenance have proven to be a valid aid to increasing performance in complex processes. The most notable new examples of Danieli green technologies that have resulted in new steelmaking technologies are the Energiron process (jointly developed by Tenova and Danieli), for reduction of iron ore using natural gas or hydrogen, to minimise carbon emissions, and the M1DA concept for Endless Casting and Rolling, with low CapEx and OpEx, to serve regional markets.

The unique capacity of Danieli to provide the whole process stream, from iron ore to finished product, is the key to the maximum energy efficiency with minimum GHG emissions: the whole transformation is done with CO₂ emissions per t of finished steel of around 800kg/t but with the unique possibility to capture from 300 to 320kgCO₂/t steel in the Energiron CO₂ absorber. This pure CO₂ can then be used for several purposes (as raw material for chemicals, synthetic fuel, for food industry, for enhanced oil well production etc.) So, the CO₂ is no more a problem, but rather a business opportunity.

RESOURCES FOR GREEN RESEARCH
Model predictive control, machine learning, and the internet of things (IoT) are some ways to transfer research teams’ experience into customer operators, with adequate training to make maximum use of it. More often, research projects are followed by skilled employees in cooperation with the most specialised universities, as in the development of low NOx burners, or water-oil emulsion lubricants for aluminium cold rolling.

BEST AVAILABLE TECHNOLOGIES
Danieli always applies the best available techniques (BAT) to its designs and is currently introducing technologies that are well established for other industrial sectors; finding synergies that have demonstrated to be justified
Reducing energy demand, particularly carbon-based energy, and using renewable energy sources, also help reduce CO2 emissions, in fulfilment of the more and more stringent international agreements on GHG emissions, with related fees.

**GREEN PROJECT GOALS**

In projects that involve new design, layout and logistics are studied to help make the workplace efficient, clean and productive. In plant revamp projects there are more physical constraints, which require a customised study to include the most advanced and efficient solutions in the existing layouts, without modifying upstream or downstream processes.

Maintenance is focused on maximum reuse or refurbishment of old equipment, which is not only economic, but also in agreement with the principles of circular economy.

Technological packages are always tailored to the actual needs of the customer, to allow full grid integration inside and outside the production site, to match with local constraints (resources, standards, regulations, etc.) Process control and monitoring are fundamental to achieve all the targets identified.

**IMPROVING OPEX**

Circular economics are revolutionising the old and unsustainable model of 'make-use-dispose', typical of the traditional linear economy. The end-of-chain materials, instead of becoming waste, now undergo suitable treatment to re-enter the production cycle, partially substituting the use of conventional raw materials.

Limited resources, like water, lime or selected mineral oils, can make several passages through the process before exhausting their potential, thus reducing significantly the make-ups required.

Energy consumption can be minimised with highly optimised processes, and waste gas and heat fluxes can be upgraded with the most modern technologies, like clean heat recovery (CHR) or BOF gas utilisation. Where possible, processes based on fossil fuels should be replaced by renewable electricity-based processes, as in the case of ironmaking with the introduction of hydrogen in the DRI-EAF route, or in the reheating furnace with the new Q-Heat induction heaters.

Reducing energy demand, particularly carbon-based energy, and using renewable energy sources, also help reduce CO2 emissions, in fulfilment of the more and more stringent international agreements on GHG emissions, with related fees.

**CAN GREEN TECHNOLOGIES IMPROVE PRODUCT QUALITY?**

The exemplary cases of matching sustainability, economics, and significant quality improvement are MI.DA. and QSP-DUE casting and rolling processes.

With these advanced technologies, rolling processes then become stable and continuous, allowing extremely good quality products and outstanding productivity and plant efficiency.

The following provides an overview of several energy-saving and recovery processes, zero waste and safety concepts developed by Danieli over recent decades.

**IRONMAKING**

**Emerging standards for CO2 emissions** BF gas has a low calorific value (CV) and is used in low temperature processes, especially if enriched with BOF gas which has a higher CV. Thus, BF/BOF off-gases are used to supply power plants (25%), coking plants (15%), plate mills (20%) and to other plants and flares. One way to reduce CO2 emissions is to utilise an increased amount of scrap or HBI/DRI in the BOF charge mix, followed by some change in operation.

Techniques for carbon capture and storage or usage (CCS or CCU) are under continuous study and some are applied already, such as recirculating the decarbonated top gas to the BF lower shaft to increase the amount of CO2 in the off-gas and to ease its separation (capture.)
Robotics and automation supporting productivity
Design of a modern cast house is driven by layout and logistical optimisation, dust and fumes reduction, and the use of robots in labour-intensive and repetitive tasks. Process efficiency is enhanced by eliminating human error and implementing the best operational practices, and the workplace is cleaner and safer, with lower maintenance requirements.

Maintenance and productivity
Maintenance represents a cost and a loss in productivity. Minimisation is desirable but only on a smart basis. While external parts of the equipment are constantly under inspection, condition assessment of internals requires dedicated and sophisticated simulations of wear patterns. Risk mitigation and projected remaining lifetime concepts produce an adjustment of maintenance scheduling. Failures are greatly reduced, stoppages for maintenance are delayed, and new layouts are designed to improve maintenance while reducing time and cost. An example is shown in Figure 2 where the Q-One system was designed to ensure simple removal of the inverter and converter units.

Gas cleaning for dust removal
With reagent injection and a pressurised bag filter, BF dry scrubbing produces an effective abatement of emissions. There is no water consumption and the process has improved power plant efficiency. BOF gas scrubbers, including a pre-humidification step and performing the scrubbing in a variable-section, annular scrubber increases the gas-liquid contact and the abatement efficiency, while decreasing the pressure drop.

DRI
Environmentally friendly production Ultra-low NOx burners will keep process NOx emissions below 25-30ppm. Where limits are more stringent, a selective catalytic reactor (SCR) can bring emissions below 10ppm.
SUSTAINABILITY

agency requirements. Dioxin emission reduction is also possible with the use of dedicated equipment such as the quenching tower or special dioxin abatement systems (when lower limits are required). For the control of other pollutants, like CO, NOx and SOx, it is preferable to act directly ‘at the source’, by properly running the EAF and by choosing good quality raw materials.

Noise control Noise reduction can be obtained by acting directly at the main source (EAF), with the installation of a dog house or with the sound-proofing of part of the building (elephant house). To reduce the noise dispersion in the surrounding areas it is necessary to control the emissions from the stacks and the new Acou-Stack solution may replace the traditional silencer installations.

Scrap selection Optimising scrap selection reduces waste material because separating inert components (mainly glass) reduces lime additions, decreasing the volume of slag. Separating organic materials, like plastic and rubber, cuts gaseous emissions and limits the need for adsorbents to capture dioxins, thus containing the amount of dust generated. Also, scrap selection optimises EAF operations so that melting models can manage power-on time.

ENDLESS CASTING ROLLING / ECR

OpEx and ecological advantages with ECR

Traditional hot rolling will reheat billets from room temperature by means of fossil fuels, and consuming around 1.2GJ/t. Up to 1% product is lost as scale, and production is not continuous. With ECR – including MI.DA. for long products and QSP-DUE for flat products – the reheating furnace is eliminated along with its energy consumption and related emissions. Furthermore, there -
The QHEAT Induction Heating System is a sustainable alternative to gas-fueled reheating with the following benefits:

- No GHG, NOx or particulate emissions
- Limited scale formation
- Short start-up/shut-down time
- High electrical efficiency
- Modularity that allows easy maintenance, optimal control and material temperature equalisation, resulting in increased product quality

Low NOx burners New-generation furnaces must respond to increasingly stringent emission limits. Design of high efficiency burners requires thermo-flow-dynamics simulations with relevant combustion kinetics and final testing of prototypes. Danieli Centro Combustion tested and refined ultra-low NOx burners (MAB and TFB) optimising flame pattern, flexibility of fuel-gas feedstock, extremely low NOx emissions (particularly in the flameless configuration) and, for indirect combustion, high radiant-tube efficiency and temperature uniformity. Modern designs allow NOx reductions of up to 70% compared to conventional 'flame mode' burners. An example is shown in Figure 5.

Clean emulsion for rolling in aluminum cold rolling, water-oil emulsions may replace kerosene-based lubricants, with increased safety and lower CapEx and OpEx, related to safety equipment and to the absorption/distillation recovery system (-10%). Lower emissions also may be expected because there are no kerosene vapours to treat.

Zero fume extraction systems An effective design of the absorption and distillation processes can reduce VOC abatement for aluminum cold rolling. The choice of the most technologically advanced packing structures in the absorption column ensures maximum contact between vapours and the absorbent, to pick up the majority of VOCs with very low leakage through the fume plant. The distillation column that regenerates the absorption solution while recovering the rolling oil is designed with a combination of temperature and pressure that minimises the degradation of the oil, which turns out to have a longer life. The internal recirculation in the distillation column acts as further protection for the oil, dampening the temperature peaks of the incoming solution.

Low temperature rolling Improved structural steel properties have been obtained mainly by:

- Restricting the carbon content
- Improving the internal cleanliness
- Using micro-alloyed grades combined with in-line thermomechanical processing

is no scale formation during reheating and no head/tail crops, reducing waste and increasing overall plant efficiency. ECR can reduce natural gas consumption by up to 32Nm³/tls.

ZERO WASTE
Zero-water discharge (ZLD) Industry must be committed to avoid wasting fresh water and so Danieli has set up a process wherein water treatment systems are able to recover blow-down water, with appropriate crystallisation processes to avoid any water discharge that may incur limits on salt content.

Zero-slag discharge (Ecogravel) Slag is a secondary raw material that contains steel scrap (4% by weight), and is an ideal aggregate (screened for different sized particles) to be used in road paving or concrete applications. The Danieli Ecogravel process has three environmental benefits:

- It avoids the use of natural rocks, and the energy for crushing and transportation
- It reduces landfill disposal
- The high wearing resistance of the obtained asphalt makes roads more durable, reducing the frequency of repaving

Zero-ASR discharge (SYNCA) ASR (automotive shredder residue) has potential as a secondary raw material. It contains 5% inert materials, 10-15% of ferrous and non-ferrous materials (which are easy to separate), and two organic fractions, equal by weight, having a calorific value up to 35MJ/kg. All evidence indicates the material may be used as a partial carbon substitute (up to 30%) for melting steel.
This last development makes it possible to refine the microstructure to produce stronger steels and to influence the time-temperature transformation of the steel to create a microstructure more suitable for heat treatment, thus reducing treatment time and therefore costs and footprint.

**POWER AND AUTOMATION**

**Q3-OPT automatic scheduling** This increases plant yield thus reducing energy demand. Upon definition of the objective functions and KPIs, the system quickly prompts and thoroughly reschedules the activities. The added value is the ability to manage complexity and to implement the most valuable know-how from experienced operators. An optimised plant, both in operation and in maintenance, minimises the energy demand and the expended resources, increasing product quality and reducing wastes.

**Q3-DEMS monitoring** This is an energy and utility monitoring and utilisation tool for collecting the widest range of information and it provides a simple interface to reprocess data into KPIs, predefined or used defined. Everything is recorded and monitored in order to highlight irregular operations or time-changing performance. Q3-DEMS supports continuous improvement in energy efficiency, according to ISO 50001:2011.

**Smart power technology** Based on inverters, assisted by an Adaptive Auto Pilot, combined with an advanced firmware and a high-efficiency induction motor, this technology eliminates the typical problems of a DC solution: low efficiency, high maintenance cost for the DC motor, low overload capability, network disturbances (harmonics and low power factor), etc.

This technology delivers an innovative control strategy for energy savings, higher productivity, process flexibility, and reduced impact on the MV/LV distribution network.

**Data analysis prolonging equipment service life** Modern sensors and a database of failure events changed the approach to maintenance from preventive to predictive. Scheduling algorithms are generated to plan maintenance, starting from analysis of current conditions and estimating remaining performance life. Stoppages can be reduced to a minimum and spare parts can be acquired only as needed, avoiding obsolescence and redundancy.

**SAFETY**

**Robotics and zero men on the floor** Robotics are key where highly accurate and repetitive processes are required, as well as where there is risk to personnel safety. For example, robots are effectively used on the furnace and casting floors, as well as to tend zinc pots for galvanising lines, for deburring, tracking, and marking rolled products, and more where other repetitive tasks are required.

‘No man on the floor’ is a strategic target and Q3-Pulpit technology is an example of current applications. 360° video cameras support operators with remote inspection capabilities. A database of critical events that require operators’ attention, constantly enriched through machine learning techniques, can activate some specific camera automatically to bring the event to the attention of the operator. Today, pulpts are ergonomic and interactive, with predefined operations already available and promptly activated. An example of the 3Q concept pulpit from a Danieli H3 rod mill is shown in Figure 6.

**Asset valorisation through personnel training** Greater skill is required to run modern plants and personnel training, together with self-learning and predictive technologies, assist operators in their choices, minimizing production issues and health hazards.

Trained workers know how to operate and maintain a plant in optimal conditions. This leads to best performances and risk reduction. Environmental benefits come from minimising energy and resource needs, and from avoiding major failures.

Danieli Training Center transfers to employees the knowledge needed to operate plants and to maintain equipment and address safety issues. **MS**

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Sustainable steelmaking – A strategic evaluation of the future potential of hydrogen in the steel industry

As a result of declining availability and quality of raw materials, environmental pollution and increasing public pressure, countries are being urged to deal with the topic of an energy system transformation whereby fossil energy-intensive industries such as the steel industry have to change their business models and technology portfolios in order to reduce CO2 emissions. Technical developments have shown that sustainable steel production based on hydrogen supplied by green energy methods seems feasible in the near future.

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Danieli Corus and University of Leoben

A growing world population and expanding urbanisation increase the demand for more infrastructure and goods, yet on the other hand, economies are facing a shortage of resources as well as environmental and political restrictions, as illustrated in Figure 1. As an impact of these drivers and restrictions, society is forced to develop sustainable technologies and to improve current processes. In the medium to long term, ‘green energy’ will aim to replace today’s fossil and nuclear-based energy sectors to avoid greenhouse gas emissions.

As a consequence of global ratification and commitment to each country lowering its greenhouse gas emissions, political activities are gaining speed. This requires governments to implement actions to reduce emissions and change the whole landscape of energy generation and raw material supply. In 2013, for the first time, newly installed green energy capacity worldwide exceeded new installations of fossil fuel-based power generation.

GLOBAL AND REGIONAL TARGETS FOR GREENHOUSE GAS EMISSIONS

Beginning in 1995, the annual UN Climate Change Conferences negotiated the Kyoto Protocol (1997) to establish legally binding commitments for developed countries to decrease their greenhouse gas emissions. In 2007, the Intergovernmental Panel on Climate Change (IPCC) recommended decreasing global emission levels by 2050 to 50-85% of the 1990 levels in order to keep global warming below an increase of 2.1°C [1].

In 2009, the European Council defined a long-term target of decreasing greenhouse gas emissions, which resulted in the publication of the Low Carbon Roadmap 2050 (2011) by the European Commission. This framework suggests a reduction of domestic CO2 emissions of 80-95% by 2050 compared to 1990 levels (with a pathway of 40% by 2030 and 60% by 2040), of which the share for industry should amount to 83-87%.

© Fig 1 Impact of global drivers on technology
of 1990 levels by 2050 (see Figure 2) [2].

In 2015, 196 nations reached an agreement at the UN Climate Change Conference in Paris that commits each country to reduce greenhouse gas emissions in order to keep the global temperature increase below 2°C, and to pursue efforts to limit it to 1.5°C, compared to pre-industrial years. By 2050, manmade emissions should be reduced to levels that can be absorbed by forests and oceans [3].

This requires governments to implement actions to reduce emissions and limit global temperature rise. While the targets in the agreement are not legally binding, the treaty requires countries to report every five years on the nation-specific goals they submitted to the UN. In 2016, 55 countries representing more than 55% of world carbon emissions have signed the agreement and met the threshold for entry into the Paris Agreement. Since then more countries have committed themselves to the goals of the climate conference and set 2050 as the target for zero emissions.

In order to meet these targets, the EU implemented the EU Emission Trading System (EU-ETS) for man-made greenhouse gases (CO₂, NO₂, PFCs) in 2005. This represents the world’s first and largest ‘carbon market’ and puts a limit on overall greenhouse gas emissions from high emitting industry sectors, and which is reduced each year. Within this limit, companies can buy and sell emission allowances as needed.

The price for one certificate (€ per t CO₂) is determined by supply and demand. In 2012, 7.9 billion allowances were traded with a total value of about €56 billion. The EU-ETS covers more than 11,000 manufacturing plants and power stations in 31 European countries, as well as air flights to and from European airports. In total, around 45% of total EU emissions are limited by the ETS: The manufacturing industry received 80% of its allowances for free but this decreased annually to 30% in 2020, with a linear reduction of 1.74% per year. In the 4th trading period (2021-2028), the total allowances will be reduced 2.2% each year to achieve a reduction of around 43% compared to 2005 [5] [6]. Several other countries are following this example or have already implemented similar systems (eg, Australia, New Zealand, South Korea), and more are expected in the future.

Due to the shortage of certificates, the price will increase. For example, the price for one certificate increased from 5€ /tCO₂ in 2017 to 25 €/tCO₂ in early 2020 (+400%). Studies suggest that the certificate price will probably increase by 2050 to between €40-200 [7], or €60-80 [8].

**ENERGY SYSTEM TRANSFORMATION**

Due to this pressure, fossil energy-intensive industries – such as the power industry, the chemical and steel industries, as well as the transportation sector – will have to revise or change their business models and technology portfolio. As a consequence, a paradigm shift is currently in progress, which will change the economic and ecological landscape of whole economies. This started with the shutdown of some fossil and nuclear energy-based power plants in several countries and the expansion of green power infrastructure. Increasingly, each sector will have to follow this path.

Over the next few decades, the production and availability of green energy is expected to increase significantly. Future scenarios expect that hydrogen produced by green energy could be used both as an energy source and an energy store, thus enabling a continuous supply of energy, away from discontinuous green energy sources (eg, wind and solar power). Due to the high weather dependency of the green energy supply and fluctuations in power grids, it is apparent that efficient and inexpensive storage facilities will be mandatory.
Excess (unused) energy from wind or solar sources, will have to be integrated into the energy system. Due to its exceptional storage capacities, chemical-based Power-to-Gas (PtG) technology has the greatest potential to store large amounts of energy long-term (months to years). PtG is the conversion of ‘green’ electricity (particularly from wind power and photovoltaic) by means of electrolysis into hydrogen or methane (see Figure 3). The gases can be transported and stored in the gas infrastructure and afterwards used in various applications.

For the steel industry, as a major emitter of greenhouse gases (~7% of anthropogenic CO₂), a multitude of questions emerge regarding how to deal with the changing landscape and which actions to take. Today, steel production is based almost entirely on fossil raw materials, but from a thermochemical point of view, sustainable steel production with hydrogen is possible. Due to the environmental paradigm shift, there is an urgent need for a strategic evaluation of the potential of steel production based on hydrogen from green energy to replace fossil energy sources. Over recent decades, various processes based on hydrogen steel production have been investigated and installed. However, to date, a reliable process has not been realised on an industrial scale so its future capability as a substitute for fossil materials urgently needs to be investigated. The feasibility of such an industrial transition depends strongly on future green energy capacity, technological readiness, distribution and storage options, electricity and hydrogen prices as well as public awareness and political actions.

CURRENT STEELMAKING AND TECHNOLOGICAL DEVELOPMENTS

Modern steelmaking can be divided into oxygen-based steelmaking (BOF) and electric power-based steelmaking (EAF). The three types of iron intermediate products in both process streams are liquid hot metal (or in a solidified form as pig iron), direct reduced iron (DRI) and hot briquetted iron (HBI). These are all virgin iron materials, produced from iron ore [10]. Scrap is charged as a recycled raw material into the process. In 2018, 70.8% of global crude steel was produced via the BOF routes (integrated and smelting reduction (SR) route) and about 28.8% via EAF-routes (DR-EAF and scrap-EAF). The remaining processes (0.4%) are outdated open hearth furnaces [11].

The current map of process technologies for iron and steelmaking is shown in Figure 4. It can be classified either into process steps from the raw material up to the finished product or into characteristic process routes (BOF, SR, DR and scrap route). The process steps comprise raw material preparation, ironmaking, steelmaking and further processing (casting, rolling/processing, finishing).

In the first step, the raw materials for the subsequent processes are beneficiated and refined. During the ironmaking stage, the raw materials are converted into liquid hot metal or solid DRI or HBI, depending on the process. This stage is very energy intensive and requires carbon and hydrogen carriers as reducing agents to remove oxygen from the iron ore by CO and H₂ and the formation of CO₂ and H₂O. The product hot metal or sponge iron (DRI/HBI) is then converted into steel in the successive process stage, where the carbon is removed and the desired steel grade is composed by the addition of alloying elements. Finally, the steel is cast, processed and finished.

The characteristic process routes can be divided into the integrated route (with blast furnace and basic oxygen furnace: BF-BOF), the alternative routes smelting reduction (SR-BOF) and direct reduction (DR-EAF) and the scrap-EAF route. Also, a combination of these routes is possible, e.g., processing HBI in the blast furnace or BOF.

The first three routes produce iron and steel from virgin raw materials using scrap as a material addition, hence the product is very pure as it is almost free from harmful or quality-sensitive elements. High quality steel can be produced by this route, but the scrap has to be clean and sorted, which is very complex and costly. Besides economic development, this is one of the reasons why the production of steel via the virgin routes will continue to dominate.

TECHNOLOGICAL OPTIONS FOR SUSTAINABLE STEELMAKING

Alternative ironmaking routes such as DR and SR have been under development since the 1950s. Since then, 73 DR and 59 SR processes were designed [14], however only a few of them reached the pilot stage or industrial application. In general, other process combinations are possible, e.g., a
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is novel. Regarding CO₂ emissions, this process would emit only 0.15t of CO₂ compared to 1.76t of CO₂ on the conventional BF-BOF route, a reduction of > 85%.

