CRM GROUP

ANNUAL REPORT 2019

CLOSING THE VALUE CHAIN OF METALS

D/2019/0124/1

Contents

Foreword

The CRM not-for-profit organisation, part of CRM Group, provides technological R&D-innovation in the fields of metal and steel production processes, product development and a wide range of metal applications, using a truly and genuine holistic product-process-application approach and focussing on industrial implementation of its developments.

CRM is supported by more than 45 industrial members, ranging from international steel groups (ArcelorMittal and Tata Steel), raw material suppliers, non-ferrous metal producers, OEM's, metal transforming companies, to members from the aeronautical, defence, energy and recycling sectors. In 2019 CRM delivered also various services to more than 285 non-member customers.

At CRM Group, health and safety remains the first priority. In 2019, a vast "VCA"-safety training plan was executed and a comprehensive action plan aiming at a health and safety management system (VCA and/or ISO-45001) has been defined and already partially implemented. Furthermore specific toolbox meetings based on critical safety events and visual tools were rolled-out, which will contribute to the achievement of an embedded shop floor safety culture.

In 2019 a specific focus was put on environmental matters. Single-use plastics were banned from offices and meeting rooms and an energy transformation plan was defined in order to decrease CRM's environmental footprint and energy consumption. CRM received the 'Belgian Circular Economy Award' for the development of an innovative Aluminium recycling process.

To fulfil its mission, the CRM Group is organised around 5 research units that are backed-up by a world class material characterisation laboratory:

1 | Metal production, energy and recycling: covering raw material processing, melting & refining, by-products treatment & valorisation

2 | Metal processing and metallurgy: including casting & solidification, rolling & thermal treatment, product metallurgy, process control & measurement

3 | Advanced & smart surface solutions: ranging from functional coatings and smart surfaces including printed electronics on steel to surfaces for renewable energy applications

4 | Innovative designs and assembly solutions in the fields of Civil engineering, Construction, Assembly & Testing and Hybrid manufacturing

5 | Industrial solutions: embracing in-house Engineering, finishing & metallic coating processes, organic coating and sandwich panels products & continuous annealing and/or coating pilot lines

Furthermore, during the last 5 years CRM has structured transversal and cross-sectorial activities within the organisation to tackle key societal challenges efficiently and to transform main new technological needs into industrial reality for our customers and stakeholders. Throughout 2019 CRM developed numerous innovative value-creating technologies in the following fields:

1 | circular economy

2 | energy shift

3 | hybrid manufacturing

4 | digitalisation

5 | construction

New prestigious associated members have joined CRM since and the overall budget devoted to these transversal fields increased continuously.

As an independent collective research centre, CRM has continued to benefit from financial support from the Belgian and Regional authorities, as well as from the European Commission. This support has been devoted particularly to our technological platforms.

At a European or regional level, CRM has continued to invest in partnerships with others research organisations. Numerous research projects, financed by the European Commission, have led to many opportunities of co-operation with specialised European partners. CRM is today active in more than 30 European projects.

The present annual report highlights the main achievements of the year 2019.

Paul PERDANG
President CRM

Joeri NEUTJENS
General Manager CRM

On April 15, 2020

Active Members of CRM

ARCELORMITTAL S.A. ..... G.D. Luxembourg
TATA STEEL EUROPE LIMITED ..... United Kingdom

An updated list of the subsidiaries considered as Active Members is available on the internet site of CRM.

The main affiliated companies are :

ARCELORMITTAL Group :
ARCELORMITTAL BELGIUM N.V. ..... Belgium
ARCELORMITTAL BELVAL & DIFFERDANGE S.A. ..... G.D. Luxembourg
ARCELORMITTAL FRANCE S.A. ..... France
ARCELORMITTAL LUXEMBOURG S.A. ..... G.D. Luxembourg
ARCELORMITTAL SCHIFFLANGE S.A. ..... G.D. Luxembourg
INDUSTEEL BELGIUM S.A. ..... Belgium

TATA STEEL Group :
SEGAL S.A. ..... Belgium
TATA STEEL IJMUIDEN BV ..... The Netherlands
TATA STEEL NEDERLAND TECHNOLOGY BV ..... The Netherlands
TATA STEEL UK LIMITED ..... United Kingdom

Associated Members of CRM

AIR LIQUIDE INDUSTRIES BELGIUM S.A. ..... Belgium
AMEPA GmbH ..... Germany
AMETEK LAND ..... United Kingdom
APERAM Stainless France S.A.S. ..... France
ARCEO Engineering ..... Belgium
AURUBIS BELGIUM N.V. ..... Belgium
BEKAERT TECHNOLOGY CENTER S.A. ..... Belgium
BIOCARBON INDUSTRIES Sàrl ..... G.D. Luxembourg
CARMEUSE S.A. ..... Belgium
CBR S.A. ..... Belgium
COMET TRAITEMENTS S.A. ..... Belgium