In the future, another option could be possible – hydrogen plasma smelting reduction (HPSR). Based on gas plasma at high temperature, molecular hydrogen is split into atomic or ionic hydrogen (H or H⁺). This hydrogen has a much higher reduction potential than molecular H₂ and can reduce all oxides to metals. The product is liquid steel. First trials at laboratory scale at the Montanuniversität Leoben in recent years were successful and a new pilot plant is currently being constructed. However, much research work is still needed [16].

Another technology, electrolytic iron production, was tested at laboratory scale within the European ULCOS project and by Nancy University and ArcelorMittal [17]. So far the trials are still at laboratory stage and for greater production output this technique does not seem suitable.

DEMAND FOR GREEN ENERGY FOR A H-BASED STEEL INDUSTRY

In order to determine the green energy demand for a hydrogen-based steel industry, the specific theoretical energy demand for the conversion of iron ore to iron needs to be investigated. Based on data of a typical DR steelpmaking route, a ‘base scenario’ (state of the art technology) and a future ‘best case’ scenario (expected technological improvements up to 2050) were evaluated. This data was used for the calculation of the overall green energy demand for a hydrogen-based steel production in all countries and regions worldwide based on the steel production in 2018 (see Table 1). The first energy intensive combination of the integrated and the direct or smelting reduction routes in order to leverage productivity and synergy effects.

From the thermochemical and energy points of view, iron ores could be converted to intermediate ferrous products by the use of carbon, hydrogen or electric power based on the simplified equations in Figure 5, where the energy position of the different ironmaking routes are shown in the tertiary diagram. In the carbon corner, the ‘carbon based metallurgy’ processes are located (BF-BOF and SR). Depending on the amount of electric power or hydrogen used in a process, the position shifts towards the H₂ and electrical power corners. These are the DR processes based on natural gas (NG) or hydrogen, which could use gas mixtures of CO and H₂ as the reducing atmosphere. In an optimum case, H₂ contents up to almost 100% could be possible. The electric power required results from the smelting of the intermediate product DRI in the EAF.

In all modern iron and steelmaking processes, hydrogen is used in different proportions as a reducing agent in gas mixtures with carbon monoxide. In the classical carbothermic production of hot metal in the blast furnace with coke as the main reducing agent, hydrogen is generated by the input of substitute reducing agents such as coal, oil, plastic or gas. The hydrogen content in furnace gas in modern blast furnaces can be up to 10%. Novel smelting reduction processes like COREX®, FINEX®, Hilsmed® or DIOS® use significantly higher amounts of hydrogen of up to 30% in the process gas, as only coal is used as a reducing agent.

DR processes operate with the highest amount of hydrogen: from 60% up to almost 100%. These processes use hydrogen-rich gases created from natural gas via catalytic gas reforming or steam reforming and do not use coke or coal as input materials. DR processes include shaft furnace-based technologies ENERGIRON® (< 85% H₂) and MIDREX® (< 65% H₂) as well as the fluidised bed-based processes FIOR/FINMET® and CIRCORED® (up to 100% H₂). While the shaft furnace processes are commercially in operation, the fluidised bed processes suffered from technical and economic problems and were shut down.

For the industrial implementation of hydrogen-based technology, the DR processes seem to have the greatest potential, with ENERGIRON® units already operating with more than 60% H₂ on an industrial scale. Due to envisaged technical developments it is expected that the amount of hydrogen in the process could be increased up to almost 100%. A process layout of such a technology based on an ENERGIRON® or MIDREX® reduction shaft is shown in Figure 6. All of these process units are proven technologies, but the integration of this process route
Depending on the quality of the iron ore, a DRI input of about 1,150 kg per t crude steel (kg/ts) is required, which increases the SGR to 1,177 m³H₂(STP) kg/ts. If scrap is added (as in the integrated BF-BOF route), the SGR kg/ts varies according to the scrap amount.

For the case scenarios and in order to compare the conventional BF-BOF route with a DR steelmaking route, the scrap input is assumed to be equal. With a scrap input of 155 kg, the SGR is 1,013.46 m³H₂(STP) kg/ts. Calculating the energy for the required hydrogen production and adding the electrical power for the melting process in the EAF, the specific energy input is 5,408 kWh kg/ts today.

In a best case scenario (with adjusted input parameters due to the future technological development of the DR route and electrolysis), the specific energy could be reduced to 4,075 kWh kg/ts.

In order to compare the DR-EAF and BF-BOF steelmaking routes, the additional energy required for the downstream processes has to be added. This is because the BF-BOF route is energy self-sufficient and produces excess energy from the process gases (coke oven gas, blast furnace gas and converter gas), which is converted into electricity in power plants on site. This energy is then used for downstream processes (rolling/finishing) as well as for other energy consumers. On the other hand, the DR-EAF and scrap-EAF routes require external energy input. As a result, a hydrogen-based DR route has to supply the energy for the downstream activities from an external source. A typical specific value for these processes is 2.8 GJ/t or 778 kWh kg/ts. Adding this value, the specific energy required gives 6,186 kWh per t HRC/final product today and 4,853 kWh per t HRC/final product in the best case.

### Table 1: Required energy for a H-based steel production and future estimations [19]

<table>
<thead>
<tr>
<th>Factors</th>
<th>Chemical minimum</th>
<th>Base Case (2020)</th>
<th>Best case (2050)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy input DRI (GJ/t DRI)</td>
<td>6.5</td>
<td>11.0</td>
<td>9.5</td>
</tr>
<tr>
<td>Calorific value H₂ (kJ/kg H₂)</td>
<td>119972</td>
<td>139972</td>
<td>119972</td>
</tr>
<tr>
<td>H₂ input DRI, mass (kg H₂/t DRI)</td>
<td>54.14</td>
<td>91.7</td>
<td>79.2</td>
</tr>
<tr>
<td>H₂ input DRI, volume (m³ H₂/t DRI)</td>
<td>602.41</td>
<td>1020.1</td>
<td>881.0</td>
</tr>
<tr>
<td>H₂ input Crude Steel, volume (m³ H₂/t Crude Steel)</td>
<td>1013.5</td>
<td>875.3</td>
<td></td>
</tr>
<tr>
<td>El. Power per t DRI (kW/h)</td>
<td>100.0</td>
<td>80.0</td>
<td></td>
</tr>
<tr>
<td>El. Power per Crude Steel (kW/h)</td>
<td>99.3</td>
<td>79.5</td>
<td></td>
</tr>
<tr>
<td>El. Power EAF (kW/h)</td>
<td>495.0</td>
<td>405.0</td>
<td></td>
</tr>
<tr>
<td>El. Power Total Crude Steel (kW/h)</td>
<td>594.4</td>
<td>574.5</td>
<td></td>
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<tr>
<td>H₂ Electrolysis (kW/h m³ [STP])</td>
<td>4.75</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>Energy H₂ produced (kW/h)</td>
<td>4813.9</td>
<td>3500.0</td>
<td></td>
</tr>
<tr>
<td>Energy Total Crude Steel incl. H₂</td>
<td>5408.3</td>
<td>4075.5</td>
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<tr>
<td>Add. Energy downstream (GJ/t)</td>
<td>2.8</td>
<td>2.8</td>
<td></td>
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<tr>
<td>Add. Energy downstream (kW/h)</td>
<td>777.8</td>
<td>777.8</td>
<td></td>
</tr>
<tr>
<td>Total Energy HRC [Hot Rolled Coil]/ final product (kW/h)</td>
<td>6186.1</td>
<td>4853.3</td>
<td></td>
</tr>
</tbody>
</table>
REGIONAL H₂ DEMAND FOR STEEL PRODUCTION

The green energy demand for the conversion of the carbon-based to H-based steel production has been evaluated for all steel producing countries and regions on the basis of 2018 data (see Figure 7). A total of 71% of the global crude steel was produced via the carbon-based BOF-routes (integrated and SR route) and 29% via the EAF routes (DR-EAF and scrap-EAF). It can be assumed that carbon-based steel of the oxygen route could be produced by H-based processes in the future. The calculation was made for a base case (Best Available Technology, comprising today’s energy figures) and for a future best case scenario with the target 2050. The required green energy for the production of HRC by hydrogen is calculated for the countries and regions worldwide.

Shifting global steel production from carbon to hydrogen will require a green energy demand of about 7,920TWh/yr for producing HRC (base case) and 6,210TWh/yr (best case). The related hydrogen requirement would be between 1,300 and 1,120 billion m³ (STP). In Figure 8, the green energy demand for HRC/final product by region is shown. Asia has by far the highest green energy demand (base case: 6,300TWh/a; best case: 4,940TWh/a), followed by the European Union (base case: 610TWh/a; best case: 480TWh/a).

Within the EU, Germany would have the highest green energy demand for HRC/final product of 184TWh/a (best case 144TWh/a) followed by France at 57TWh/a (best case 43TWh/a) (see Figure 9).

CONCLUSIONS

As a result of declining raw material availability and quality, environmental pollution and increasing public pressure, countries are being urged to deal with the topic of an energy system transformation to minimise CO₂ emissions. Fossil energy-intensive industries in particular – such as the steel industry – have to revise or change their business models and technology portfolio. Today, approximately 75% of global steel is produced via the carbon-intensive BF-BOF route, but technical developments have shown that sustainable steel production based on hydrogen from green energy does seem feasible in the near future.

For the industrial implementation of a substitute H-based approach, the direct reduction processes (DR-EAF route) seem to have the greatest potential, as they already operate on an industrial scale, using about 60% H₂ as the reductant.

Due to the further expected technical developments in the upcoming years, it is expected that the amount of hydrogen in the process could be gradually increased to almost 100% and CO₂ emissions could be reduced from 1.76t of CO₂/ts (conventional BF-BOF route) to 0.15t of CO₂/ts (DR-EAF with H₂).

All of the DR process units have proven technologies, but the integration of the H process route is novel. Other H-based technologies are being developed and tested. However these processes will still need decades to reach industrial scale.

From a quantitative point of view, a transition from carbon to H-based steelmaking would require enormous amounts of hydrogen, and thus green energy. The feasibility of such an industrial transition strongly depends on future green energy capacity, technological readiness of sophisticated electrolyzers, H₂ distribution and storage options, electricity and hydrogen prices as well as public awareness and political actions.

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Energiron – effectively decreasing CO$_2$ emissions in steelmaking

Energiron direct reduction technology complies with the world’s strictest environmental regulations, producing significantly less CO$_2$ than alternative processes. It also allows the products generated during the reducing reactions of iron ores to be used as by-products.

Reducing CO$_2$ emissions is one of the main goals of the modern economy and it is particularly critical in the most energy-intensive industrial areas, such as iron and steelmaking. Many industries are taking action to comply with current CO$_2$ regulations and making plans for their next steps on a five to 20-year outlook. The steel industry is one of the largest industrial sources of CO$_2$, accounting for approximately 7-9% of world emissions, thus it has a significant environmental impact in terms of global warming from greenhouse gases (GHG).

Energiron direct reduction technology is the most effective way to reduce the CO$_2$ emissions in iron and steelmaking in compliance with the world’s strictest environmental rules, and is ready for further improvements in line with the COP21 long-term vision for a prosperous, modern and climate-neutral economy by 2050.

If steel is produced by EAFs fed by direct reduced iron produced by the Energiron direct reduction process, up to 90% fewer CO$_2$ emissions are produced compared to a typical integrated steel plant. This is achieved partly thanks to the possibility to intensively use hydrogen as reductant instead of carbon monoxide, and partly due to the selective capture of the CO$_2$ produced by reduction of iron ores. This CO$_2$ can then be commercialised as a valuable by-product for several industries, ensuring a prosperous circular economy.

Danieli provides customised solutions for progressive reduction of CO$_2$ emissions up to this limit, maintaining the same steel quality and planning a sustainable capital investment strategy.

TRANSITION FROM BF-BOF ROUTE TO DR-EAF ROUTE

In DR plants, iron ore is converted to metallic iron in solid form without melting (see Figure 1) by means of gaseous reducing agents. The reduction of CO$_2$ emissions compared with the traditional BF-BOF route is due to the use of natural gas (NG) or hydrogen (H$_2$) instead of coke. The, DRI produced can be used as a partial substitute for input materials for both BFs and BOPs and, because primary reduction has already taken place in the DRP, less coke is required in the BF to reduce the remaining burden, and this finally results in lower overall CO$_2$ emissions. The DRI also can be used as partial or exclusive input material in EAFs: by adding pure iron units, higher quality steel grades can be produced and CO$_2$ emissions can be further reduced.

Currently, the EAF route (with ever increasing quantities of DRI replacing scrap) provides approximately 30% of the steel produced worldwide, and its share is continuously increasing thanks to the higher operating flexibility, lower investment cost and environmental compliance.

ENERGIRON ZR: MINIMUM ENERGY AND MINIMUM EMISSIONS

Energiron is a strategic alliance between Danieli and Tenova HYL for the development and implementation of the most efficient and flexible technology in the current mix of DRI production methods, aiming to provide customers with the lowest CapEx and OpEx in any environment. This alliance started in 2006 and has achieved excellent results at several benchmark installations, such as at Emirates Steel DRI plants No.1 and 2 (UAE), Suez Steel (Egypt), Nucor Steel Louisiana (USA), and Ezz Steel (Egypt).

Of all the DR technologies, the Energiron process is the one that makes it possible to minimise CO$_2$ emissions. The Energiron zero Reformer (ZR) is based on the unique feature of carrying out the natural gas reforming stage within the reactor without requiring an external reformer, using the DRI itself as a reforming catalyst (see Figure 2). In this way,
Finally, hot or cold DRI is discharged by automated mechanisms, consisting of pressurised bins and special valves. Figure 5 shows an Energiron tower with reduction reactor, external cooler and HYTEMP towers which feed the EAF.

CIRCULAR ECONOMY RELATED TO ENERGIRON PLANTS

The transition from traditional integrated mills to a modern, environmentally sustainable Energiron plant can generate a circular economy in which several industrial activities are organised so one plant's waste becomes another's resources. In fact, the premium quality and internal energy of Energiron DRI gives electric steelmakers the possibility to optimise steel production costs, increasing competitiveness and providing opportunities for new business:

- DRI can be used in addition to steel scrap to dilute the impurities from the scrap which, in some cases, can represent a limitation in the quality of EAF steel.
- The outstanding energy efficiency of Energiron plants (lowest natural gas consumption 2.35Gcal/t) is possible thanks to the proprietary auto-reforming technology and to the use of energy recuperation systems. Energiron ZR can produce DRI with a carbon content in a range of 1.5-5 % giving the steelmaker the possibility to use the most economic mix of chemical and electrical energy input to the EAF.
- Further efficiencies can be achieved thanks to the proprietary Hytemp® system, a safe and reliable solution to convey the DRI to the EAF at high temperature. This unmatched efficiency provides the lowest OpEx and a responsible use of the natural resources.
- Energiron ZR plants can use any reducing agent locally available. Any eventual excess of reformed gas, coke oven gas, hydrogen, naphtha that is purged or incompletely used by existing plants can be used as a reducing agent. In this way, OpEx can be further reduced and plant managers have the possibility to adjust feedstocks according to market trends.
- A variety of iron ore grades can be used, including BF pellets. This allows using the resources locally available at the most competitive price. Moreover, the high operating pressure of Energiron plants allows the use of finer iron ores, recovering part of those valuable natural resources that other technologies would discard.
- Thanks to the selective capture of CO₂, Energiron is the technology best fitted to provide Carbon Capture and Use (CCU) and Carbon Capture and Storage (CCS) solutions applied to the steelmaking industry. Among the other possible applications, CO₂ generated by Energiron plants is captured and used to produce beverages, conglomerates, dry ice and used in Enhanced Oil Recovery (EOR) applications.
CO₂ EMISSIONS IN ENERGIRON PLANTS
In general, the carbon footprint of a DR-EAF plant is about 50% of that of an integrated plant. Figure 6 shows a comparison with a number of process routes.

Energiron plants typically work with a H₂/CO ratio of between 3 and 5, as use of H₂ is thermodynamically more efficient, about five times that of CO. Energiron ZR, however, has the possibility to selectively capture the CO₂ generated by the reduction of iron ore and this leads to a reduction in emissions by a further 60%.

A further step in CO₂ emission reduction can be achieved by increasing the proportion of hydrogen in the reducer gases. Trials using up to ~90% H₂ have been successfully conducted. Figure 7 shows a comparison of CO₂ emissions with different reductants and DRI carbon contents: the greater the %H₂ and the lower the carbon, the lower are the CO₂ emissions.

CONCLUSIONS
Energiron DR technology, due to its inherent characteristics, is the most effective way to minimise the CO₂ emissions in steelmaking. It complies with the strictest environmental regulations worldwide and allows the re-utilisation of some effluents and emissions as valuable by-products, boosting the development of circular economies. Danieli supports its customers by providing sustainable and tailor-made solutions for the reduction of CO₂ emissions, from feasibility studies to the execution of Engineering, Procurement and Construction (EPC) projects. Optimised solutions based on Energiron plants that may be either stand-alone, integrated with electric minimills or with blast furnaces, are developed to optimise the OpEx with no compromises on steel quality, within a sustainable capital investment strategy.

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Steel production and CO$_2$ emissions: a growing global concern for manufacturers?

The world steel industry is a major emitter of greenhouse gases but is strenuously increasing its efforts to decarbonise through development of lower CO$_2$ emitting processes and increased recycling of both steel products and steelworks’ so-called ‘by-products’. Harsco has been involved in recycling and by-product management for many years, working with steel companies in more than 30 countries.

**BACKGROUND**

It is estimated that 9% of all direct fossil fuel emissions come from the global steel industry[1], with 1.8 tonnes of CO$_2$ being generated per tonne steel manufactured by the integrated BF-BOF route and 0.25-0.50t/t via the EAF route. The industry therefore has a vital role to play in tackling climate change. Reducing CO$_2$ emissions would provide significant support toward creating a sustainable future for the steel industry and the global environment.

It is worth noting that, even though the average energy consumed per tonne of steel produced has been reduced by 61% since the 1960s, further improvement is required[2].

Positive changes are underway, as key players in the industry are working hard to address the issue. Although efforts to reduce CO and CO$_2$ are not universally supported by government legislation, many currently deployed technologies and processes are setting new standards for lower emissions, driving additional deployment and furthering environmental improvement.

One proposed solution for reducing emissions is to apply carbon taxes on CO$_2$-generating industries. However, as the primary steel industry frequently operates with low profit margins, simply imposing a carbon tax to mandate CO$_2$ reduction will likely result in many steel plant closures, negatively impacting communities and society downstream. Decreasing the CO$_2$ emissions per tonne steel is therefore a valid approach to realise environmental improvements while retaining the employment in communities that are dependent upon steel production for their livelihood.

In their comprehensive paper[3], The Energy Transitions Commission (ETC) states that “it is confident that complete de-carbonisation of the steelmaking industry is achievable by mid-century, with a modest impact on end-consumer prices and costs to the overall economy”. To reach zero carbon emissions, however, the steel industry, while clearly improving, still has some way to go. Harsco is aligning its technical development and deployment efforts to help achieve this goal.

**HARSCO ENVIRONMENTAL**

Harsco Environmental is a company with sustainable by-product recycling solutions at its core, and today it
operates at sites in over 30 countries in scrap and waste recycling. A range of activities is shown in Figure 1 and this is continually developing to support deployment of specialised techniques for reusing steel plant by-products. By-product materials handling, blending and agglomeration processes are used to re-engineer previously discarded materials from steel plants into products for reuse in the steelmaking process and in external applications. This provides the dual benefit of decreased CO₂ emissions and lowering steel plant operating costs. Four specific examples are described below.

WASTE RECOVERY AND RECYCLING

Waste into briquettes for steelmaking

The need for processes that allow the reuse of by-product fines has increased in recent years, driven by steel mill demand. Harsco Environmental therefore developed specialised handling and agglomeration techniques designed to generate larger product sizes (briquettes) with consistent chemistries. This has allowed previously discarded carbon, iron and minerals to be recovered. In doing so, millions of tonnes of previously wasted materials have been reused in an acceptable form. The process decreases overall steelmaking production costs as well as solid and gaseous environmental emissions. A basic flow diagram is shown in Figure 2.

Waste into micro-pellets for ironmaking

Some steelworks’ waste products are unsuitable for recycling to the sinter plant because they are either too fine, too wet or both. To address this problem, Harsco has developed a customised micro-pelletising process which is incorporated in the recovery flow diagram shown in Figure 3.
It starts by selecting by-products that minimise the use of materials high in lead, zinc and sulphur, while those high in carbon, iron, lime and magnesite are maximised. The piles are segregated into different composition batches to facilitate the selection process. After achieving the ideal balance of chemical and physical characteristics, the chosen product recipe is blended at high speed with speciality binders and at the target moisture levels. (The only pure, new materials in the mixes are the binders.)

Carbon, iron oxide, mineral dusts and sludges are micro-pelletised for reuse in BF sinter plants which reduces the need for new raw material purchases. The resulting micro-pellets (see Figure 4) are at an optimal size and chemical consistency to be sintered at high temperatures into fused agglomerates for use in the blast furnace. The micropellets thereby become part of the sinter product feed for the blast furnace.

The contained carbon, iron and mineral units are thus used to make liquid iron for subsequent use in the steel plant. The goal of waste minimisation is realised while simultaneously decreasing the cost of the ironmaking process. The need for new iron ore, coke and lime purchases, and the associated CO₂ emissions, are decreased.

These micro-pellets are consumed in the sinter plant to generate a suitable BF feed product with an associated reduction in new raw material purchases, thus reducing purchasing costs and the CO₂ production associated with mining and transporting virgin ores.

Harsco Environmental was able to deliver this sustainability improvement by combining a wealth of process engineering experience with a keen understanding of material science. In addition, effective methods of handling and blending wastes with proprietary binders in custom-designed micro-pelletising and briquetting processes were developed. The result is a now-proven ability to deliver maximum by-product recycling efficiency.

**COMMERCIAL EXAMPLES**

At a 12Mt/y steel plant in India, Harsco has recovered millions of tonnes of by-product materials, which would otherwise have been landfilled. Previously, finely sized waste streams containing value were generated at this plant without being recycled back into the steelmaking process. Harsco designed and deployed processes to solve this problem and recover these valuable chemical units. In doing so, new material purchases were reduced, as were operating costs and CO₂ tonnes generated.

Today, that plant is annually consuming more than 200,000t of Harsco briquettes (see Figure 5) back into the BOF for effective recovery of valuable iron units. In addition, more than 800,000t/y of carbon, iron oxide and mineral dusts and sludges are micro-pelletised for reuse in the sinter plant.

In conjunction with increasing their steelmaking capacity to 18Mt/y, the Indian steel plant requested that Harsco increase its production of recycled by-product agglomerates to keep up with the increased steelmaking capacity and by-product generation rate.

At Harsco’s facility in Sarver, Pennsylvania, USA, pilot briquetting trials had proven that the required product strength could be met while incorporating the desired selection of several by-product streams for recycling. Iron-rich by-products were chosen to replace virgin iron ore materials in the steelmaking BOF, culminating in reduced production costs through iron substitution.

**BOF SLAG FOR CONCRETE**

Cement manufacturing generates about 0.37t CO₂/t product, so it is a large contributor to greenhouse gas emissions. Processes involving carbon dioxide use are being developed to consume more of the remaining unused gas quantities generated by the steel and other industries. Last year, Harsco Environmental invested in CarbCrete™, a novel cement-free and carbon-negative technology that combines steelmaking waste slags with CO₂ to manufacture concrete for building applications.

The technology consumes both CO₂ and waste slags to...
avoid using the cement currently needed to make similar building products. The ground steel slag is added to the concrete mix, in place of cement, and is cured using CO₂. Immediately after this curing process has finished, the concrete has reached its full-strength.

The process is used to decrease the global requirement for cement and the subsequent tonnes of CO₂ generated in making cement. The technology enables a process for making precast concrete that uses no cement whatsoever. Certification will be accomplished as part of the pilot project. However, products that have been tested using all the standard concrete tests have matched or outperformed their cement-based equivalents.

Harsco Environmental is a key consortium member in a demonstration programme to make this cement-free, carbon-negative concrete. The investment by Harsco, along with a grant awarded to CarbiCrete™ by Sustainable Development Technology Canada (SDTC), will finance the programme within a developmental consortium which includes a manufacturer of commercial concrete blocks (see Figure 6). The programme is scheduled to start in the summer of 2020.

CONCLUSIONS
The steel industry is reducing its CO₂ emissions by increasing the percentage of steel made in EAFs. In addition, more applications for using by-product gases from integrated steelmaking plants are being developed and, combined with new energy recovery technologies, are further reducing the environmental impact of making steel. Additionally, by recovering and reusing by-products as well as waste refractories and slags, Harsco is increasing the economic and environmental benefits to their customers through specialised by-product recycling.

By developing and adopting these technologies, Harsco is partnering with their customers to ensure a brighter, greener environment. As steel will remain a key building block of our global communities for the foreseeable future, it is the duty of all parties involved in the steel industry to maximise their efforts to mitigate CO₂ generation and move toward a truly sustainable future. This will help to maintain the steel supply needed for the modern world to function, while simultaneously addressing the environmental needs of our global community for current and future generations. M5

REFERENCES:

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Peak BOF steelmaking has occurred

The last five years have seen a significant rise in the production of steel via the electric arc furnace (EAF) route, particularly in China. It has resulted in the first fall in the percentage share of steel made by the basic oxygen furnace (BOF) route, and so is a significant milestone. The drivers are climate change, EAF process efficiency gains and scrap availability.

With reference to Table 1 the percentage of EAF steel produced worldwide has increased from 25.4% in 2013 to 28.8% in 2018; with a corresponding decrease in BOF share from 73.3% to 70.8%. This is the first time that the percentage of BOF steel has decreased over a significant time scale since the process was invented.

China has contributed significantly to this event. The amount of steel produced annually by the EAF route in China has increased from 48.4Mt in 2013 to 107.6Mt in 2018, a phenomenal increase (see Table 2). This equates to a share of 5.9% and 11.6% respectively for those two years. 11.6% is still low compared to the three next highest world steel producing countries: India at 53.3% EAF, Japan at 25.0% EAF and USA at 68.0% EAF, but with such a large steel industry in China, this increase is highly significant. Note: China now produces more EAF steel than the total steel output of any of the other three countries mentioned.

That there will be a reduction in BOF tonnage has been suggested by a number of authors, eg, ref [2], but not before about 2025. The above data is still showing an increasing tonnage of BOF steel, but at a lower percentage, so using that definition it would appear that peak BOF has occurred!

The drivers worldwide for increased EAF production relate to:
- Climate change – the need to reduce CO₂ and energy consumption per tonne steel produced
- Other environmental concerns such as NOx, SOx and dust
- The increased availability of, and reducing cost of, renewable electricity
- The increased availability of scrap. In China in particular, scrap availability will continue to increase as steel from consumer goods, transport and some infrastructure produced during the earlier years of industrialisation becomes available for recycling
- The increasing cost and process competitiveness of EAFs (note their increasing capability to produce steels historically restricted to the BOF route:
  - Copper levels are now readily controllable by better scrap selection and benefication, better copper removal processes, and use, when needed, of DRI or HBI
  - Nitrogen levels are now better controllable, even for low C steels
- The rise of mini-mills with their smaller capital footprint, flexibility (ie, on-off) and low conversion costs
- The BF-BOF route is increasingly adversely affected by constraints over the cost and availability of good quality coking coals and iron ores.

2018 still saw 1.28 billion tonnes of steel produced by the BF-BOF route. The BF remains a very efficient converter of iron ore into liquid iron, and has seen off competition from alternative ironmaking methods for over two centuries. The BF-BOF route does, however, have a high carbon footprint (typically producing about 1.8 tonnes of CO₂ per tonne steel produced), compared to a scrap fed EAF of about 0.25 tonnes and a DRI fed EAF of about

<table>
<thead>
<tr>
<th>Year</th>
<th>Crude steel Mt</th>
<th>EAF Mt</th>
<th>EAF %</th>
<th>BOF Mt</th>
<th>BOF %</th>
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<tbody>
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<td>25.4</td>
<td>1210</td>
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<td>520</td>
<td>28.8</td>
<td>1280</td>
<td>70.8</td>
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© Table 1 Steel production by year and method [data ex Ref 1]
This article was first published in Millennium Steel China 2019, pp16-17. At the time of printing, data for BOF/EAF tonnages were not available for 2019, although the total crude steel produced in China and the world increased to 993Mt and 1,842Mt respectively (refer Tables 2 and 1 above) It will be interesting to see if the predictions were correct.

REFERENCES
1. World Steel Association statistics database at https://www.worldsteel.org
4. HYBRIT Hydrogen Breakthrough Ironmaking Technology http://www.hybritdevelopment.com/hybrit-research-project-1

CONCLUSIONS
The BOF will continue to decline and the EAF to rise as, over time, scrap availability increases and capital-intensive coke, sinter, pellet and blast furnace plants reach their end of life (worn out or unable to meet the required environmental standards) and are replaced by EAF plants. Some industry estimates suggest the ratio of BOF to EAF will stabilise at about a 50:50 production split by around 2050. The still-significant remaining blast furnaces (or their process equivalent replacements) will have a lower carbon footprint than today’s variants. MS

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<table>
<thead>
<tr>
<th>Year</th>
<th>Crude steel Mt</th>
<th>EAF Mt</th>
<th>EAF %</th>
<th>BOF Mt</th>
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<td>107.6</td>
<td>11.6</td>
<td>821</td>
<td>88.4</td>
</tr>
</tbody>
</table>

Table 2 China steel production by year and method [data ex Ref 1]
Induction replaces arc.

Induction furnaces outperform arc furnaces as more steel melt shops are seeing the benefits that come with induction for steel making applications. They include lower investment costs, better control of bath metallurgy and homogeneity, cleaner melting and quieter operation—all while requiring less space. Lower refractory costs and other consumables are another benefit along with minimum voltage notching and the lowest harmonic generation at lower power levels.

Inductotherm Corp. • 10 Indel Avenue, PO Box 157 • Rancocas, NJ 08073-0157
1.888.INDUCTO • sales@inductotherm.com • www.inductotherm.com

Important: Appropriate Personal Protective Equipment (PPE) must be worn by anyone in proximity to molten metal.
Primary Processes

46  30+ year campaign of IJmuiden blast furnace No. 6
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    Tata Steel, IJmuiden and Danieli Corus, IJmuiden

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From the mine to the steel mill
30+ year campaign of IJmuiden blast furnace No. 6

Tata Steel’s blast furnace No. 6 of in IJmuiden was blown-in in April 1986 after a full reline and improvements to the lining cooling and top charging systems. The hearth design from the 1970s was only marginally changed and the air cooling of the bottom and spray cooling of the sidewall were retained. After 16 years, the hearth refractory was replaced, but the bosh and stack were not repaired. Currently, after more than 33 years since the original blow-in, the furnace is still performing very well in terms of productivity, efficiency and reliability, aided by good instrumentation, excellent process control and comprehensive asset management.

This paper discusses the long and ongoing campaign of more than 30 years of blast furnace No.6 (BF6) at Tata Steel’s IJmuiden site. Design aspects and operational conditions are described, explaining how this exceptionally long campaign was achieved.

TATA STEEL IN IJMUIDEN

The site of Tata Steel Europe in IJmuiden celebrated its 100 years of existence in September 2018. The primary end of the site consists of two coke plants, a sinter plant, a pellet plant, two blast furnaces and a BOF steel plant. 6.2Mt of hot metal and 7.0Mt of liquid steel was produced in 2018, only slightly lower than the highest annual hot metal output of 6.4Mt achieved in 2007 at an average total coke rate of 270kg/tHM.

An overview of the blast furnace characteristics is presented in Table 1. The configuration with both a sinter and pellet plant on site leads to a blast furnace burden with typically 40% sinter and 60% pellets. The site is self-sufficient in coke, and on average, a net coke exporter.

HISTORY OF BF6 CAMPAIGNS

BF6 was built as a column-supported furnace of 1,843m³ working volume, with a hearth diameter of 10.0m and two tapholes. The first campaign started in November 1967 and lasted until April 1975 and 8.1Mt of hot metal were produced. A repair to the bosh and lower stack was done after three years due to excessive wear in the lintel area (see Figure 1).

A full reline was performed in 1975 when the furnace...
design was changed from a lintel furnace to a free-standing one. A tower structure was established to carry the BF top and structures. The original double shell evaporative cooling in the bosh area had not performed very well and was replaced by plate coolers, with an improved plate cooler pattern in the stack.

The hearth diameter was increased from 10.0 to 11.0m, with the working volume increasing from 1,843 to 2,159m. The throat diameter did not change because the original double bell top was maintained. Due to this, the stack angle decreased from 83° to 80.7°.

The general arrangement is shown in Figure 2, and more details can be found in [1]. The second campaign lasted nine years.

This campaign suffered from high heat losses in the belly and lower stack, high refractory wear, and cooler failures due to the unfavourable throat:belly diameter ratio. Hearth erosion was minimal due to the relatively low productivity and short campaign length. Total production was 14.0MtHM.

THIRD CAMPAIGN DESIGN

The throat diameter was increased at the last reline in 1985. A bell-less top was installed and a third tap hole added. The stack angle was optimised to the ideal 83.3° by increasing the throat diameter and maintaining the belly diameter. As a result the working volume increased to 2,328m³. The hearth diameter was kept at 11.0m. The campaign started in April 1986.

The bosh, belly and stack design included copper plate coolers, but a significant improvement has been realised as the number of copper plate coolers was increased from 1,872 to 2,268. Another important improvement included the application of graphite and silicon carbide refractory in the bosh, belly and stack. The use of the graphite and silicon carbide design had been demonstrated since the 1970s at BF4, despite concerns that graphite oxidation, abrasion and erosion risks could cause havoc to its performance.

Research models, experiments and test panels had demonstrated that the high thermal conductivity and elasticity of graphite prevent thermal cracking and oxidation. In its turn, silicon carbide has an outstanding resistance against abrasion and erosion. Combining these qualities with a high-density copper plate cooler design and an optimal stack angle has resulted in a near-indestructible system, facilitating a smooth furnace operation. This fact is demonstrated by the current on-going campaign performance since 1986 and by comparable designs at many other furnaces today.

An overview of the design is shown in Figure 2 and more details can be found in [2].

The hearth shell was not replaced during the 1985 reline.
as the hearth performance was not of concern in the previous campaigns. The previous campaigns also included bottom air cooling, which has neither been repaired nor upgraded ever since commissioning in 1967. This bottom air cooling system with a flat bottom plate is unique in our industry today; modern BF designs commonly include bottom water cooling.

Hearth shell spray cooling has been used throughout all the campaigns and the system has proven to be effective and economical, although regular inspections and maintenance are necessary.

Since 1986 important improvements have been realised in the field of blast furnace process control, enabling a smooth-running process. These process improvements resulted in low heat loads in the bosh, belly and stack areas, thus facilitating low wear in these regions. The improvements also secured a low coke rate and high productivity operations. This, however, created higher heat loads on the hearth refractory such that the original 1985 hearth design could not cope with these conditions in the long term, making an intermediate hearth repair necessary in 2002.

During this repair the refractory design was optimised on heat transfer from hot face to the hearth cooling system including high-density graphite. New local jacket cooling systems were adopted at the tapholes during the 2002 hearth repair including ammonia chillers to reduce and control the hearth cooling water temperatures (see Figure 3).

Fundamental constraints of the BF6 hearth design include its relatively small hearth diameter of 11.0m and sump depth of 2.4m, resulting in a small hearth volume. The relatively thick bottom with a top layer of silimanite, is in place to resist bottom erosion and protect the vulnerable air-cooled bottom plate. Due to this, and considering BF6’s high productivity and low coke rate operations, the heat loads are concentrated especially at the side walls of the hearth just above bottom level. Despite the improved refractory design this only contributes to a moderate lifetime expectancy, necessitating comprehensive hearth monitoring and asset management systems.

CAMPAIGN RESULTS

Hot metal production increased throughout campaign No.3. The average daily output at the start was about 5,500tHM/day and it gradually increased to 7,800tHM/day in 2007. In the same period the coke rate was reduced from 370 to 262kg/tHM. BF6 was idled in December 2008 for seven months due to the economic crisis. After re-starting in 2009 the furnace could not restore its best performance (see Figure 4) primarily due to the limited availability of high-quality raw materials at this time. Later, hearth refractory issues hindered further improvement.

![Fig 3 Hearth arrangement in 2002](image)

![Fig 4 HM production and coke rate 1986-2018](image)

![Fig 5 Campaign productivity and duration; after [4]](image)
These issues were caused by heat transfer problems: due to hearth shell deformation, gaps between safety graphite and the shell caused high temperatures and erosion. A grouting programme solved this problem around 2013. These grouting activities were also reported in 2015 (see reference [3]). Since then the performance gradually increased again. In 2018 an average coke rate of 274kg/tHM was achieved at a daily production rate of 7,300tHM.

To April 2019, 76.6MtHM have been produced in the 33 years since the blow-in in 1986. Expressed in production per unit of volume, this translates into 32,885t/m³ WV or 28,590t/m³ IV. In a presentation on the ICSTI 2018 in Vienna, the campaign duration and productivity of different blast furnaces worldwide were graphically represented (see [4]). The graph from this publication is modified to include the BF6 result and is shown in Figure 5.

**PROCESS CONTROL**

Since the start of the campaign, important improvements have been realised in the field of blast furnace process control, with burden distribution becoming a more distinguished part of process development after the introduction of coal injection.

Coal injection made it possible to increase blast furnace productivity, but the decrease in coke rate also caused challenges in the gas distribution. A too large gas volume in the centre hampers blast furnace efficiency and productivity, but too much gas at the walls leads to lining wear and possible leakages of the copper plate coolers.

A desired gas distribution is defined based on the optimum between heat losses at the wall and top gas efficiency. The gas distribution in the top of BF6 for both temperature and composition, is monitored by four above-burden probes. To monitor the wall zone and drying zone in the upper part, four in-burden probes are installed. The probes measure the temperature and gas composition between 30 and 90cm into the burden.

The burden distribution philosophy at IJmuiden is based on several principles. Coke is charged in the centre to create a central coke chimney to ensure and control the central gas flow. The amount of coke can be varied by several standard charging programs depending on the blast furnace behaviour. An almost flat burden profile is charged to minimise the rolling of raw materials and so minimises the influence of material properties on burden distribution. The charged fines are distributed along the radius to prevent concentration at centre or walls. Under normal conditions the ore base is fixed, however, the most important part is the repeatability and consistency of the burden distribution.

This philosophy is translated into a desired burden distribution. The charging programme is designed using...
a burden distribution model which has been developed over a number of years and improved by using trajectory measurements which were mostly done with the furnace being off blast. A project is ongoing to do online trajectory measurements, to be able to follow the trajectories of the charged raw materials at any time.

To monitor the result of the desired and implemented burden distribution a radar profile meter was installed in 2004. Based on the results of this profile meter, several key performance indicators are calculated. The current implementation of a 2D acoustic temperature measurement in the furnace top will help in improving furnace efficiency and controlling the gas flow at the wall. Figure 6 shows how the different measurements and calculations are combined to arrive at the desired burden distribution, and Figure 7 shows typical output of the radar profile meter measurements.

More detailed descriptions of the developments in process control and instrumentation can be found in references [5] and [6].

In recent years, the ironmaking community has faced challenges of both availability and quality of certain raw materials. Changes in raw materials can have a significant impact on the burden distribution in a blast furnace so to minimise their impact a number of improvements have been implemented in the existing stock house. These had the objectives to increase the flexibility to cope with the raw material variations and improve the mixing of different raw materials to optimise gas distribution in the furnace.

**ASSET MANAGEMENT: BOSH AND STACK**

Twice per year the refractory wear of bosh, belly and stack is measured during scheduled stops. For this purpose, ceramic rods are installed in the bosh, belly and stack refractory. Based on the principle that the rods will wear at the same rate as the lining, their length is a reliable indication of the residual thickness of the lining.

Nine levels of ceramic rods are installed in the belly and stack. There are three rods per level, approximately 120° apart. Each rod is positioned in the middle of two plate coolers at the spot where the highest wear is expected. On the shell there is a nozzle with a gas-tight cap.

The length of each rod is measured with an ultrasonic device, and physical measurements are done when a rod is broken and replaced, and during plate cooler changes. Based on the ultrasonic measurements, an actual wear line can be made, and a recent version is shown in Figure 8.

A typical example of the historic development of the ceramic rod measurements since 1986 is shown in Figure 9, in this case for row 22 in the lower stack. Refractory wear is observed in the first few years only, after which the lining thickness stabilises. For many years, no additional wear was seen, but recently some wear is observed. It
should be noted however, that the lining thickness is still considerable.

A recent development is that the wear in the upper stack and throat is checked by a 3D measurement device every scheduled stop, as shown in Figure 10.

Copper plate cooler management is essential to control refractory wear. Water leakage causes oxidation of refractory and harms skull stability due to steam formation. Management of leaking coolers is also important in regions exposed to high heat loads. Improper handling causes local severe refractory wear in those areas.

The BF department in Ijmuiden formulated a golden rule: ‘Water leakages are not accepted’. This means that during every shift, all copper plate coolers are checked and any found leaking are disconnected from the cooling system immediately. In the lower stack, belly and bosh area the leaking copper plate cooler is directly grouted to prevent loss of containment. Only the copper plate cooler rows situated directly above the tuyeres are not disconnected; in these cases the furnace is prepared for a stop within 24 hours when the copper plate cooler will be replaced. At every scheduled stop all identified leaking copper plate coolers are replaced.

This refractory and copper plate cooler management has secured the integrity of the system for more than 30 years. In all those years no severe wear has taken place and at no time has external cooling of the bosh, belly or stack shell been necessary.

The excellent condition of the lining is also visible in the photographs taken during the seven month outage for the world financial crisis (see Figures 11 and 12).

**ASSET MANAGEMENT: BOTTOM AND HEARTH**

Due to the fundamental constraints of the BF6 hearth design and the high productivity and low coke rate operation, hearth integrity management is much more challenging than that for the bosh and stack.

This requires a comprehensive hearth monitoring system. Currently the hearth includes an extensive grid with more than 600 thermocouples. The state of the hearth is monitored continuously using automatically calculated alarm temperatures based on their location. The alarm temperatures, together with a standard set of measures, are in place to prevent wear of the safety graphite.

Graphite and semi-graphite hearth refractory can only survive the hearth conditions when the system is able to create a skull that protects the graphite from dissolving into the hot metal, and excellent heat transfer from hot face to the hearth shell cooling system is required to establish this. There are many failure mechanisms that may compromise good heat transfer conditions, such as:

- Calcium deposits on the hearth shell (fouling)
- Gas leakage

![Fig 12 Bosh condition in 2009 after 51Mt](image1)

![Fig 13 Hearth design in 2013](image2)
Water leakage
Gap formation between shell and hot face
Zinc and alkali deposition

Each of these failure mechanisms is managed to prevent hearth wear, and for this purpose, a control plan was developed.

Water quality of the spray cooling system is controlled by a continuous monitoring system to prevent deposition of calcium. The hearth shell is regularly cleaned with high pressure water to secure heat transfer from the shell to the cooling water.

‘Gas leakage is not accepted’ is another golden rule. Gas leakage can cause carbon deposition in the lining, in particular in areas where Fe is present to catalyse this process. Gas leakage via the hearth shell facilitates gas transfer via the refractory, thus causing carbon deposition between skull and graphite or, even worse, in the graphite itself. To prevent this, a monitoring system is established.

This means that every month, all thermocouples mounted on the hearth shell are checked for gas leakage. All identified leaks are rectified directly. If necessary, the blast furnace is stopped for repair.

Gas leakage of the bottom plate is continuously checked. Gas monitors are installed on the ducts of the four fans of the cooling of the bottom plate. Gas leakage via the tap hole face is controlled by tap hole management with plugging, grouting and tap hole face construction used to minimise the gas leakage.

Water leakage causes steam or hydrogen formation in the blast furnace. Steam formation is destabilising to skull preservation, and at high temperatures, water ingress can also cause graphite refractory oxidation.

Water leakage management in IJmuiden is therefore very strict. Copper plate cooler leakages have been discussed above, but tuyere leakages are also not accepted. If a tuyere nose circuit is leaking, it is immediately disconnected from the cooling circuit, but the tuyere will remain with cooling on the body circuit only. For an identified leaking tuyere body circuit, the BF is shut down within a maximum of eight hours to replace it.

Gap formation is an important issue for BF6. This is mainly due to hearth shell deformation. The current hearth shell of BF6 was erected in 1975 and deformation at elephant foot level has developed over the years and is now more than 100mm at certain spots. Since 2002 some spots deformed more than 60mm. The reason for this is the relatively thin hearth shell (40mm), in combination with the hearth design and operation mode. For this reason, a shell deformation monitoring programme is established.

Gap formation between the hearth shell and the safety graphite is detected by flux thermocouples installed in the shell and safety graphite. Changes in flux ratio indicate better or worse contact between safety graphite and shell. If necessary, grouting is applied to restore contact.

Gap formation or degradation of the ramming layer is also detected. Heat flux calculations from the thermocouples in semi-graphite are compared with heat fluxes in the safety graphite. Correction in this case can also be via grouting.

Assessment of contact between refractory and skull is under development. Tests were performed with a thermocouple in the skull, but to date, no valuable or reproducible data could be produced.

Deterioration of refractory by Zn or alkali is controlled by setting upper limits on the burden input. Use of high-density graphite and gas leakage management also helps to slow down this degradation mechanism. In the IJmuiden situation, this degradation phenomenon is not of concern.

**NEW DESIGN BF6**

At this moment, the next reline of BF6 is scheduled for the end of 2021. By that time, the furnace stack will have produced over 80MtHM, and hearth production will be almost 50Mt.

A project was started in 2013 to develop the scope of the reline. At that time, it was foreseen to further increase production capacity. The existing bosh, belly and stack design could facilitate this, but it was decided to improve the hearth design, eliminating the fundamental constraints such as the volume and sump depth. A complete hearth shell replacement would be necessary. The hearth shell cooling would be upgraded to modern techniques i.e. hearth shell shower cooling to be replaced by jacket cooling and the bottom air cooling would be replaced by a modern water cooling system.

It was decided to replace the semi-graphite refractory by super micropore carbon refractory to reduce the risk of dissolution in liquid hot metal and a ceramic cup was introduced to extend the hearth campaign. The design combines all the knowledge gained from the running third campaign. A target campaign life of 25+ years was set comparable to the lifetime performance of the stack.

The hearth design as it was developed in 2013 is shown in *Figure 13*. The reline strategy, however, changed in 2017 due to the possible future effects of CO2 emission reductions, as it is not clear if blast furnace hot metal production in Europe will still be viable after 2030. For this reason, it was decided to limit the target campaign to 15 years instead of 25+ years.

It was therefore decided to re-use the existing hearth shell with only localised repairs to eliminate shell deformation. The principle is shown in *Figure 14*. This means that the fundamental constraints of the
The hearth will remain during the next campaign. The refractory design is, however, further optimised and includes supermicropore carbon and a ceramic cup.

Figure 15 shows the hearth design as planned for the next relining.

CONCLUSIONS

BF6 has been operating 33 years at a low coke rate and high productivity since blow-in in 1986. The low coke rate was aided by an effective process instrumentation and process control approach.

The long campaign life has been possible by the bosh, belly and stack design with copper plate coolers, graphite and silicon carbide, supported by effective process control procedures, as these made sure the gas distribution and heat loads were optimised at all times.

The high productivity and original design constraints caused erosion of the hearth throughout the first 16 years of the campaign which necessitated a hearth repair in 2002 after 34.3Mt. Effective asset management is critical for a long campaign life and at IJmuiden this includes a comprehensive monitoring program and ‘golden rules’ that must be adhered to.

The next relining is currently scheduled for 2021. The original design for bosh, belly and stack will be used. A new design will be implemented for the bottom and hearth to deal with some of the constraints currently in the design.

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Hot blast system development: technology, operations and campaign management

The hot blast system is key ancillary plant equipment with respect to safe and stable operations during a long blast furnace campaign. Hot blast stove designs have been optimised to such an extent that in some cases, their lifetimes have surpassed the campaign lengths of the associated blast furnaces by a substantial margin, with the exception of the burner and a few critical areas. This article presents recent developments with respect to designing, building new and operating existing hot blast systems for a long lifetime and at optimised performance. These developments include fundamental improvements such as dome combustion designs as well as increasingly comprehensive packages for inspection, assessment and maintenance techniques. Examples of such techniques are burner replacement with the hot blast system at operating temperature, improved double shell approaches and time-of-flight diffraction measurement applications.

MATURITY OF HOT BLAST STOVE TECHNOLOGY

The steel sector is confronted with a global drive towards energy efficiency and reduced environmentally harmful emissions, in particular with respect to cutting carbon dioxide emissions. These demands come on top of a highly competitive environment that puts pressure on production costs. An added factor is pressure from residents near steel plants to cut emissions of toxic gases and particulates. The hot blast system is a significant contributor to these forms of pollution, meaning that design and maintenance are key factors for management to consider. Existing and future demands must be constantly monitored because, as a result of degradation of the system and resultant decline in capacity, constant attention is required. In cases of doubt, thorough assessment of the hot blast system is needed to check actual against theoretical performance on the basis of the key criteria of campaign length, efficiency, capacity and emissions.

Any effective long-term strategy for the configuration of the hot blast system must be based on integrated plant optimisation. It should look not only at the stove as a piece of stand-alone equipment that needs to be optimised, but at optimisation of the entire plant. The options range from use of relatively low dome/hot blast temperature in combination with the addition of oxygen or coke oven gas injection in the blast furnace to ultra-high hot blast temperature to minimise coke consumption. Use of advanced software models combining heat and mass balance calculations, process scenarios and flow sheet configurations are key. A typical example of a result sheet is shown in Figure 1.

OPERATIONAL RISK WITH EXISTING SYSTEMS

New designs such as dome combustion-type hot blast stoves are coming onto the market that have yet to demonstrate their longevity but, in general, current hot blast stove technology has attained a level of maturity such that to all intents and purposes campaign length is effectively infinite and extends beyond the campaign length of the other installations involved in ironmaking.

While this is true for relatively new systems, the remaining campaign life capability of the bulk of the existing hot blast stoves that have been in operation for some years or even decades may be anything from a day to 30 years.
Continuing to push these systems is the awareness that specific components are reaching the end of their effective operating life and not anticipating potential problems arising from the failure of these components holds risks for the company concerned.

Certain critical events are of a catastrophic nature. Domes have blown off hot blast stoves on a few occasions over recent decades as a result of stress corrosion cracking, with obvious and serious consequences for health and safety, as well as high costs arising from repairs and lengthy outages. Less serious events, which are also capable of causing lengthy unscheduled interruptions to operations, along with the associated costs are, however, more common. Examples include burner degradation resulting in reduced combustion capacity and related operating temperature and higher emissions. Another is shell hotspots that indicate internal refractory degradation which could result in degradation of steel quality and accelerated shell cracking.

Campaign management Plant management faces a choice. It can press ahead with operations on a day-to-day basis confronting problems as they arise as many repairs are relatively easy to carry out with no or minimal downtime. Repairs of this kind may extend campaign length by, say, a year, but if the required campaign length is longer, this approach may prove more costly in the long run - ‘penny-wise, but pound-foolish’ – and result in frequent repair work to correct faults, with as a consequence, repeated outages, resultant costs and loss of production capacity. The better alternative is to plan repairs and modifications based on assessments of the process and the plant, against relevant criteria, such as campaign length, stove capacity and the emissions restrictions stipulated by law.

The aim of this ‘campaign management’ approach is to optimise preventive maintenance with the long-term objective of achieving operating security by optimising the allocation of investment to maintenance effort, optimising the operating costs and minimising unscheduled outage.

Assessment Plant management needs to establish a baseline campaign management program based on an assessment of the operation and the equipment. This program can be analysed into three major components:

1) **Process** reviewing capacity, efficiency and emissions
2) **Shell** reviewing operating life and operational security
3) **Internals** reviewing operating life and operational security

The Condition Assessment conducted by Danieli Corus at the hot blast system equipment that is critical for the process related performance will take in:

1) The analysis of historical operating data and trends
will be accompanied by ‘control room discussions’ with the people who know what is going on in their plant: the operators. These data, along with face-to-face discussions and analysis of shift logbooks provide the necessary input needed for a thoroughgoing assessment of operating practices. Examples are shown in Figure 2. Key aspects of the process condition assessment include waste gas measurements – O₂, CO₂, CO, NOX, SOX – and pressure drop measurements across components.

The actual hot blast stove performance is compared with theoretical capacity on the basis of the Danieli Corus ‘BLARE’ stove simulation model. This carries out simulations based on a given operating mode, comparing how the hot blast system performs in actual practice compared with the theoretical performance in terms of continuity of blast volume and temperature, gas consumption, percentage of excess air, pressure drop, efficiency and emissions. Aspects for discussion include whether valves are operated manually or computer-controlled. The latter offers room for improvement in terms of efficiencies and emissions.

2) Shell thickness measurements by means of ultra-sound can provide an indication for the amount of corrosion – in terms of thickness decrease – of the shell. Full penetration cracks are identified using ultra-sound and/or soap tests. Other methods are TOFD (time-of-flight diffraction) measurements for stress corrosion cracks, thermography or stress calculations based on actual norms and shell thickness. These inspections (see Figure 3) are executed at the most crack sensitive locations: at intersections of circumferential and vertical welds in the dome area, combustion chamber high temperature areas and nozzle connections. Recent references for TOFD assessments include a complete stove shell inspection in Europe and an assessment of four external combustion chamber stoves in India. In the latter, the extent of the inspected area was limited to selected weld intersection as much as time and accessibility permitted. Based on the measurement data, an indicative status of the shell condition was provided. Such a status report can be...
have proven their value to establish the refractory condition of normally inaccessible areas of the hot blast stove, such as the combustion chamber and dome area. With limited effort, suitable access points can be created at a manhole, draft hole or instrument nozzle. Normally an opening of 80mm is sufficient for the camera to enter the stove. Within a regular schedule blast furnace maintenance stop, physical inspections are possible below the checker grid and ceramic burner (combustion gas and air inlet) if adequate safety measures are taken.

CAMPAIGN EXTENSION PROGRAMS AND MEASURES

Plant management needs to draw up a strategy based on current and future required capacity, efficiency and emissions standards, and anticipated remaining campaign length (lifetime). Again, this strategy will be formulated on the basis of the subdivision above into: 1) Process, 2) Shell and 3) Internals.

For any of these areas the corrective measures, repairs, improvements or investments can be placed in a timeline following the overall plant strategy. An overview of the portfolio of measures, sets of which constitute scenarios or programs for campaign extension and – in connection with the prior assessment program – are the backbone of the campaign management activity, is shown at the end of this article.

The first priority for anyone is to keep the hot blast system a safe working environment. Continuous attention to cracks and hot spots and solving these at the earliest opportunity prevents further degradation and will extend the lifetime of the internals and steel components. For hot spots ‘online grouting’ – injecting insulating refractory material while the system is on blast – is an effective solution. The injection material has good flow properties and does not contain water, which could evaporate and leave voids. An example is shown in Figure 5. An additional advantage is that feedback of the effectiveness of the grouting action can be obtained directly using an infrared camera. The number of injection points can be easily adjusted to the situation.

Prior to looking at equipment upgrades as a way to improve operations, the blast furnace department should review process efficiency. Danieli Corus specialists can assist in objectively assessing and analysing the process parameters and operating practices, which helps operators to find the right priorities and way forward. In practice various plants still rely on operator controlled valve settings and change-over timing instead of using automatic stove operating settings. If the reason is an automation system that is not working to expectations or insufficient experience within the blast furnace process group, in both situations Danieli Corus can provide support by upgrading...
the automation system or organise dedicated training.

Danieli Corus stove optimisation automation – one of the modules of the blast furnace Level 2 system – is a valuable tool that can help the blast furnace team to further optimise energy efficiency and operating cost. This Level 2 automation can be applied in any hot blast system, an example (see Figure 6) that illustrates this is the Level 2 system installed for a brownfield hot blast system upgrade.

After the mechanical survey of the hot blast system, the stress calculations should be updated with the inspection results and evaluated against the applicable industry pressure vessel norms. The corrective measures – ranging from emergency/temporary crack repairs to complete stove double shell solutions, or even full shell replacement – will depend on the outcome of the evaluation. Reliable campaign extension solutions include reinforcement plates and rings. With the proper engineering and a consistent maintenance program the lifetime of crack affected areas can be extended by more than 10 years. Danieli Corus recently designed and engineered a double shell solution for two local sections (upper combustion chamber and checker chamber) of external combustion chamber stoves. Within this project the reinforcement plate solution and a double shell solution for a section of approximately 3m high were compared.

When it comes to maintaining the condition of stove refractory there is not really anything between an emergency repair, such as grouting or hot gunning/ceramic welding and an internal repair good for another ‘10 years plus’ lifetime. There are two reasons for this: (1) a proper repair will function as if it was new. Any substandard design, refractory quality or installation will show signs of degradation within a within one or two years after commissioning; (2) any refractory repair in the hot blast stove will have a significant impact. Either going back to a two stove operating mode and reducing production or building a third stove to maintain the existing production level both require long term planning.

There is always the choice between hot and cold repair. The main factors that affect this decision are the extent of the repair, available time and access to an experienced team. Partial repairs offer an excellent opportunity to improve those areas of the stove that are the most critical in terms of lifetime of weak points in terms of efficiency. Danieli Corus’s latest development to improve ceramic burner emissions in internal and external combustion chamber stoves can be implemented in any comparable configuration and only requires replacement of the top few layers. An illustration on model calculations and design is shown in Figure 7.

In addition to upgrading the hot blast stove burner by replacement of the top refractory courses, Danieli Corus offers the option to convert existing, rectangular ceramic burners to the multi-slotted ‘grid’ design with an optimised burner crown. Figure 8 shows both designs for reference. This burner conversion can be executed with minimum impact on the existing refractories. Figure 9 shows how, when compared to an in-kind replacement of the existing rectangular burner, the burner’s encasing, insulation, support and air/gas inlets can remain in place with the conversion. For both approaches, the grey areas indicate material that remains in place; the coloured areas indicate new material.

Danieli Corus’s hot repair projects have been completed safely, within the planned construction time and complying to the highest quality standards. The perception of the industry towards cold repairs – allowing a more extensive repair scope within the same working time as a result of the more efficient working conditions – is that they require several months of shutdown and are a risk for the integrity of the sound refractory of the stove. Although cooling down and heating up will, together, take 20 to 24 days, Danieli Corus has developed safe and secure procedures, that will provide unrestricted access in the stove resulting in better opportunities for design improvements (see Figure 10). An example is a stove in Latin America where, early in the campaign, cracks developed in the combustion chamber refractory as a result of an ineffective expansion design. Severe cracking developed in the partition wall with a high risk of short circuiting. A new refractory skin wall using Danieli Corus’s expansion design philosophy was applied in combination with an additional insulation layer in the partition wall and parabolic dome design for improved stability (see Figure 11).
If a further degree of refractory deterioration is confirmed after the condition assessment – quickly rising waste gas temperature during the heat up cycle, a rapidly declining hot blast temperature during the blast cycle, high pressure drop in the checker work, general cracking and debris in the lower part of the stove, overall degradation of the refractory insulation continuously resulting in hot spots – a complete reconstruction of the internals should be considered. Several options are possible depending on the condition of the hot blast system mechanical components. Although the stove shell is probably the most critical component due to the cyclic load, other aspects must be considered, such as sizing of process mains, waste gas main design in relation to heat recovery, valve control in relation actual safety and energy efficiency requirements, etc. reconstructing a new stove using the latest design and material standards can result in considerable cost savings.

Stove reconstruction projects always have to be considered in the light of future plant operating requirements and existing boundary conditions: restrictions related to the hot blast system configuration but also financial limitations. This results in different solutions for apparently similar situations. Two examples of projects in Europe with new internal combustion chamber stoves illustrate this. Both plants operate stoves with an internal hemispherical dome, both with alumina refractories in high temperature areas.

For the first project, the preference was for alumina dome refractories, and from an investment cost perspective, the internal refractory dome design was chosen. Based on the long-term strategy of the plant, the lifetime expectancy of the new, additional stove did not have to exceed 15-20 years. Nevertheless, significant design improvements in the burner area and expansion design will accommodate a long campaign without intermediate repairs. For the other project, where an old hot blast stove was replaced completely, the new design included silica in high temperature areas and a ‘mushroom’ dome (see Figures 12 and 13).

For a third stove reconstruction project in Europe, an internal combustion chamber stove was designed, replacing an external combustion stove, and re-using the checker chamber of the original stove without reducing the capacity of the stove. This was only possible by using higher efficiency checkers.

The next step in hot blast system upgrades is an extension of the system by a fourth stove with the aim to increase capacity. Although, depending on the design limits of the blower, it is often possible to achieve higher hot blast system duties without major changes to peripheral components.

Different options are illustrated in Figure 14. Once the decision for a fourth stove has been taken, the design concept should be evaluated carefully. Based on the required capacity external, internal and dome combustion concepts can be considered. Depending on
CONCLUSIONS
Optimisation of a hot blast system can only be determined in relation to the complete blast furnace plant capacity, efficiency and required campaign length. Assessing flow sheet configurations and hot blast system process scenarios against the requirements set by blast furnace mass and heat balance calculations lays a solid foundation for optimised campaign management.

The condition of the hot blast system should be evaluated constantly against the current and future operating and campaign lifetime targets. A complete assessment includes an analysis of the process performance, mechanical components condition review and refractory condition inspection. A complete TOFD analysis of the stove shell is a ‘must’ in case of a stove internals reconstruction.

Measures to comply with future operational targets can be subdivided in three areas – process, mechanical and internals – and can be placed on a timeline indicating the expected lifetime, divided into: Short term repairs, campaign extension measures, structural repairs and strategic investments.

Examples of different successful optimisation, campaign extension, improvement and reconstruction scenarios were described. For every situation, Danieli Corus is looking for optimum, tailor-made solutions. For this purpose, it helps if the end-user has set clear and deliberate long term targets.

It is clear that a straightforward ‘in-kind’ repair or replacement of equipment is no longer acceptable in today’s demanding industry environment as a result of required energy (CO₂) reduction and minimal polluting waste gas emissions. Major reconstruction projects can be postponed if the safety, performance and reliability of the hot blast system allow.

In such case it is important to take – often low cost – measures to keep the hot blast system up to date:

- Stop hot spots and gas leakages as soon as these are identified. Online grouting has proven to be effective in removing hot spots.
- Monitor shell condition and take preventive measures to slow down the process of shell cracking, such as applying reinforcement bands at circumferential welds and insert plates at critical intersections of weld lines.
- Optimisation of hot blast system operations. Danieli Corus operating specialists’ assessment and analysis helps operators to find the right priorities and way forward. Danieli Corus’s Level 2 stove optimisation module is a useful tool for this purpose. MS

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Conveying equipment for extremely hot bulk materials

In the current situation in world steel, with overcapacity, turbulent markets and geopolitical conflicts, many producers have tended to focus on their short-range outlook, solving today’s problems to get rapid results in the immediate future. This often results in a preference for simple and traditional technical solutions. However, something which looks good in the short term may bring disadvantages in the long term, and there are alternatives. Three examples of technological solutions which fall into this category for the transport of hot sinter and pellets are described, illustrating the benefits of tailor-made solutions.

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In integrated steelworks there are a small number of vital areas where hot bulk materials have to be conveyed. In the traditional blast furnace (BF) route there are basically three of these:

- Hot coke from the coke battery
- Hot sinter from the sintering machine
- Fe pellets from pelletising plants

There are two examples in DR plants:

- Charging of hot DRI into the EAF
- Inter-process stage material transfer with fluidised bed DR plants

SINTER PLANTS

In almost all traditional BFs the sinter plant has typically been in operation for several decades. When we visit such plants we often see situations where existing installations have reached the end of their useful life. In these cases the most common approach has been to replace the existing conveyor systems with similar designs. This usually follows recommendations produced by conservative feasibility studies. However, with the technological advances of recent years, innovative solutions are gaining ground.

Adapting and optimising existing machinery, rather than just replacing like for like has, in some plants, led to significant increases in capacity, and large improvements over previous design concepts. Some examples will be given.

Strand exit to cooler A specific area for improvement is in the conveying of hot sinter immediately after the sinter strand to the cooler. Here it has been common practice for some time to arrange one, two or more vibratory conveyors in a row. But in many countries requirements have changed considerably in recent years, in terms of noise protection and health and safety, making like for like replacement more difficult. Another challenge is to limit the wear of the troughs, which can be done to a certain extent by using improved wear-resistant materials in the fabrication, however this increases the operating costs. The replacement of worn troughs also requires downtime to cool and dismantle the equipment.

An alternative option is to use a metallic plate conveyor as illustrated in Figure 1. This has a number of advantages:

- Significant energy savings
- Better working conditions from a considerably lower noise level
- Less downtime and lower maintenance costs
- The overlapping design of the metallic plates prevents the formation of the fine particles produced by vibration conveying, which in turn reduces the amount of fines to be returned, leading to increased productivity at lower costs

Sinter cooler exit to secondary cooler Traditionally the still hot sinter exiting the cooler is transported to a secondary cooler via rubber belts. These are relatively inexpensive, however, the temperature of sinter (or pellets)
at the outlet of the cooler has been rising continuously over the years as sinter machine productivity has increased, resulting in reduced service life and ever more frequent belt changes and hence higher costs.

Our customers report that the cost of replacing the belts is only one aspect of this cost impact. A more important consideration is the downtime when production is hindered. On the one hand, there are personnel costs for dismantling and assembly, and on the other there is a great deal of effort involved in maintaining the necessary material flows. The sinter material for charging the blast furnaces has to be produced in advance and kept in stock, which creates another set of logistical challenges.

These days, steel plate conveyors are available which can transport very hot and abrasive sinter material without problems (see Figure 1). In some plants this type of conveyor has been operating successfully for around 10 years, needing very little repair during that time. Over the same period these conveyors and their components have been constantly improved and increasingly adapted to the requirements, with conveying capacities up to 1,500t/h currently in use. An example is shown in Figure 2.

Plate conveyor design  Replacing existing belt conveyors with more modern metallic plate conveyors for the transportation of very hot bulk materials does not, however, involve just a simple exchange of machines. Dimensions such as height and width will vary due to the different conveying speeds, as belt conveyors operate at considerably higher velocities than metallic conveyors. Material will be layered at a greater height on a steel plate conveyor than on a belt conveyor, and plate widths are also greater than belt widths. Therefore a metallic plate conveyor will not necessarily fit into the space vacated by a belt conveyor without some modification to the surroundings, and the machinery manufacturer has to work closely with the plant project team so that a suitable installation site for the metallic plate conveyor is created, by making adaptations at the existing location. This can often be achieved by modifying platforms, supporting bridges and steel structures, but in some cases the foundations also have to be adjusted. The solution is always tailor-made for a specific situation – there is never a ‘standard’ situation – and the equipment is always customised.

Once the solution has been found and the metallic plate conveyors installed, plant operators have consistently been pleased with availability and low running costs.

As AUMUND has been designing and developing this innovative type of metallic plate conveyor and its components for more than 10 years, it is a solution which is optimised for this application. Since no water is required
to cool the sinter and the conveying is vibration-free, neither ageing nor chemical changes of the sinter are caused. Nevertheless, we are constantly improving the design based on practical experience gathered.

PELLET PRODUCTION

We find a similar scenario in pelletising plants with regard to the comparative age and condition of the plants. When planning a pelletising plant, dimensioning the cooler is a decisive criterion for the overall cost of the plant. Even if the cooling capacity is sufficiently calibrated at the time of commissioning, an increase in the temperature of the pellets at the outlet of the cooler can be achieved by continually optimising the plant and consequently increasing productivity. Some plants have even been able to double their projected capacity. As with sinter plants belt conveyors are also provided as standard after the cooler. These were originally designed for material temperatures up to 100°C but are now in situations requiring them to operate with temperatures up to 600°C, or even higher.

Depending on the local situation, pellets are usually transported either to a storage area, a logistics centre or a port. Instead of a rubber belt conveyor, we recommend using a metallic plate conveyor from the outset in a new plant.

As with sinter plants, when replacing or modifying an existing belt conveyor the steel plate conveyor must fit into the space which was designed for a belt conveyor.

Some customers consider this conveyor to be the most critical part of the whole plant as it is the last place they want a bottleneck. Specific cases have been reported of belts having to be renewed every 40 days because they were burned by the hot pellets, significantly affecting production. Resources were permanently required for the belt changes, both in terms of the cost of the belts themselves, the personnel required and the time needed for the belt change operations.

An example of a pellet plate conveyor is shown in Figure 3.

SUMMARY

As sinter and pellet plant outputs rise due to process improvements, the temperatures of these materials has been rising, putting the traditional vibratory and rubber belt conveyors under considerable stress. Although metallic plate conveyors have a higher capital cost, they are custom designed for an individual plant and have lower downtime, maintenance and environmental costs.

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Badische continues its journey towards manless EAF operation and launches the Tap Hole Manipulator (THM)

The latest tool geared towards the goal of zero accidents started at their plant in Kehl, Germany on January 30th 2020. It can be seen in the context which Badische calls "The Future is Manless": As Badische Stahlwerke (BSW) sees their personnel as the key factor for success, it is critical to keep them safe. BSW is known as one of the most efficient and safest EAF operations in the world. As part of the group, its Engineering division (BSE) is bringing the same technology to customers all over the world. But let's take a step back and have a look at the long history of safety tools at Badische.

In 1985 the first Lance Manipulator worldwide went into operation (see Figure 1), replacing the manual power-off time. Outside of the USA, BSE is the market leader in installing and manufacturing this technology. In 2010, the era of robotics was introduced to the German steelmaker. It replaced the TSM and marked a leap towards a true manless operation. The MultiROB (see Figure 3), as it was named, is also capable of automatic cartridge changes. Another important capability is the tool changing, where it can use a camera tool to safely spot water leakages inside the furnace or inspect the refractory lining.

As it was identified early on, water leaks are probably the most dangerous operational risk factors. Accordingly, Badische recently developed a Smart Leakage Detection (SLD) system that can identify leakages as little as 25 litres per minute. This technology allows now a constant measurement and therefore adds a full redundancy for water leakage detection.

As a consequence, as presented here, it was only logical that Badische began putting its attention to probably the last highly human exposed area at the EAF, the eccentric bottom tap hole (EBT). In previous steps various safety modules like: an automated flap, EBT balcony flap, a camera system as well as a pneumatic filling system were installed. For a further EBT service, the idea of the Tap Hole Manipulator (THM) was born. As always, Badische first implemented and tested this new tool first at its own plant – the best evidence to our customers that we fully trust our engineering solutions.

oxygen and carbon injection system which had been standard until then.

Seven years later the Temperature and Sample Manipulators (TSM) at both EAFs at BSW were installed. This series of manipulators became a big success with over 300 installed versions at various locations, including LFs, converters, spouts, etc. as well as EAFs.

The next step to better safety was with marked in 1988 the spray roof. Back then, under license of UCAR, Badische had the first manufactured and installed spray roof EAF in Europe (see Figure 2). With this pressureless design, potential water leakages from the roof were no longer dangerous. Furthermore, even in case of a leak, steel production could be continued until the next
THE TAP HOLE MANIPULATOR (THM)
The THM addresses two fundamental, regular tasks of every EAF plant with an EBT: the clearing of bulky items, and the cleaning from contamination and build up after tapping. These steps unfortunately are still done manually in most plants today.
Implementing design concepts which Badische applied to be patented, the THM realises another step toward the ultimate goal of 100% safety at an EAF plant. It addresses it, once more, with smart automation of previously human tasks.

Another aspect is standardisation: This is always not only helpful for safe manufacturing and efficient maintenance processes, but also for economic reasons, i.e. plant productivity. Conclusively, it was taken into account as a project target for the concept as well.

Here the summary of the THM’s development goals:
- Optimal work safety
- Standardisation of the tap clearing and cleaning process, resulting in shorter power-off (set-up) times
- Material savings through more careful and efficient cleaning

In January 2020, during the annual shut-down, the THM was successful put into operation at EAF #2 at BSW (see Figure 4). Since then, the safety and operative results have met all expectations.

After start-up, the following advantages were realised, and could fully be demonstrated:
- Work safety improvements as planned, by taking operators further out of harm’s way
- Automated clearing process of objects from around the tap hole
- Standardisation of the cleaning process resulting in consistently shorter set-up times

As a positive side effect and important ergonomic benefit, the physical strain for employees was significantly reduced.

THE FUTURE IS MANLESS!
As demonstrated once more by the Badische Group, we are moving again one step closer toward manless EAF operation on the shop floor. Badische is convinced the best place for a steel maker is not in a danger zone – but instead in a place where we can make best use of the human talent, safety. The future of safe and immediate operational tasks in harm’s way must be manless. The THM is another significant step towards that goal. MS
The Future is Manless
Solutions to keep our people out of harm’s way

Principles.
- Manless, automated operation for EBT clearing and cleaning
- Installation adaptable to most EAF designs, customizable in many design parameters
- Clearing of the EBT tap hole from debris and bulky items after tapping by hydraulic force, with a robust, powerful tool tip
- Cleaning of EBT tap hole with oxygen blowing function
- Unique tool design and concept (BSE patent pending)

Concept.
- Robust design for minimum maintenance and maximum reliability
- Fully customizable for each EAF layout and requirements
- Careful operation with smart hydraulics, limiting overstress and potential damages on tap hole
- Additional concepts possible, e.g. integration of sand filling, automated EBT tap hole flap, camera inspection etc.

Advantages.
- Taking operators out of harm’s way, as part of BSE’s vision of a “manless” EAF operation for maximum safety
- Eliminating human procedure in a challenging ergonomic situation
- Standardization allows for reduction in scheduled power-off time, improving overall plant economics (productivity, capacity, cost)
- Concept, design and installation support package available

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Ideal bearings for cost-optimised operation of continuous casting machines

_Schaeffler offers steel manufacturers a practical and future-oriented solution with its sealed spherical and cylindrical roller bearings for continuous caster support rollers, suitable for both new and existing caster designs. The use of sealed bearings enables longer caster runtimes and lower operating costs, which contributes to more environmentally friendly steel production. The investment in sealed rolling bearings is recouped in just a few months._

**Author:** Philipp Weippert  
_Schaeffler Technologies AG & Co. KG_

From the very beginning, operating continuous casting machines efficiently and economically have been driven by the following factors related to rolling bearings:

- Quantity of steel produced for each set of bearings
- Operational safety: unplanned failures due to cooling or lubrication system failures, blocked rolls, bearing damage, etc.
- Operating costs arising from grease consumption, coolant water treatment, system cleaning, the disposal of grease and scale residue, etc.

Due to the extreme heat, high humidity and heavy dust and scale contamination, continuous casting machines (see Figure 1) are, without a doubt, a severe test for rolling bearings in strand guides. To compound the matter, the slow speeds of the strand guide rolls inhibit effective distribution of lubricant within the bearings and the mechanical forces exert tremendous stresses within the bending area of the machine. Therefore, bearings designed specifically for these adverse conditions are absolutely essential to cost-effectiveness and reliability of the casting process.

The past 20 years have seen steel producers use a variety of operating strategies for rolling bearing maintenance. While some companies overhaul lines of rolls and replace bearings after a fixed period, say every million tonnes of steel produced, others rely on one-time reconditioning of the bearings. Still others will push the limits of the rolling-bearing arrangement and produce far in excess of one million tonnes of steel with a single bearing set.

The greater the quantity of steel produced, the higher is the risk of unplanned failure and therefore, the demands placed on the bearing solution are high. In some circumstances, this necessitates use of specialised...
coatings, high quality and expensive lubricants, and above all, larger quantities of lubricants. This, along with shorter maintenance intervals, drives up operating costs. It is difficult to generalise in favour of one or another operating strategy so steel producers should compare and contrast the various bearing and seal concepts to optimise their solution based on durability and/or operating costs.

Schaeffler offers both open and sealed cylindrical and spherical roller bearings from its continuous casting bearings (CoCaB) product portfolio for the bearings used in strand guide rolls. In the following, the article is focused on these bearings.

Besides that, the upper segments use INA needle roller bearings whereas for applications using driven rolls, split FAG cylindrical and spherical roller bearings are available. Special FAG bearing housings with water cooling complete the CoCaB product portfolio.

STANDARD SOLUTION WITH AN OUTER SEAL
Open rolling bearings in combination with additional housing seals (outer seals) continue to be popular. The lubricant feeds through the bearing outer ring by a central system and lubricates the bearing and outer seal from which a portion escapes forming a bead of grease as a barrier against coolant water and scale. Due to the very slow speeds, the system requires large quantities of lubricating grease to ensure both that the bearing is sufficiently lubricated and that the protective bead of residual grease remains intact. This solution results in the highest costs due to the amount of required lubricant, water and scale treatment, and grease disposal.

BEARINGS WITH INTEGRATED SEAL AND OUTER SEAL
Bearings with integrated seals represent an alternative to the standard solution and are ideally suited to the rough operating conditions during continuous casting. They are greased at manufacture and are maintenance-free while in operation. Schaeffler offers FAG spherical roller bearings of series 240 and 241 from the CoCaB product portfolio and feature a robust sheet steel cage and integrated seals made of Fluorelastomer (FKM) on both sides. They can directly substitute for open bearings on a one-to-one basis, having the same outer dimensions. An example is shown in Figure 2.

The new, sealed FAG cylindrical roller bearings from the CoCaB product portfolio serve as floating bearings. Compared to the open versions, they have the same outer dimensions and are equipped with FKM seals. Schaeffler designs the dimensionally stabilised bearing rings and the FKM seals for the high operating temperatures in continuous casting machines (see Figure 3).

Both types of bearings are factory filled with a high quality
Schaeffler Arcanol grease. With both types of bearings, the seal concept allows for an additional reservoir of grease at both sides of the rollers. The seal design precisely considers the clearances and tilting of the bearings to guarantee the sealing effect under all operating conditions.

**INTERNAL BEARING GEOMETRY SPECIFICALLY DESIGNED FOR CONTINUOUS CASTING MACHINES**

Many of the floating bearing solutions on the market entail a compromise between variability of axial displacement, load-carrying capacity and compensation of angular misalignment and do not optimally meet the requirements in continuous casting machines. Thanks to the special profiling of the bearing elements, the CoCaB-CRB combines the advantages of a full-complement cylindrical roller bearing and a spherical roller bearing, namely high radial load-carrying capacity, forceless axial displacement, and compensation of angular misalignment. The profiling, specifically designed for the heavy loads, prevents edge stresses on the rollers and is designed to allow the cylindrical roller bearings to compensate for angular misalignment of up to eight angular minutes under heavy loads.

The expansion of the shafts is easily and unconstrained compensated with the CoCaB-CRB since it is still a cylindrical roller bearing type. The same load conditions are guaranteed in all axial positions, making axial presetting of the bearing unnecessary.

**OPERATING STRATEGY**

For-life lubricated rolling bearings in strand guide rolls offer steel manufacturers two options: operation with or without re-lubrication of the outer seals.

**With re-lubrication** In this option only the outer seal is lubricated and the escaping grease forms an additional barrier against dust and scale. Following a transition from open to sealed bearings, low-cost grease is sufficient since it serves primarily to keep abrasive contamination and water away from the outer sealing lip and not as a bearing lubricant. This also leads to reduced grease consumption. Significant savings are achieved with this concept due to the bearings' demonstrably long life as shown in field tests, reduced lubrication consumption, and low disposal costs. This solution is easily implemented and highly flexible with regard to outer seal design.

**Without re-lubrication** With this option the aim is to eliminate re-lubrication altogether. While the dry-running outer seals required for this are not yet widely used, they have been successfully used for several years. They need to withstand the wear caused by abrasive particles for a sufficiently long time and are more expensive than seals.
that are lubricated with grease. They do, however, make it possible to operate the bearing arrangement completely without re-lubrication when combined with bearings that have been lubricated for life. Durability testing has shown that Schaeffler sealed spherical and cylindrical roller bearings installed in strand guide rolls produced 1.2 million tonnes of steel with no re-lubrication required.

There are numerous advantages to this solution:
- The coolant water is no longer contaminated with grease, making it less expensive to treat
- The costs for disposing of the mixture of grease, dust, water, and scale are avoided
- New continuous casting machines do not require investment in a lubrication system for the guide rolls
- The risk of failure from leaking screw connections, clogged lines, empty lubricant reservoirs, etc. is eliminated

Payback A comparison between open and sealed bearings shows the projected savings (see Figure 4). The costs are based on an open bearing with an outer seal and a bearing with an integrated seal and an outer seal with re-lubrication. Also considered are costs needed for the separation of grease from the cooling circuit and its disposal. Due to lower operating costs and the longer life expectancy of sealed bearings, their higher capital cost is amortised within just a few months.

RECONDITIONING OF ROLLING BEARINGS
During guide roll maintenance, most steel manufacturers replace the existing rolling bearings with new ones. It is, however, quite possible to recondition these used rolling bearings. Common practise shows that one-time reconditioned bearings attain the same runtime performance as new ones. To recondition the bearings, they are dismantled and cleaned, the raceways are examined and polished if necessary, the ovality of the rings is measured, and the internal clearance is checked after reassembly (see Figure 5). Moreover, the new load zone is marked on the outer ring, and the reconditioned bearing is remounted with the outer ring positioned accordingly in the housing.

Many system operators’ safety concerns sometimes predispose them to overlook the cost-saving options that are available. Reconditioned bearings have a more favourable price, shorter lead times and a lower environmental impact than new bearings. Schaeffler not only offers reconditioning of bearings from its own production but also for third-party products.

OUTLOOK AND MARKET ASSESSMENT
Due to their importance for environmental sustainability, the issues of grease reduction and disposal are also gaining political significance and increasing disposal costs in the short to medium term are anticipated. However, Schaeffler offers steel manufacturers a practical and future-oriented solution with its sealed spherical and cylindrical roller bearings of identical installation size. Both new and existing casters can very easily be fitted with these bearings.

In addition to sustainability benefits, the use of sealed bearings also enables longer runtimes and lower operating costs with the investment in sealed rolling bearings being recuperated in just a few months.

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The way towards the learning steel plant

The steel industry now finds itself in the age of digitalisation. High plant availability, consistent plant conditions, and maximum product quality are key factors when it comes to optimum plant operation. Today, it is increasingly important not only to produce efficiently but also in a resource-saving and sustainable manner. The demand for digital products that also address the subjects of artificial intelligence and machine learning is on the rise. SMS group and its digital entity SMS digital are the ideal partners when it comes to opening up the full potential of a plant and, thanks to their modular software solutions, are able to provide all the tools for full plant connectivity and capacity utilisation.

SOFTWARE FOR INDUSTRY 4.0 – DIGITAL APPLICATIONS FOR EXCELLENT PLANT EFFICIENCY

A modern steel mill with a highly flexible process chain and state-of-the-art technologies for ensuring high-quality steel products, as installed at Big River Steel (BRS) in Arkansas, USA, consists of a large number of highly specialised systems generating an enormous amount of data. These data contain information about almost everything that is going on in the mill. When these data are integrated in the right way, they are able to provide answers to questions relating to plant status, process accuracy and the way in which it determines the product quality or operational cost drivers. Therefore, these data are of great importance for various types of performance evaluation and system adaptations.

SMS group and SMS digital have already realised their vision of the learning steel plant at BRS, the world’s first learning steel plant. Here, SMS has succeeded in digitalising a complex steel mill in such a way that stable and resource-saving production is optimally controlled. In order to concentrate digitalisation competence in the best possible way and to activate the full potential of digital solutions, SMS digital relies on strong partnerships. In this way, SMS digital, in cooperation with noodle.ai, a leading provider of Enterprise Artificial Intelligence®, is further optimising the learning steel plant at BRS by developing digital applications using state-of-the-art data analysis technologies such as artificial intelligence and machine learning. The goal is to operate the mill in the most resource-friendly and energy-saving manner possible.

In order to meet the challenges of digital transformation, companies in the metals industry need software that processes large volumes of data and analyses them to identify important interrelationships. The age of digitalisation and Industry 4.0 calls for getting maximum performance out of plants and processes. High-end technology and intelligent digitalisation solutions help to generate more added value. If plant expertise, experience in process modelling and state-of-the-art data science are cleverly combined, improvements in production efficiency, product quality and plant condition can be achieved.

Many companies are already collecting and storing data along their entire process chain. Therefore, the data volume is increasing, but the companies do not use the data efficiently. Storing large volumes of data, however, should always be associated with added value. Otherwise, it does not make sense to store unorganised data – they simply cannot be used. SMS digital uses a data-oriented approach to find out, together with the customers, which data are available and how they can be best used. The goal is to add value to the plants and their processes by achieving a faster return on investment.

A plant is designed in such a way that it uses advanced automation in all production phases. The production systems of the plant monitor and control each process step and the large data volumes that are generated in the process. These data are used to verify the correct procedures used for production and to ensure that the product meets the customer’s requirements. These data are also important for monitoring the condition of the various units within the plant. Each of the production units maintains its own data storage and generates its own reports. Combining data from several sources and the generating reports across several production units can be a difficult and time-consuming process.

In order to prepare a steel mill for digitalisation, certain measures must be taken to extract the data and make them usable for applications, digital products and services. These data can usually be extracted through the...
various automation levels, such as sensors, process models, etc. and are mainly used by systems and solutions that concentrate on a certain process stage.

**SMS DIGITAL’S VISION OF THE LEARNING STEEL PLANT**

For SMS digital, the learning steel plant is one that permanently controls and optimises itself autonomously with regard to its essential performance parameters such as product quality, lead time, adherence to deadlines and yield. This can be achieved by interlinking all involved persons and systems to form a network. The plant uses artificial intelligence algorithms to determine and evaluate suitable scenarios, ie, it trains them, monitors itself with learning algorithms and draws appropriate conclusions from real events. To achieve optimal results along the entire production chain, it is necessary to model the processes from material provision through production to distribution and to fully master the relevant machine, process and product data.

Although the majority of SMS group’s business is in the steel industry, digital technologies are of course also being used in many other sectors, such as aluminum or copper. However, the digital technologies and methods developed by SMS group are so universal that they can be used in other industries such as paper and glass manufacture.

The term ‘plant’ is scalable with regard to the scope of the project. Digital solutions can be made available for individual parts, for example in the form of an innovative platform for ordering spare parts, for a specific machine type by providing first-class automation systems, for an entire plant complex which enables efficient production planning, quality or logistics processes, right through to solutions connecting several locations, for example in the form of business intelligence solutions that allow for company-wide transparency.

The main task of the learning steel plant is to turn data into value. It makes use of all the advantages of innovative technologies to increase its productivity and user-friendliness and has an enormous positive effect on sustainable green steel production. Being part of a multinational company, SMS digital has access to specialised domain knowledge from around the world regarding every production route in the steel industry.

Under the umbrella of the three main pillars of planning, quality and plant condition, the solutions provided by SMS digital cover digital products and consulting services with regard to operational competence, platform services, customer-specific development solutions as well as data analysis and preventative maintenance.

With the aid of modern agile methods of working such as design thinking, new products can be developed right from the start in close cooperation with the customer, the end user and the experts of SMS group. In this way, the best possible solutions can be achieved, as the solutions are perfectly tailored to the individual needs of the customer – with immediate added value and maximum profit.

**EXTRACTING ADDED VALUE FROM DATA**

In order to create a basis for all digitalisation applications and to finally obtain added value from data, the plant data must be available in a structured and well-organised form. For this purpose, SMS digital offers the ‘SMS Data Factory’ which is used to convert raw data such as relational data, process data, time codes or files into usable data. Figure 1 shows a general overview of the concept. The Data Factory collects data from the existing plant automation system and makes them available to other applications. It consists...
of a local component and a cloud component, with one or the other components being in the foreground depending on the application and the specific requirements of the respective plant.

The Data Factory is a scalable product, which can be used for a specific plant or machine as well as for a complete plant complex or for an entire company. In this way, a specific plant section can be used for starting small and the application can later be extended to further plant components.

In a first step, data have been enriched with added value. Now, to make these data visible, SMS digital uses the mySMS platform (see Figure 2). With this industry-specific software-as-a-service (SaaS) platform for the metals industry, SMS digital hosts and combines the most important applications for the fast and direct digitalisation of a company and guides the customers step by step on their way to the learning steel plant. Users benefit from a single sign-on for all applications in one interface.

This feature is supported by simple and intelligent user and role management. All data is hosted in highly secure data centers, data transmission takes place using end-to-end encryption and is secured by encrypted drives. SMS group and SMS digital are constantly expanding the portfolio by adding new and innovative applications to the mySMS platform. In this way, customers will be able to test new developments early on and can add real added value to applications with their feedback.

**EFFICIENT PRODUCTION PLANNING**

Digital solutions for production planning include all products and services that serve to optimise production planning and control. They focus on KPIs such as output, finance, delivery performance or warehouse management. One of the key products offered by SMS digital in this context is the production planning system X-Pact MES 4.0 (Manufacturing Execution System) as illustrated in Figure 3. Like all modular software solutions from SMS digital, MES 4.0 uses the methods of machine learning, artificial intelligence and big data analysis to monitor all production steps along the entire process chain. Thanks to the modular structure, MES 4.0 can be supplemented by further applications and integrates smoothly with an existing IT landscape. The entire process can be tracked, from receipt of the customer order to the product leaving the plant.

For MES 4.0, one of the most attractive areas of application is the field of production planning, when it comes to achieving improvements through digitalisation. Seamless vertical and horizontal connectivity, optimisation algorithms and data-controlled models, in particular, improve the flexibility of production planning without adversely impacting operational productivity or stability.
Nevertheless, the technological knowledge in the field of metallurgy continues to be a decisive factor. Today it is more important than ever that this specialist knowledge can be easily and intuitively integrated into dynamically growing MES functions. After all, the dynamic changes in market demands, triggered by the Internet of Things, require considerably shorter cycles of automation modernisation as we head towards Industry 4.0. Rising volumes of data and new means of exchanging information are resulting in closer collaboration between full-line suppliers of plants and automation systems, and plant owners and operators. The flexible adaptation of products at consistently high product quality must be ensured. The production lead times must be minimised and a high level of adherence to delivery deadlines must be achieved. At the same time, resources must be optimally utilised with reduced stock, and maximum yield must be attained to ensure profitability.

Around 15,000 signals are available in a modern compact strip production (CSP®) plant. Knowing the origin of the signals and the way they are created is of vital importance for the analysis, and is thus a crucial factor for long-term production optimisation. AI algorithms have been integrated to enable the best possible dynamic re-planning.

Thanks to the integration of MES 4.0 at Big River Steel, SMS group and SMS digital have jointly been able to contribute to achieving maximum plant performance with minimum maintenance as well as high product quality and yield. Therefore, MES 4.0 is an essential component in the successful change to the Smart Factory in the spirit of Industry 4.0.

**SOLUTIONS FOR QUALITY OPTIMISATION**

Even today, quality management is not an automated process in most rolling mills. A great deal of time and effort is invested in quality monitoring by humans, for example to determine the exact cause of defects. Deviating quality data require decisions and measures by the monitoring staff, such as redirecting or, in the worst case, scrapping a coil, which results in losses. In the past, IT implementation of quality assurance was almost impossible, due partly to the broad variety of products manufactured and small batch sizes for customer-specific steel products. Another critical factor is that quality and process data are usually stored on several local systems, so that a large part of them cannot be accessed directly. The user-friendly approach of the Quality Execution System (QES) enables the systematic introduction of an automatic coil release system for all production lines.

The QES data integration supports digital connections between different departments, sectors and supply chains, thus enabling users to improve cooperation, coordination and transparency. This enables both horizontal integration, eg, between processing lines, and vertical integration by making data from the field and process levels usable for higher control levels, eg, through communication with MES 4.0.

**CONDITION MONITORING FOR OPTIMAL PRODUCT LIFECYCLE MANAGEMENT**

Many plant processes in companies have already been digitalised. However, the evaluation of the generated data is very time-consuming. Intelligent maintenance solutions make it possible to carry out automatic system-wide analyses, thus improving quality and efficiency. These products and solutions focus on aspects such as plant availability, inventory management or maintenance planning. Here, SMS digital offers just the right tools that can be easily integrated into existing system environments and are seamlessly integrated with each other: Problems in the plant are first detected by Genius CM and forwarded to Smart Alarm (see Figure 4) to inform the maintenance personnel. Using eDoc, suitable spare parts can be identified and ordered so that a visual plant inspection can be planned using the production planning software MES 4.0. IMMS coordinates the personnel, tools and materials required for this task – precisely and on schedule.

Let us have a closer look at the application. Genius CM® enables permanent monitoring of the plant components, which facilitates early detection of critical situations and prevention of unplanned shutdowns. The monitoring functions include diagnostic vibration analysis, temperature monitoring, monitoring of dirt particles, oil flow, water level and hydraulic fluids, a torque analysis system and process monitoring using the mill diagnosis system. The installed sensors on all important plant components along the process chain constantly transmit measured data to Genius CM®, which, unlike other systems, compares the measured values with the process data. The software then compares these findings with the tolerances and triggers an alarm if limit values are exceeded. In this way, considerable damage from over stressing and unforeseeable consequential damage can be prevented.

The production processes are monitored by means of PCA® (Process Condition Analyser). The software evaluates all types of data, such as data from surface inspection systems, technological measuring systems, basic automation systems, process models and from the Level 3 system with regard to production and plant conditions along the entire process chain. It visualises where the production conditions are not within the limits and where the corresponding equipment can be found in the plant. This information, together with the complete documentation, starting with data sheets for sensors and functional descriptions, circuit and hydraulic diagrams, up-
to expert recommendations and mechanical drawings, is made available to the personnel as a web application on mobile devices. For this purpose, eDoc is connected to PCA® or can be used separately. eDoc is a digital solution that makes technical documentation available in a modern and easy-to-use manner. In this way, the shift personnel can react more quickly and effectively to any defects that occur and assume more responsibility.

The detection of changes in the long-term behaviour may trigger maintenance activities in the regular maintenance shifts. That is why PCA is linked to the integrated maintenance management system (IMMS). As a result, the maintenance approach is shifted from a mainly cyclical to a mainly predictive one, thus enabling a more cost-efficient operation. Suitable maintenance measures allow individual parts to be serviced in such a manner that the optimum strategy for the respective plant is obtained. The focus lies on prioritised measures with the right amount of documentation – achieving more efficient results than with conventional methods.

Through mutual harmonisation, all software functions work perfectly together. Maintenance management is practice-oriented and is based on the principles of reliability-oriented maintenance and an ideal mix of repair strategies, supported by the rules for failure mode and effect analysis (FMEA) and critical analysis.

If deviations are detected by means of the applications, the plant personnel are informed via Smart Alarm. Smart Alarm is an intelligent alarm and maintenance management system that helps to increase plant availability, optimise maintenance activities and make available expert knowledge for all employees. A major advantage is that the plants can extract data from a large number of systems and aggregate and evaluate these data using a central software. The visualisation option on the dashboard provides a sorted overview of all processes as well as necessary maintenance activities and can be called up in real time from any mobile device.

The interaction between the individual digital solutions enables comprehensive monitoring and control of the entire plant and of all production steps in order to achieve overall transparency of the plant. In conjunction with artificial intelligence and machine learning, the plant is able to optimise itself – the learning steel plant has become reality.

**SUMMARY: ADVANTAGES OF THE APPLICATION OF DIGITAL SOLUTIONS**

Steelmaking in the age of digitalisation calls for new approaches. The demands for more efficient and sustainable production processes are growing all the time, and the higher level of automation calls for modular solutions that create connectivity. The interaction of all modular solutions from SMS digital is bringing plants a step closer to becoming a learning steel plant.

Industry 4.0 needs to come up with an answer to a very simple question: How can digitalisation help steel producers to improve the efficiency and profitability of the entire value chain? In the face of economic competition, only sustainable digital solutions will survive. SMS digital is able to meet the challenging market conditions within the scope of digitalisation. Digitalisation is not hype, it is a multi-stage process for optimising the overall efficiency of the plant. MS

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MIDA endless and direct casting and rolling: the Danielli way to energy efficiency and CO₂ reduction

Danielli's minimills based on MIDA endless and direct casting and rolling processes are now well established worldwide, providing greater productivity, lower capital and operating costs and lower greenhouse gas emissions than hitherto possible. The technology and plant examples are described.

Authors: A De Luca, F Tortul, M Cimolino and S Ronco
Danieli SpA

Prior to the 1960s, construction steel, including rebar, was made mainly from new raw materials, and large volumes of CO₂ emissions were produced, up to 2.5t of CO₂ per t of hot rolled product. Since the early 1970s, the mini-mill philosophy pioneered by Danielli has been marked by low investment costs, minimal manning, and low operating cost plants that serve specific geographic areas with a good balance of scrap supply and markets for finished products. With this EAF scrap recycling route, CO₂ emissions have been lowered to a more sustainable 0.4-0.6t per t of hot rolled product. However, in the late 1990s global CO₂ emissions exceeded 30Gt and the steel industry was responsible for around 6.5% of the total emissions[1].

Under these circumstances, the steel industry has recognised the need to take actions to limit the impact of its own activities on climate change: one of the most effective initiatives was to establish a method to calculate the CO₂ emission intensity of steel plants, irrespective of products manufactured and geographic characteristics[2]. Also clear is the relationship between CO₂ emission reduction and energy efficiency as roughly 60% of CO₂ emission reduction can be attributed to energy-saving activities.

Over the past 20 years sensitivity to environmental issues has increased and the technology has evolved to fulfil the vision of green steel production. Cooperating with customers, Danielli has developed a multi-part approach in the casting-rolling process to cope with more demanding requests for sustainability and profitability.

The MIDA ECR (Endless Casting and Rolling) process, introduced in 2000 to reduce energy in reheating before rolling, among other factors, is now a commercial reality, reducing the total amount of CO₂ emissions down to 0.3t per t of steel (-30%). Moreover, Danielli has remained determined to pursue improvements in energy savings and productivity by exploring new solutions to be combined with the already proven, high speed casting technology called Power Mould[3].

In this context Direct Casting and Rolling (DCR) technology has been also developed with a new approach in layout and operations. The relevant results of this new solution compared to the existing state-of-the-art for rebar steels and the latest experience in FENG HSIN, Taiwan, are described.

MIDA TECHNOLOGY CONCEPTS

A key factor for energy conservation is the integration of discontinuous process flows, for instance, the production and storage of billets in continuous casters, transport to rolling mills, reheat through gas furnaces, and finally rolling to finished size. The focus has been on operations in continuous casting machines and rolling mills to achieve higher billet temperatures, thereby achieving significant energy savings through not having to reheate the billets.

Hot rolling is performed at a temperature of about 1000°C to produce the final shape, so in order to feed billets at this temperature into the rolling mill, a gas-fired continuous heating furnace (pusher-type, stepping-type) is usually used. With older mills the billets are cold charged (~20°C), and in some more modern ones a proportion may be warm charged (600-800°C) direct from the caster (see ‘A’ and ‘B’ in Figure 1). The furnace usually includes three preheating zones, a heating zone and a soaking zone.

By contrast the Direct and Endless Casting and rolling processes pioneered by Danielli are shown in ‘C’ and ‘D’:

‘C’ DCR – single or multiple billets cast at high casting speed are directly rolled after passing through an induction heater, with or without use of a billet welder for endless rolling.

‘D’ Endless casting and Rolling (ECR) – extremely
high speed endless casting and rolling is applied, with or without utilising an induction heater.

A. CONTINUOUS CASTING WITH RF COLD CHARGING FROM STORAGE

In this traditional configuration, cold billets are transferred to the reheating furnace (RF) from a cooling bed or from a storage area. Considering an ambient temperature of 20°C, an estimate of energy consumption for reheating is about 1.2GJ/t [4]. The scale produced during reheating could be up to 1%, in addition to what may be produced in continuous casting.

B. CONTINUOUS CASTING WITH RF HOT (WARM) CHARGING

If the billet is moved from the cooling bed to the reheating furnace at about 600°C, the possible saving in terms of reheating energy is estimated at 0.4GJ/t. The scale losses are lower compared to the cold charge option.

C. DANIELI MIDA DCR – DIRECT CASTING AND ROLLING

Direct Casting and Rolling layouts have been designed to take the major energy saving benefits from high speed continuous casting and, at the same time, reduce CapEx and OpEx.

The core of the process is the high speed caster equipped with a Fast Cast Cube (FCC) oscillator and Power Mould (see Figure 2), so as to be able to cast at very high speed then quickly hot charge the rolling mill at a temperature in excess of ~850-950°C, having the possibility of additional heating when necessary through an inductive heater. To minimise radiation losses the roller tables to the mill are insulated. The majority of losses are due to the radiative thermal effect and they are heavily affected by the time needed to cut the billet and to take it from the cutting area to the induction heater. This process permits energy savings up to 1GJ/t.

The induction heater allows close control of billet temperature because the power is set according to the actual thermal load of the individual billets, hence contributing to additional energy saving. Moreover, it has limited emissions (electrical power supply) compared to the other furnace types. Additionally, its compact design contributes to lower investment cost, future maintenance and the length of the production line.

As an example, at the same total productivity, a three-strand caster operating at 5.0m/min saves up to 0.15GJ/t comparison to a five strand caster operating at 3.0m/min.

Danieli MIDA DCR technology is proposed for production exceeding 500,000t/y, with one or more casting strands, with or without the installation of a billet welder for endless rolling, and with the latest induction heater technology.  

DANIELI MIDA ECR ENDLESS CASTING AND ROLLING

An example Danieli MIDA ECR plant is shown in Figure 3 [5]. The single-strand process eliminates the need for billet cutting, which, along with eliminating multiple head and tail crops on the final product, maximises product yield and guarantees stable conditions in the rolling process over several hours. This allows tight control of product physical and dimensional tolerances, and dramatically improved the run-light opportunities. Rebar production at 5% continuous run-light has been reported.

Over the years, fine-tuning of the operation and technological improvement has progressed, with casting speeds increasing up to 8m/min. The high casting speed helps keep the thermal charge in the billet and compensates for the thermal losses during the transfer to the rolling mill, such that today’s mills operate practically without induction heating.

As a result, billet reheating energy is reduced by 50% when compared to the best conventional reheat furnace hot charge, and drops to zero in ECR mode. Table 1 shows there are no reheat emissions in this option while Figure 4 compares energy requirements for the four options A, B, C and D, described earlier.
THE ECR SUCCESS STORY
The ECR process began in the late 1990s at the ABS Luna plant (Italy), following extensive research on high speed casting and endless rolling. The first industrial application at Sidenor Sovel (Greece) started in 2005 where one of six existing casting strands was upgraded to high speed casting by installing the Power Mould and the FCC oscillators.

Later, Danieli approached Commercial Metal Company with an endless design concept that eventually led to the construction of a mill in Arizona, CMC Steel Arizona. The plant started in 2009. Since then Danieli has commissioned nine more ECR plants in North America, North Africa, the Far East and MENA regions.

Plant No. 11 at Nucor Steel Sedalia (NSSED) started recently. With a rated capacity of 380,000 short t/y for #4 to #11 rebars (12.7 to 35.8mm) in straight and spooled bars, and featuring the latest energy saving and environmentally friendly melting, casting and rolling processes. This plant also includes the Danieli ECS® scrap preheating system which continuously charges hot scrap into a 40t side-charge AC EAF, which is followed by a ladle treatment furnace. The core of the endless casting-rolling section is a single-strand, high speed continuous casting machine connected to a 16-stand, ultra-compact rolling mill. Finishing facilities consist of Danieli-patented, Direct Rolling and Bundling (DRB) system and K-Spool technologies.

A second ECR for Nucor in Frostproof, Florida is under construction together with a twin ECR plant in China equipped with one co-rolling line to produce 700,000t/y of ribbed wire rod and a second line to produce 700,000t/y of rebars. A second twin ECR is planned to startup in China in 2021, so within the next few years, twenty Danieli MIDA ECRs will be in operation worldwide.

The advanced automation and innovative digital solutions fully integrated and optimised into the MIDA ecosystem, not only to supports the operators in decision-making with an impressive flow of information but also replaces them in the most unsafe operations and dusty places.

DANIELI MIDA DIRECT CASTING AND ROLLING
The Danieli MIDA DCR design capitalises on the best available technologies, where melting, casting and rolling are carried out in one continuous and uninterrupted production process, from scrap to finished product, and...
which can guarantee CapEx savings and outstanding OpEx results by conserving energy and improving yield and final product quality.

Direct charging layouts also take great advantage of high speed casting, introducing the possibility of reducing reheating energy consumption by up to 0.15GJ/t, compared with a conventional speed casters.

In 2010, Sidenor Sovel in Greece was the first plant to take full advantage of direct casting and rolling, increasing the plant's production capacity by 300,000t/y to a total of 1,200,000t/y. Strand 0 had been previously upgraded to high speed casting by installing the Fast Cast Cube and Power Mould technologies for ECR configuration to produce special quality 140mm rebar in bars and coils, from 8 to 20mm diameter.

After optimising production, the new target was to conserve energy in the production chain, particularly for reheating furnaces. In 2014, a bypass roller table was added in the route to the old mill and a new set of induction heaters was installed at the entrance of the old mill, disconnecting it from the gas reheating furnace (see Figure 5). The new configuration and a different setup in the caster have contributed to an energy saving up to 0.1GJ/t. Since 2014, the plant has operated in 100% direct-charge mode, with zero reheating furnace gas emissions.

In addition to high speed casting, the Danieli Q-Heat induction heating technology has proven to be a key factor in the efficient operation of direct casting and rolling.

**Q-HEAT – INDUCTION HEATING**

Based on the extensive experience in endless and hot charging, and the know-how in converter units, Danieli Automation has developed an advanced induction heating system, Q-HEAT (see Figure 6).

The system perfectly fits the Danieli Automation 3Q concept – Quality, Quantity, Quickness – and is designed according the MIDA philosophy of reducing OpEx costs. Electrical efficiency is one of the most important drivers in the system design. The induction heater includes a converter cabinet with a Voltage Source Inverter based on the most modern Insulated Gate Bipolar Transistors technology (IGBT). Thanks to the AC/DC converter characteristics, the power factor is greater than 0.95 in any working condition.

This high power factor makes it possible to reduce losses on the upstream distribution equipment and cables due to a lower reactive current. The power coils are specifically designed by Danieli Automation, with particular care in the selection of the materials (eg, premium grade copper and high quality refractory), allowing for a high electrical efficiency, best quality and long life. Particular attention is paid to design low power-loss electrical connections between the equipment (converters, resonating capacitor...}

<table>
<thead>
<tr>
<th></th>
<th>Conventional production route through reheating furnace</th>
<th>DANIELI MIDA casting and rolling process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nox [g/t]</td>
<td>7-12</td>
<td>none</td>
</tr>
<tr>
<td>Sox [g/t]</td>
<td>7-12</td>
<td>none</td>
</tr>
<tr>
<td>CO [g/t]</td>
<td>5-10</td>
<td>none</td>
</tr>
</tbody>
</table>

Table 1 Emissions from reheating

Fig 5 Sovel Almyros layout of caster and rolling mill

---

**Fig 4** Energy use and savings with various process routes
banks and heating coils); special coaxial cables and water-cooled bus duct are used.

This focus on electrical efficiency immediately translates into a low OpEx cost.

Other drivers in the design process are the flexibility, modularity and high availability of the system. It is important to highlight that each individual coil is controlled independently by an individual power generator. The independent power control of each inverter and related coil allows for precise control of the temperature rise during reheating. Also, it allows for optimum setting of the discharge temperature, and for adjusting the head-to-tail temperature variations, thereby optimising material temperature equalisation. Figure 7 compares measured billet entry and exit temperatures.

The system was designed to have the possibility of excluding individual coils without stopping the process. In this case the automation control system will automatically rearrange the power distribution on the other active power inductors. The power equipment incorporates a simple and quick maintenance concept. The modules are designed for quick-change operations and the system is ready to be connected in remote teleservice, if required.

The control structure is based on a powerful, state-of-the-art Danieli Automation Process Automation Controller (DA-PAC) that communicates with a power part controller (modulator board), with Ethercat, and with any field bus with Level 1 and Level 2 plant automation. The system receives the temperature samples from the pyrometers installed on field (Level 1), temperature set from Level 2 and automatically calculates and sets the right amount of power on each coil to achieve the target temperature.

THE FENG HSIN EXPERIENCE
Established in 1969, Feng Hsin, based in Taiwan, today produces over 1.8Mt/y of commercial steel grades in sections, bars, wire rod, and large rounds in coils. Having expanded its market position over the years, Feng Hsin now competes successfully with the major steel suppliers in the region.

Danieli’s cooperation with Feng Hsin started in 1983 with the first caster installation, followed by several other plants in subsequent years. The most important of these was the 425,000t/y ‘Super Flexible Rolling Mill’ for bars and sections installed in 1993. Other projects there have included new roughing stands, a rolling mill for small profiles and LF, VD and caster for meltshop No. 1.

In addition, in 2015 Feng Hsin contracted Danieli to supply a new, high speed bar mill, confirming the continuing decades of successful partnership with the Taiwanese long-products producer.

This latest high speed bar mill shown in Figure 8 produces...
Level 2 automation and all the electric systems for the whole plant.

Today the operating practice is to process more than 99% of rolling operations by direct charging, and with a 98% yield, this rebar mill is a competitive, energy saving and high quality operation.

Another important factor contributing to energy and cost savings is the possibility of rolling low alloy rebar thanks to the inline Ultra-Fine-Grain (UFG) process, which allows a significant reduction in the expense of alloying elements, such as niobium and vanadium.

With a dedicated and optimised chemistry, it is possible to minimise and even avoid the use of some alloying elements in low carbon-manganese steels through low surface temperature rolling. In this way the low mechanical properties that result from poor chemistry are balanced by the microstructure obtained via the UFG process, which promotes a very fine microstructure (1-5 μm; see Figure 9) and enhanced final mechanical properties. A typical mill temperature profile is shown in Figure 10.

Grain size-controlled grades can ensure high stress ratios.
and ductility, thanks to a dedicated, controlled temperature rolling strategy (hardness difference between surface and core should be less than HV 40). Higher ductility than with a conventional QTQ quenching process are possible.

The UFG process is the most advantageous way to produce structural steel grades in bars and coils due to the reduction in microalloy additions, so avoiding the martensitic microstructure phase during rolling.

The average transformation cost savings resulting from the absence of vanadium micro-alloy addition have been evaluated at ~17US$/t.

Considering the overall CapEx and OpEx index, the Feng Hsin MIDA DCR mill has become a very competitive, world benchmark operation.

CONCLUSIONS
Since the end of the last century, Danieli has understood and accepted the challenge posed by new trends in the energy-saving economy and arrived at a new vision, which eventually led to the innovative MIDA concept, an extremely compact mini-mill producing rebar in bundles and coils, with a high-speed caster directly connected to the rolling mill.

With zero emissions for billet reheating the Danieli Energy Saving Compact Minimill MIDA, featuring Direct or Endless Casting and Rolling technologies, are now a consolidated technology – the best available in the market – to fulfill the demands of high efficiency and energy saving in the production of rebar bundles, spooled coils and wire rod. 

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Experimental and numerical study of gas jet cooling at high Reynolds number*

* is an important dimensionless quantity in fluid mechanics used to help predict flow patterns in different fluid situations

In order to achieve the necessary strip cooling rates for today’s high strength steels, values as high as 110-120°C/sec are needed to obtain the necessary temperature drop, typically between 800 and 250°C. This requires removal of about 350KW/m² per side of the strip. For galvanised strip which cannot be quenched by water for surface quality reasons, specific gases are used. This requires a very high heat transfer coefficient in the range of 650 to 750KW/m² depending on the temperature of the gas used. Laboratory experiments with air and computer modelling are described.

**D**ue to the demand for lean composition multi-phase high strength steels by the automotive industry, the cooling rate after annealing has increased dramatically over recent years. In the 1980s, the standard cooling rate was in the range of 50°C/sec for 1mm strip thickness. This was to promote the precipitation of carbon during overageing in order to make DDQ (deep drawing quality) grades, a material with excellent formability. Today, values as high as 110-120°C/sec are demanded for a temperature drop typically between 800 and 250°C. This requires removal of, on average, 330 to 360KW/m² per side of the strip.

Such high cooling rates are quite easy with water thanks to boiling as well as its high specific heat capacity. However, this method is not possible for hot dip galvanised steels due to the fact that the surface cannot be oxidised before dipping to ensure good coating adhesion and surface quality. Therefore, the present technology consists of blowing a non-oxidising gas at high velocity on the hot surface located very close to the nozzle. The exit velocity from the nozzles typically ranges from 100 to 150m/sec and nozzle to strip distance is as low as 40mm.

Cooling by gas convection is well known and in order to reach 350KW/m² the average heat transfer coefficient has to be in the range of 650 to 750KW/m² depending on the blown gas temperature.

The available published work for high heat transfer coefficients is, however, limited. The Martin correlations [1] are well known and used for both slot and round nozzles, but they have some limitations for round nozzles:

- The correlations are valid for a Reynolds number below 100,000.
- Distance to diameter ratio (Z/D) between 2 and 12. It is however worth noting that Attalla [2] shows that the coefficient is maximum for a ratio of 6.
- The correlations from Martin have been identified by mass transport analysis and so are not real heat transfer measurements.
- The case of a high temperature difference (higher than 400°C) between the strip and the gas is not considered.

The work described here had the objective to determine the heat transfer coefficient as well as the Nusselt number, used in fluid dynamics to determine the ratio of convective to conductive heat transfer at a boundary in a fluid, that is required for Reynolds numbers up to 150,000 with an array of round nozzles. The investigated range of Z/D is from 5 to 6 which corresponds typically to an industrial design with 14mm nozzle diameter blowing on a strip at 70-85mm distance.

**ADDRESSING THE PROBLEM**

The methodology followed consists of a laboratory experimental approach and use of computational fluid dynamics (CFD). This is because it is impossible to characterize and measure in the laboratory the industrial situation where the cooling section may be as large as 20m long for a strip width up to 2m. An example of a typical industrial blowing plenum is shown in Figure 1. The laboratory experimental design as described below, has the objective to measure the average heat transfer coefficient in a “cell” and compare the results with published data as well as numerical results done on a similar design

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von Karman Institute and John Cockerill Industry Metals
(see Figure 2). The laboratory experiments are, of course, done using air and the prediction for a hydrogen and nitrogen mixture is done by using the Nusselt approach and the physical properties of the gas used. The numerical approach was conducted to compare the computed heat transfer coefficient and then estimate the reliability of the results obtained with the classical published model [1]. This is key because CFD is the only way to estimate the industrial heat transfer on a full strip width when hydrogen is used as well as high strip temperature both of which are impossible to test at laboratory scale.

**MEASUREMENT OF HEAT TRANSFER**

Measurements of the heat transfer coefficient were performed using quantitative infrared thermography. The investigation was focused on an ARN configuration (array of round nozzles and equilateral pitch), consisting of one central jet surrounded by six additional as shown in Figure 3. The arrangement has the following geometrical characteristics:

- Diameter of the nozzle: \( D = 14 \text{mm} \)
- Stand-off distance: \( Z = 50, 70 \) and \( 85 \text{mm} \)
- Nozzle spacing: \( W = 70 \text{mm} \).

The flat plate on which the jets are impacting is uniformly heated by the Joule effect. The heat input is constant and fixed at 4,300W/m\(^2\). The strip temperature is measured by an infrared camera. The thermograms are analysed by an in-house DIP (Direct Inlet Probe) program allowing the determination of the heat transfer coefficient knowing the imposed heat flux and the incoming jet temperature measured inside the plenum.

The strip emissivity was checked by comparing the strip temperature measured either with thermocouples or an infrared camera. Tests were performed for Reynolds numbers ranging from 40,000 to 160,000, based on the mass flow passing through the tubes. The test bench with the different elements is illustrated in Figure 4.

Two different configurations were tested: A standard configuration perpendicular to the target with a normalised standoff distance \( Z/D \) varying from 3.5 to 6. The second configuration consists of a \( 10^\circ \) inclined plate keeping a constant \( Z/D \) for the different jets in which the nozzle to strip distance is constant for all nozzles. The two configurations are shown in Figure 5 with a typical heat transfer map obtained for a Reynolds number of approximately 80,000. Corresponding temperature profiles along the centreline are also plotted. In the perpendicular configuration, a symmetric map of heat transfer coefficient was obtained.

The mean heat transfer value is extracted from a hexagon geometry centred on the geometrical impact point of the central jet, as illustrated in Figure 3. Values of mean heat transfer coefficient were obtained as function of the...
Reynolds number and used as quantitative data to compare with correlations and CFD results.

In the second configuration (right part of Figure 5), all the seven different jets produce similar maximum heat transfer coefficients, but we observe asymmetry in the shape of the heat transfer map, linked to the inclination. The effect of the plate inclination can clearly be seen on the imprint of the central jet. In addition, it turns out that the heat transfer is better on the inclined strip than on the classical case.

When blowing at high Reynolds numbers, the heat transfer coefficients are very high and therefore the temperature differences between the incoming jet and the heated plate decrease significantly, especially at the impact point. To guarantee enough accuracy for the determination of the heat transfer coefficient, it was verified that the minimum \( \Delta T \) was always higher than 10°C. Repeat tests have shown an estimated error of +/- 5%.

**THE CFD APPROACH**

CFD simulations were performed in parallel to the laboratory experiments. The geometry of the computation domain follows exactly the geometry of the experimental set-up. Figures 6 and 7 show the computation domain of the two configurations with the flow structure of the central jet illustrated by coloured path lines. The inclination of the plate has an effect on the flow structure.

The mesh used in the CFD approach combines hexahedral elements and tetrahedral elements with a fine refinement close to the walls. The design has a total of 4,480,000 cells with a cell wall distance as low as 10\( \mu \)m on the area where the heat transfer is computed.

Simulations have been performed for different Reynolds numbers by changing the inlet mass flow of each tube and for different stand-off distance between the outlet of the tubes and the heated plate. Mean heat transfer coefficient on the same hexagon defined from the laboratory investigation was extracted from the numerical simulation.

The flow structure of Figure 6 has been validated using simple wool visualisation as illustrated in Figure 8. The piece of wool is indicated by the white arrow.

**RESULTS AND DISCUSSION**

A detailed presentation of the results is inappropriate for this article, but in summary they are:

- The measured heat transfer is higher for an inclined plate than a perpendicular one. This can explained by the totally different structure of the flow as shown in Figures 6 and 7.
- For all cases the exponent in the power correlation is much lower than that predicted by Martin: 0.35 to 0.5 versus 0.68 for Martin.
- Measurement and CFD give similar values in case of Reynolds numbers of 80,000 and 70mm distance.
The dependence with distance obtained by CFD follows the same rule as that obtained by Martin (exponent ~0.45) but the Martin values are lower than the CFD ones.

Figure 9 shows the different results obtained for a stand-off distance of 70mm (Z/D=5). Martin's correlation applied to this ARN configuration gives the lowest value of heat transfer coefficient and the exponent in the correlation is equal to 0.66. The different experimental points show that at low Reynolds number, higher heat transfer coefficients have been measured compared to Martin's correlation while, when the Reynolds number is above 80,000, the heat transfer coefficient is getting closer to the values of the correlation but lower than those computed by CFD. The exponent in the experimental data correlation is reduced to a value of 0.41. Heat transfer coefficients obtained by CFD simulations are higher than Martin's correlation with an exponent of 0.57 for the inclined configuration and of or 0.69 for the perpendicular configuration. However when the distance is increased to 85mm the CFD results show that the inclined configuration gives better heat transfer (see Figure 10).

Therefore, great care should be taken when using CFD for the design of a system working at Reynolds number above 80,000. CFD simulation with a classical steady state approach and a K-Omega turbulence model over-predicts the heat transfer coefficient.

LOOKING AT THE INDUSTRIAL SITUATION
From the previous results, it turns out that the target heat transfer coefficient in the range of 650 to 750W/m²/°K cannot be reached with air or with pure nitrogen. It is however, well known that a mixture of H₂ and N₂ significantly improves the heat transfer thanks to the high conductivity of hydrogen. Therefore, the prediction of the capable cooling rate can be obtained by applying the correction based on the Nusselt approach:

\[ h(\text{HNX}) = h(N_2) \times \frac{\text{Conductivity(HNX)}}{\text{Conductivity(N}2\text{))}} \]

Figure 11 show the benefit that can be obtained by HNX with a mixture containing 20%H₂; the heat transfer coefficients are multiplied by about a factor of 2. Therefore, using for example the results of Figure 9, the heat transfer coefficient of 700W/m²/°K can be obtained with a Reynolds of 100000 and only with 20%H₂.

THE REYNOLDS QUESTION FOR HIGH STRIP TEMPERATURE
The literature as well as our experiments investigated the effect of Reynolds on the heat transfer coefficient. This dimensionless number is well known and describes the ratio of...
CFD simulations using two different strip temperatures have been conducted with fixed mass flow and for both air and a mixture of N\textsubscript{2} and 30\%\textsubscript{H\textsubscript{2}}. It turns out that the computed heat transfer coefficient is about 10\% higher for a low strip temperature than a hot one and this is true for both air and HNX mixtures.

CONCLUSIONS
The heat transfer coefficients of an array of round nozzles blowing on a surface perpendicular to and with a 10\(^{\circ}\) angle have been investigated experimentally and with steady state CFD for a Reynolds number range as high as 150,000. The nozzle to strip distance ratio varied from 5 to 6. The situation of a cold gas cooling a hot surface was also addressed. The results can be summarised as follows:

- The laboratory heat transfer coefficients using air and CFD results are quite similar for Reynolds numbers below 100,000. Over that value, CFD gives significantly higher values than those measured. The exact cause needs to be investigated.
- This difference can currently not be explained, but cannot be attributed to errors in the measuring technique. Some unsteady simulations with less turbulence need to be made to clarify this.
- The CFD results show that the heat transfer coefficient is about 10\% higher when the steel is at 350\(^{\circ}\)C compared to 650\(^{\circ}\)C.
- The target value of 650 to 750W/m\(^{2}\)/K is not reached when using air or nitrogen but can be with a mixture of N\textsubscript{2}+20\%\textsubscript{H\textsubscript{2}} with nozzle to strip distance ratio of 5 to 6.
- Great care should be taken when using CFD for the design of a system working at Reynolds number above 80,000 as it over-predicts the heat transfer coefficient.
- The desired heat transfer coefficient of 750KW/m\(^{2}\) was not achieved with the experimental setup.

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(Global Head of Communication)
Automatic tagging, tying and tracking of long products

_AIC provides automation solutions to automatically tie and tag bundles of profiles, sections, rebars and wire rod coils. The main benefits are increased operator safety, better plant productivity, cost reduction and reduced errors in product identification and tracking._

**Authors:** Antonio Ambra and Andrei Molchan

_AIC North America Corp. and Automazioni Industriali Capitanio srl._

Tagging of semi-finished or finished products is a requirement at steel plants and requested by customers for material tracking, and to aid product quality control. Manual tagging of bundles of bars in mill stocking areas with pre-printed labels as illustrated in Figure 1 is the traditional method but it has a high error rate. Typically 5% of bundles are not tagged or tagged with the wrong tag, which equates to an average of 30 bundles per shift at the average plant. Such an operation tends to occur in the stocking areas of mills, so there are hazards associated with heavy equipment, roller tables and overhead cranes.

**AUTOMATIC TAGGING**

An automatic tagging system is one which is part of the plant tracking system, is situated within the process line (ie, before the stocking area) and which minimises or eliminates human activities in hazardous or hot areas and contributes to an overall upskilling of personnel at the plant. Our data indicates that automatic tagging reduces the number of bundles not tagged to 0.2%, a significant reduction.

![Fig 1 Manual tagging of pre-printed labels](image1)

![Fig 2 Typical automatic tagging island layout](image2)
The Automatic Tagging island has been designed by AIC as a solution. A typical layout adjacent to a process line is illustrated in Figure 2, and Figure 3 illustrates its component parts, namely:
- Anthropomorphic 6-axis robot
- 3D vision system installed on the robot wrist
- Set of printers for the identifying tags
- Machine to create and distribute the tag supports
- Welding machine
- Electrical panel that commands the complete island and includes the relevant HMI’s for diagnostics and alarms

The island has a small footprint and is completely contained in an industrial container properly designed and engineered to include all the machinery in an air conditioned and protected area.

Anthropomorphic robots are nowadays well proven devices and are used in several different applications in the steel industry. There are ‘foundry’ models available that are specifically designed to work in harsh environments and that are versatile in use.

The 3D vision system adopted by AIC is a double camera system specifically engineered for harsh environments and which does not require a laser beam (see Figure 4). With this system, there is no need to scan the product in order to create the cloud of 3D points but a simple acquisition, like a picture is enough in order to recreate the 3D profile of the product. The sensor used is a matrix sensor and not used for profilometry. In this way, no special movements of the robot are needed to finalise the material scan, and only positioning the bundle on the conveyor is required.

Measurements have been taken on a rebar rolling mill where the robotic tagging application is running at 180tph with a cycle time of 8 seconds where the bundle...
FINISHING PROCESSES

Fig 6 Tag and metallic support

Fig 7 Metallic support machine

Fig 8 Stud dispenser

Fig 9 Stud application machine
is stopped on a conveyor for tagging. 1.2 seconds is the timing dedicated to a 3D scan of the bundle.

The 3D vision system can automatically detect the type of product without any specific setting thanks to advanced analysis algorithms. Figure 5 shows two examples of 3D vision system output. The colour codes are shown in Table 1.

This ‘photo’ appears on operators control panel and it is also saved on a network data storage device, together with all other images used during the image processing procedure. This data is used for algorithm remote assistance, for quality control, and are accessible for remote control/operations.

**Printers and tagging**

The printers installed in the tagging island are of the thermal transfer type. There is an external tag charger to handle up to 10,000 tags, able to cover one full production week at site without the need of replacing the tags and ribbon. The tags can be applied using a metallic support (see Figures 6 and 7) using a specifically engineered machine or they can be applied with a stud as illustrated in Figures 8 and 9.

The metallic support is used to keep the printed tag away from the head of the bundle when material temperatures are still high. Studs are used when the application is done on relatively cold material where it is not a problem to keep the printed tag to the minimum distance between the head of the bundle and the tag itself. For both these purposes, there is a welding machine installed. Figures 10 and 11 show examples on steel bundles.

The robotic tagging application has many additional options that increase the flexibility of the system to meet customers’ needs:

- The robot can be used for counting the pieces inside a bundle.
- Other locations where it is possible to install the tagging robot are:
  - At billet caster exit
  - The finishing area of a wire rod mill. Here, thanks to the 3D vision system and advanced image recognition algorithms, the robot chooses the most suitable position for the tag and applies it to the wire rod coil by using a metallic support created directly in the robotic island, without the use of a welding system. The clip is applied to the selected rod with a dedicated movement of the robotic wrist. Figure 12 shows 3D schematics of coil position identification, while Figure 13 shows a tagged coil.
  - Trolleys and guides can be used in order to tag coils coming from several production lines.
TYING MACHINES

Tying machines are designed to automatically tie bundles, sub-bundles and packs with steel wire. They are positioned downstream of the product formation area and have the shortest tying cycle available on the market (6.8 seconds for complete double turn tying); Figure 14 illustrates different designs. The main parts of the machines are:

- **Main body with guides** A welded steel structure is mounted on combination bearings that run on horizontal guides. For cleaning and maintenance the machine can be retracted to keep the rolling table clear. Inductive sensors and a gear driven motor provide online or offline positioning. Moreover, two vertical guides are also installed in the part where the tying head moves driven by a hydraulic cylinder, another inductive sensor is provided for device positioning in stand-by and a photocell for tying.

- **Tying head** This is positioned in a solid, welded, annealed and machined steel structure where all the cables and pipes run through ducts. It comprises a wire feeding device, a knot forming device and the guide clamps. The wire feeding device is made of two steel plates with a characteristic profile shape assembled in order to set up a conical channel between them where the wire will be loaded and trailed. The knot forming device is a revolving tool steel head driven by a hydraulic motor with jaws and wire cutting knives built inside. The guide clamps are arc shaped plates of wear resistant steel that supports a set of rolls that drive the wire around the bundle. An appropriate number of movable rolls is provided for the feeding of the tie wire and his recover during the tying process.

- **Bundle retaining jaws** The jaws are installed in the welded steel structure pivoted on a common base. They are driven by two hydraulic cylinders that allow them to close in order to keep and hold the bundle in the correct shape during the tying process.

- **Valve bench** The valve bench drives the hydraulic devices of the machine and is installed at the back of the machine.

The machine is installed after the material bundle forming station. Once the product stops in the tying position on the roller table, the automation system sends a signal of ‘BUNDLE READY’. A pair of jaws holds the product while the wire is tightened with one or two turns (selectable via control panel) and twisted. The roller table will move the product to the next position, and the cycle will be repeated when all the required ties are made. At the end of the tying process bundle is transferred to the discharging area for its tagging and final storage. An example is shown in Figure 15.
CONCLUSIONS

Automatic tagging reduces the number of bundles not tagged to 0.2% compared to 5% for manual systems. Measurements have been taken on a rebar rolling mill where the robotic tagging application is running at 180t/h with a cycle time of 8 seconds where the bundle is stopped on conveyor for tagging. 1.2 seconds is the timing dedicated to 3D scan of the bundle.

The tying machines described above have been designed in order to have the following advantages: the shortest tying cycle available on the market (6.8 seconds for a complete double turn tying); smooth integration in rolling mill layouts due to optimised dimensions and complete supply of mechanical, media, electrical and automation systems; heavy and sturdy machines minimise maintenance cost and reduce downtimes and production loss. All the above allows simplified routine operations and increases efficiency of the plant.

The material tracking system directly connected with automatic tagging systems assures the tagging of each single product with the right identification data and improving traceability of finished products. Data connection to database makes the traceability complete following the product in all the production operations until the end user.

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Improved coil side trim quality control with Unilux Edge Tech

Edge trimming of steel coils during processing is standard practice, however, unless edge quality can be continuously monitored, the time delay between a deterioration and rectification can result in excessive amounts of rework or even scrap. Unilux have developed Edge Tech, a camera-based system which continuously scans both strip edges and provides immediate display of edge quality to operators. Extensive data and performance analysis algorithms help provide numerical data on trimming knife settings, trimming performance and coil quality.

BACKGROUND

Steel coils are side trimmed with rotary knives as part of the manufacturing process: to remove edge defects, to minimise edge defects during subsequent processing, and to produce the ordered coil width. Cut edge quality is affected by a number of variables such as knife gap, knife sharpness, steel coil grade and thickness. Figure 1 shows a coil with good edge quality. Occasionally, poor edges as illustrated in Figures 2 and 3 can be produced, resulting in downgrading, re-trimming or scrap, resulting in considerable cost, particularly if the effects are not quickly noticed and remedied. Some edge defects such as burns can frequently damage rollers and cause surface-quality problems.

In traditional trimming lines, up to three or four coils could be affected before the problem was noticed and corrections attempted, but of course unless the technical relationships between edge cut quality and cause are well understood these corrections may not be adequate.

EDGE TECH

To address these issues Unilux, a company that specialises in industry vision technology, has developed the Edge Tech remote inspection system using a combination of lighting, cameras and powerful software that allows detailed inspection of the trimmed edge on both edges of the strip immediately after the trimming operation is performed. Strip edge quality, rotary side trimmer knife wear and knife cracks can be seen in real time on a display corrected and then checked to ensure that the problems have been eliminated. It has applications in standard coil processing lines, pickling lines and galvanising lines.

Because edge quality and knife wear can be seen in real time the necessary plant adjustments can be made long before the coil is complete, eliminating the need for additional processes like re-trim, downgrading or complete coil rejection. Figure 4 shows a coil with sawtooth detected as it is just beginning.

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Unilux USA

Fig 1 Coil with a good edge quality

Fig 2 Example of poor quality on a steel coil

Fig 3 Coil with sawtooth defect
In order for these benefits to be realised, operators must be empowered with the following information while trimming:
1. Immediate knowledge of a defect (see Figure 4)
2. Ability to identify the defect
3. The proper corrective action to address the problem
4. Immediate feedback that the corrective action resolved the problem
5. A record of the problem so that further corrective actions can be assessed to ensure the issue does not happen again

SYSTEM FEATURES
1. Immediate viewing of the coil edge right after knife trim operation on both edges of the strip
2. Optimal cut-to-break ratio defined for benchmarking
3. Coil edge quality captured in real time
4. Examination of the entire circumference of trim knives
5. Adjustable knife position
6. Inspect edge detail in slow motion with pause, play and back-up capabilities
7. 8x magnification of the strip edge
8. On-screen measurement of anomalies for problem assessment
9. High definition image capture and display
10. On-demand image storage
11. Machine learning features provide faster response to defects identified as being critical

BENEFITS
Data from Edge Tech installations is indicating the following benefits:
1. Inspect proactively and document production data
2. The short time scale to identify problems, make adjustments and verify the success of corrections is possible after less than 100m of coil at full production speed
3. Higher yield and productivity resulting from less on-site downgrading. Re-trimming and scrap plus better inspection has also reduced the number of coils rejected by customers
4. The return on investment can be measured in numbers of coils instead of months. Because there is more confidence in coil edge quality there is less need to inspect coils further down the process line and to schedule jobs more efficiently
5. The large amount of data produced is an ideal source of information for all sorts of process improvements, using cause and effect analysis and statistical process control
6. Improved operator safety by limiting interaction with the line to only when necessary
7. Retrofittable to existing lines

The Edge Tech system is mounted within 1m downstream.
of the knives, as shown in Figures 5a and 5b. Images of the edges provided immediately after the cut not only enable operators to assess the condition of the edge, but also of the knife and its effect on the coil trim. By knowing the knife wear, operators can either change knives early or extend trimming use, instead of just using a designated trim distance for knife changes. This becomes even more critical with new knives designed to work with the growing number of high strength steels.

At any time during the processing of each coil, operators can look at a monitor in the safety of the control room or pulpit to see if trimming is within tolerance and see if the knife requires adjustment. A visual display of the knife’s cut-to-break ratio can alert them when the ratio is out of range, enabling them to make an adjustment or just fine-tune the settings for the best results. The inspection system then allows them to verify immediately that they’ve made the correct adjustment. Before Edge Tech and its knife-circumference monitoring capability,

**DEFECT IDENTIFICATION**

Figure 6 shows some typical screen displays with defects highlighted. Figure 7 shows knife crack, how it appears on the Edge Tech monitor and where it can be seen in a processed, rewound coil. Detecting the knife crack as soon as possible allows the operator to schedule knife replacement to minimise coil re-trimming.

**DATA PROCESSING**

The Level 2 computer connection collects data on all corrective actions taken by operators during coil inspection, and they become part of the records used for documenting quality for customers and internal data systems used to measure productivity and production costs. As operators make adjustments to trimming knives, the mill’s computer system can automatically capture images and permanently store all the information in data packs related to the coil.

The Level 2 connection also includes a documented error log for each sensor, further allowing operations managers to search for information, such as the location of a defective edge in a coil. Process engineers can also reference the data when developing solutions to specific problems.

With the automatic image collection and storage capability, image-storage capacity is limited only by the storage space provided by the mill or coil processing facility. Further, IT administrators can set up internal systems to store those images and other production data in folders that will make them more accessible to personnel who need the information.

The net result of the Level 2 computer tie-in is that Edge Tech now becomes an integral part of a coil management system instead of an add-on. This automated data capture can become more critical for pinpointing actions taken because of metallurgical differences in each coil.
ACCOUNTING FOR METALLURGICAL VARIATIONS
Even though a number of coils being processed consecutively may have the same composition specification, a number of factors in the rolling process can change their properties in highly significant ways. Changes in strength or temperature can change metallurgical properties which, in turn, can affect how the trim knives interact with the coil. While the differences in metallurgy may be imperceptible to plant operators, their effects on trim quality can be picked up by the Edge Tech cameras, and operators can make the necessary adjustments.

The enhanced view of coil edges allows for more involvement from plant metallurgists to isolate and monitor the effects of mill operations on coil quality. This in-production perspective is then used to set protocols for critical mechanical settings and, as a secondary level of response, the effects of changes in upstream processes such as coil heat treatment.

Figures 8 and 9 illustrate the differences in cut/fracture surface and edge profile of hard and soft steel sheet. It should be noticed that the harder steel has less knife penetration but more tearing and end distortion. The ratio of these values is called the Cut-To-Break ratio and is based on the material strength (MPa) and thickness:

- 1021/22 stainless steel (and many of the higher strength low alloy steels): typically 10% cut, 90% break (10:90), but some may require as little as 5% cut with 95% fracture
- 1005/06 mild steel = 25% cut, 75% break (25:75)
- 1001/03 aluminium = 50% cut, 50% break (50:50)
- Some mills may also choose to set a minimum and maximum for cut-to-break if they run a consistent hardness, eg: 20:80 minimum to 25:75 maximum

Edge Tech allows better control of this ratio by numerical algorithms versus ‘trial and error’. The operator is able to determine that the proper cut-to-break ratio is being met, and should any variation outside of an acceptable range occur, the operator is alerted in real time and immediate action can be taken. Incorrect depth of the cut can lead to burrs at the bottom of the strip which in turn can damage the surface.
of work rolls, resulting in surface defects on future coils.

THE EFFECTS OF KNIFE VARIABLES
Knife manufacturers have long-established guidelines for the identification of common defects that can occur. Mills without edge inspection typically replace knives based on time in use or linear product runs such as every ‘X’ number of hours or in ‘n’ x 100km based on a ‘guess’ that it is time to make a change.

In-line inspection systems have established a new standard for a detailed view of the strip edge while in production which means new ways to increase the life of knives and better control of preventative maintenance of knife changes. With visual feedback from Edge Tech, they can make an educated decision and extend the knife life by up to 1.5 times or more, but have the ability to replace them sooner if they start to deteriorate.

The effect of variables that can impact knife life, such as different grades of steel, upstream variables, or metallurgical properties can be monitored directly. A real-time visual indication of these variables can be used to determine and document the ideal knife setting based on the historical data for each grade of steel. A mill could also use this information to build a history of knife quality, such as performance and life from different manufacturers.

Lastly, a mill can use the documented data to optimise run time based on the history of each type of knife on different materials. Teams can identify at what point in the run time would an adjustment in knife settings extend life or determine the true effects of adjustments commonly made at the end of the knife life to finish a run, such as increasing lap or downward pressure causing damage to work rolls.

CONCLUSIONS
Inspection systems eliminate trial-and-error. Operators respond to a quality concern by correcting the issue immediately, before any further damage is done. In this example, technology empowers the operator to no longer guess if corrective action will solve the issue but to know it is correct, and document their experience for repeatability.

Further consistency is achieved via the ability to establish ideal settings for repeatability of each coil and job. Operators follow a set process, react immediately based on established protocol and confirm results in real time. Mills can now build a library of observed cause and preferred reaction, which can lead to further enhancements such as the automation of knife settings by the mill based on real-world scenarios as experienced by mill personnel on mill equipment.

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Process control on android system ‘goMobile’

John Cockerill has developed ‘goMobile’, a WiFi-based android system to use mobile phones and tablets to acquire data, store, display and operate equipment to enable operators to work more efficiently from any location. Mobile devices can access control systems through customised gateways.

Connectivity allows people to interact in real time in a plant environment – both with each other and with machines, so as to enjoy similar sensory experiences to those who experience it locally, near the equipment. In any industry, the typical control room or pulpit is equipped with computers and monitors to check, link with, and control machines and processes. Currently most industrial processes are controlled by well-established Supervisory Control and Data Acquisition (SCADA) systems. These are systems of software and hardware elements that allow engineers/operators to:
- Control industrial processes locally or at remote locations
- Monitor, gather, and process real-time data
- Directly interact with devices such as sensors, valves, pumps, motors, and more through human machine interface (HMI) software
- Record events into a log file

There is nothing fundamentally wrong with this approach other than it confines operators and managers to those locations. This may reduce their capability to multi-task, summarise data from many processes at one place or to make faster decisions.

Mobile phones and tablets have significantly advanced in their processing capabilities in recent years, and this trend will continue. John Cockerill has, therefore, developed ‘goMobile’ an intranet-based system to use these gadgets to acquire data, store, display and operate equipment to enable operators to work more efficiently. PLCs and controllers can be accessed through customised gateways/connectors and data is gathered in databases. The functions of goMobile are designed in customisable modules for easy single and/or cluster implementation.

GOMOBILE MODULES

**HMI-goMobile** This is the human machine interface (HMI) on android devices to provide a complete overview with all the functions as available to operators in control cubicles, ie, SCADA, but wirelessly.

This approach gives accessibility to operators to know what is happening in the system at any given point in time, online, and most importantly, when the person is not near the control station or near SCADA systems. An example of a mobile screen display is shown in Figure 1.

The key advantage of such mobile availability is that operators and managers can virtually access it from anywhere through the web browser on their smart phones, tablets or desktop computer.

**Control Desk-goMobile** This is the concept in which a virtual representation of a physical control desk is created where operators can ‘see and operate’ the plant and equipment remotely through an android device.

For any process to be operated locally, there are control desks at the actual site. These desks have various elements to operate the system manually under the supervision of an operator either in process or maintenance mode. These control desk elements are wired to one of the nearest remote.
intermediate through signals that are connected to the main PLC. With the introduction of WiFi we can make such control
desk elements mobile and flexible enough to configure.

*Figure 2* illustrates a virtual control panel, showing control
buttons and a camera view of the equipment. Any end user
with valid login credentials can access and operate any
physical process remotely. This gives operational mobility
and flexibility of operator ‘desks’.

**Camera-goMobile** This is the online IP based camera
module where an operator can view the process line
from anywhere. Even with mobile connectivity, situations
can arise at the plant when an operator may not have
a clear view of the system. This may have both process
and safety implications, so to overcome this ‘loss of sight’
of a machine/process line, a camera system has been
introduced.

The use of cameras for observing equipment and for
virtual meetings is well embedded in industry. With
Camera-goMobile these features are now available ‘on
the move’. As well as operational benefits, operator and
plant safety can be improved as operators can ‘see’ the
current equipment status prior to making process changes.

A camera with a good microphone is an added benefit.

*Figure 2* shows a camera example.

**Parameters-goMobile** In this feature all the necessary
live process parameters are linked directly from the
controller and can be remotely seen on mobile devices.
This enables operators to see the live parameters from any
equipment online for faster, on-the-spot decision making.

**Trends-goMobile** This module provides graphical
analysis, archives trend functions, helps to visualise signals
and compare plant performance, therefore empowering
engineers towards faster process and error analysis and
thus decision making. Any process engineer interested in
knowing the equipment/machine/system performance
on an archive or real-time basis can view the details on a
mobile device. An example is shown in *Figure 3*.

By using this feature one can analyse multiple parameters
together on mobile devices. goMobile modules can
access the electrical parameters of all connected power
equipment such as motor control centers (MCCs), drives,
actuators, solenoid valves and sensors. This application
can also view online parameters from these devices and
live trends can be plotted to optimise energy consumption
and check for possible losses in those devices, for example,
parameters from power incomer, drives and blowers.

Intelligent MCCs can be viewed with process parameters
to check performances of individual equipment as well as
process as a whole. Energy savings and optimisation goals
can also be obtained.
**DailyLog-goMobile** This is the ‘report manager’ module to give online and assorted management for any reports/ incidents information, and also draw attention to intended personnel. Reporting can become one of the major features when it comes to addressing an issue, fault finding, brainstorming or reporting detailed analysis of any incident such as equipment failure. A log book will help people in the field and on maintenance jobs to report the events instantly to intended persons.

The module can take pictures such as of equipment failures, plant cleanliness, add categorisation logs, say in terms of severity, create a ticket and email to the concerned personnel (see Figure 4).

**CONCLUSIONS**

The concept presented in this article is aimed at making any process digital, not only from an operational point of view, but also, and very importantly, from administrative and safety points of view. With safety being the top priority, particularly for remote operation of a plant, John Cockerill Automation is currently finalising an internet-based platform that will allow access to the described modules anywhere and anytime, truly empowering operators and managers by giving them access to all critical data and allowing them to visualise parameters and get reports or logs from wherever they are. The components presented here above are currently used by steel companies on a trial basis, as illustrated in Figure 5 which shows their use in a coil processing plant in Europe.

The obvious key advantages of such mobile availability is that operators and managers alike can virtually access it from anywhere through the web browser on their smart phones, tablets or desktop computer.

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High temperature baking-resistant Cr-free passivation coating for aluminised steel

Inorganic CrIII passivation or organic Cr-free passivation/TOC are commonly applied on aluminised steel coils to further enhance corrosion resistance. However, the poor machinability of inorganic CrIII passivation and poor baking resistance of organic Cr-free passivation/TOC coating limit their application. Henkel has, therefore, developed a new inorganic Cr-free passivation coating, BONDERITE M-PA 1344, based on sol-gel chemistry, providing both outstanding high temperature baking resistance as well as good corrosion resistance and machinability.

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Aluminised steel coil is steel coil which is hot dipped in aluminium, 90%/silicon, 10% alloy. Aluminised steel has good heat resistance and heat reflection and so is widely used in applications such as automotive muffler, heat exchangers in residential furnaces, commercial rooftop air conditioning units, fireplaces, kitchen ranges, water heaters, barbecue burners, ovens, baking pans, and so on.

Only South Korean and Japanese steel mills produced aluminised steel coil in Asia before around 2015, with Chinese steel companies starting to develop and produce it in recent years.

The aluminised alloy layer can provide better corrosion protection than a Zn galvanised layer, however, pinhole defects often appear on the surface and result in poor corrosion protection of the Fe substrate. Additionally, if the Al/Si alloy layer is too thick it can decrease the stamping/bending properties of the steel sheets.

To enhance the corrosion resistance of aluminised steel sheets inorganic CrIII passivation and organic Cr-free passivation/TOC are normally applied, however, the poor machinability of inorganic CrIII passivation and the poor baking resistance of organic Cr-free passivation/TOC coating limit their applicability in some situations.

BONDERITE M-PA 1344

To overcome these disadvantages Henkel has developed a new inorganic Cr-free passivation coating, BONDERITE M-PA 1344, based on sol-gel chemistry.

The sol-gel process helps provide an intact protection film on the metal substrate which provides excellent both high temperature baking resistance and corrosion protection. This process is essentially based on the hydrolysis and condensation reactions of alkoxysilanes (such as teramethoxysilane TMOS), metal alkoxides
(M(OR)n), alkoxides of titanium, and zirconium, and organo-silanes.

COATING PREPARATION AND PERFORMANCE

In order to get a passivation film with good properties, we recommend a coating weight of BONDERITE M-PA 1344 in the range of 0.2-0.6g/m². If the coating weight is too high, the inorganic film may perform better as regards corrosion resistance and alkaline resistance, but it may not dry sufficiently easily and may crack due to inner stress of the film. On the other hand, if the coating weight is lower than 0.2g/m², the film may not perform well in corrosion resistance, although it could have good baking or stacking resistance. Thus, the coating weight should be well controlled during application of this passivation product to the metal substrate.

Figure 1 shows a schematic of BONDERITE M-PA 1344 coating. The main binders of inorganic passivation are alkoxysilanes, silica and silicate, which can form a dense protective film thanks to the dehydration-condensation reaction in the silanol. Meanwhile, the dehydration-condensation reaction between the silanol and the hydroxyl groups on the surface of metal improve the adhesion between passivation film and substrate. Furthermore, zirconium- and titanium-based complexing agents and corrosion inhibitor were selected to further improve the crosslinking density of the film. In addition, de-foaming agents, levelling agents and wax additives were introduced to prepare a defect-free, anti-friction film.

A whole range of tests have been performed to demonstrate the effectiveness of BONDERITE M-PA 1344 coating.

120H neutral salt spray test (NSST) results under ASTM B117 conditions (35°C, 5% NaCl, pH 6.5-7.2) are shown in Figure 2. The table on the right shows the the corrosion area percentage on the aluminised substrate with 0.4g/m² passivation coating as a function of the salt spray time. No corrosion was observed up to 96h, and even after 120h NSST, only around 1% corrosion area was found, which indicates good anti-corrosion performance. This is due to the introduction of the nano-sized silica, which not only worked as a chemical cross-linker which can improve the crosslink of resultant film, but also worked as a physical filler which can seal any micro-hole in the film.

The most end applications of aluminised coil are in high temperature environments, like automotive muffler, ovens and baking pans. Hence, high temperature baking resistance is a key requirement for passivation on aluminised coil. BONDERITE M-PA 1344 shows excellent high temperature baking resistance and has been certificated by many key customers in China.

To evaluate the baking resistance of the film, we performed a number of tests in an aggressive testing environment. The coating was applied on aluminised substrate (coating weight is around 0.4g/m²) and cured at PMT (peak metal temperature) 80°C. After seven days aging, the panels were baked at 250, 300 and 350°C separately for 6h. Figure 3 shows that all the resultant colour variation ∆E before and after baking are less than 3. It is believed that due to its inorganic composition, this product provides superior high temperature baking resistant properties compared to competitor product, which would be obviously yellowed and degraded under these high temperatures, colour variation ∆E is 6.78 after baking at 250°C for 6h. The sample photos and exact data are shown in Figure 3.

The machinability of BONDERITE M-PA 1344 was evaluated by a friction coefficient tester ALTEK 9505. The original friction coefficient of aluminised steel is larger than 0.25. And the friction coefficient would be decreased...
into a range of 0.1-0.2 based on different substrate surface roughnesses. An additional benefit of Bonderite M-PA 1344 is that it is compatible with rust-preventative oil, thus a post-treatment spray with oil can further improve corrosion protection and machinability of the substrate.

We have also studied other properties of BONDERITE M-PA 1344 coating. The results of various tests are shown in Figure 4.

- 6a Paintability (liquid paint (Zhenghua Coating), DFT 40-60 μ, cross-hatch, 3M 600 tape peeling test, no coating peel-off)
- 6b Paintability (powder paint (Akzo Nobel EA05BH), DFT 40-60 μ, cross-hatch, use 3M 600 tape peeling test, no coating peel-off)
- 6c Surface energy (38# dyne pen, no shrink of ink in 2 seconds)
- 6d Moisture resistance (120H stacking test, 49°C, RH98%)
- 6e Alkali resistance (dip coated panels into 20% NaOH, 25°C for 30s, and then test colour change ΔE)
- 6f Solvent resistance (rub test of coated panels with 80% EtOH for 20 times, and test the colour change ΔE)

The results demonstrated that this passivation coating performed well, not only in its high temperature baking resistance, but also in corrosion protection, moisture resistance, chemical resistance and good adhesion of top coatings.

Normally, the coating thickness of Cr-free siloxane/silicate passivation coating is monitored by XRF using the Si element line. However, as the Si element in Si/Al alloy layer strongly interferes with the results the alternative K element line is preferred. IR can also be used to monitor the passivation coating weight, but only without rust-prevention oil.

**CONCLUSIONS**

BONDERITE M-PA 1344 is a novel inorganic chrome-free passivation coating which provides a homogenous and dense film to protect aluminised steel sheet substrate from corrosion. This newly developed anti-corrosive coating shows outstanding high temperature baking resistance as well as good corrosion resistance and machinability. Additionally, it also provides good paintability and can be used with rust-preventative oil.

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PRODUCTS & SERVICES

**Equipment supplied:** High-Speed Wire Rod wire compactor, Bar Bundling Machine, H-beam tying machine, Strapping Machine, Spray Marking Machine, Decoil & Recoil, Compactor Spare Parts.

**Spare Parts:** Universal Joint Shaft, Gear Coupling Gear Coupling, Hot Rolling Mandrel, Cold Rolling Mandrel, Shear Blades, Sliding Plate.

**Remanufacturing:** Rolling Mill Housing Frame - Laser Cladding Remanufacturing, Laser Remanufacturing of drive Shaft, Stepped Plate.


**General Contractor Service:** Full Life Cycle Management and Service.
In our highly competitive global industry, steel producers continue to face challenges that are increasingly difficult to overcome. With every economic cycle and each crisis, the operating environment becomes more demanding.

We have firm roots in the IJmuiden integrated steel plant, which stands as a benchmark for many aspects of iron and steel production. Since the creation of Danieli Corus in 1977, we have carried out operational assistance and consultancy projects for steelmakers around the world.

**We embrace your challenges as our own.** The experience, expertise and creativity of our teams are at your disposal. We are determined to contribute to your performance, in good times and in bad.

Some highlights of our operational assistance and consultancy services are:

- Blast furnace process optimization and assessment against e.g. raw material and demand scenarios
- Shutdown services for good burden preservation and secure restart, with or without salamander tapping
- Secure, safe and quick restart after prepared or unprepared shutdown using oxyfuel lance technology – if required
- Plant assessment, campaign extension and campaign management consultancy
- Cost optimization using comprehensive flowsheeting model for the entire process chain

We reach out to offer our support. You **can rely on us.**