DE LEUZE S.A.	Belgium
DREVER INTERNATIONAL S.A.	Belgium
DUFERCO S.A.	Switzerland
EMG Automation GmbH	Germany
ENSIVAL-MORET BELGIUM S.A.	Belgium
E.S.W. A.G.	Austria
EVERZINC S.A.	Belgium
FABRICOM INDUSTRIE SUD S.A. (ENGIE SOLUTIONS)	Belgium
FONDERIES MARICHAL, KETIN & Cie S.A.	Belgium
HERAEUS ELECTRO-NITE INTERNATIONAL N.V.	Belgium
HERSTAL S.A.	Belgium
INDUCTOTHERM S.A.	Belgium
INSTITUT BELGE DE LA SOUDURE asbl	Belgium
INTERNATIONAL MANGANESE INSTITUTE	France
JOHN COCKERILL S.A.	Belgium
LHOIST Recherche & Développement S.A.	Belgium
LIBERTY LIEGE-DUDELANGE S.A.	Belgium
MAGOTTEAUX INTERNATIONAL S.A.	Belgium
NLMK CLABECQ S.A. – Plates	Belgium
NLMK LA LOUVIÈRE S.A. – Strips	Belgium
ORBIX SOLUTIONS S.P.R.L	Belgium
PAUL WURTH S.A.	G.D. Luxembourg
PHARMA TECHNOLOGY S.A.	Belgium
PRAYON S.A.	Belgium
PRIMETALS TECHNOLOGIES AUSTRIA GmbH	Austria
RECYDEL S.A.	Belgium
RESA S.A.	Belgium
R-TECH S.A.	Belgium
SAFRAN AERO BOOSTERS S.A.	Belgium
SARCLAD Ltd	United Kingdom
THY-MARCINELLE S.A.	Belgium
TI GROUP AUTOMOTIVE SYSTEMS S.A.	Belgium
TMT sarl	G.D. Luxembourg
WESTINGHOUSE ELECTRIC BELGIUM S.A.	Belgium

On April 15, 2020

Board of Directors of CRM

President

Paul PERDANG, General Manager, Head of capex investments, Group Finance, ARCELORMITTAL

Vice-Presidents

Pinakin CHAUBAL, Vice President & Chief Technology Officer, ARCELORMITTAL
Vincent RITMAN, Director R&D Europe, TATA STEEL

Directors

Ivan AERTS, Adviseur, Centrale der Metaalbewerkers van België
Phil CLEMENTS, CTO, TATA STEEL UK
Philippe COIGNE, Directeur Général, Groupement de la Sidérurgie (GSV)
Renaud COLLETTE, Conseiller, SPF Economie, PME, Classes moyennes et Energie
Mark DENYS, Director Technical Strip Products, TATA STEEL Mainland Europe
Joao FELIX DA SILVA, Directeur Général, John Cockerill
André FOUARGE, CTO Finishing, ArcelorMittal Europe - Flat Products
Leo KESTENS, Professor, Universiteit Gent
Greg LUDKOVSKY, Vice-President of Global R&D, ARCELORMITTAL
Anne MERTENS, Associate professor, ULiège
Stéphane PIRON, Secrétaire Fédéral – SETCa Fédéral
Nicoleta POPA, Head of Construction applications, Infrastructures and Long Products, ARCELORMITTAL Global R&D
Mario SINNAEVE, R&D - Quality Control Manager, S.A. des Fonderies Marichal, Ketin & Cie
Gabriel SMAL, Secrétaire Général, ACV-CSC METEA
Thinus VAN DEN BERG, CFO, ARCELORMITTAL Global R&D
Sven VANDEPUTTE, Managing Director, OCAS N.V.
Manfred VAN VLIERBERGHE, CEO ARCELORMITTAL Belgium
Simone VOOIJS, Director Technical Tata Steel Downstream Operations, TATA STEEL

Observers

Rose DETAILLE, Inspectrice Générale, Département de la Recherche et du développement technologique, Service Public de Wallonie
Yvon MASYN, Adviseur, Vlaams Agentschap Innoveren en Ondernemen
Joeri NEUTJENS, Directeur Général, CRM

Auditor

Dominique JACQUET-HERMANS

Iron and Steel Committee of CRM

Members

ARCELORMITTAL
Jean-Paul ALLEMAND
Michel BABBIT
Marc DI FANT
Eric HESS
Pedro PRENDES
Mayte RODRIGUEZ
Sven VANDEPUTTE

TATA STEEL
Mark DENYS
Loes JANSEN
Wim MOONEN
Hans VAN DER WEIJDE

CRM
Joeri NEUTJENS
Griet LANNOO
Eric SILBERBERG

Quality Management

The CRM is accredited ISO 17025 for calibration & testing and certified ISO 9001:2015 for all its activities.

QUALITY MANAGEMENT SYSTEM CERTIFICATE

ISO 9001 : 2015

BQA we hereby declares that the management system of CRM Group

CRM GROUP

located at Avenue du Bois Saint-Jean, 21 B27 – Quartier Polytech 4 - 4000 Liège and Rue du Bois Saint Jean, 8 – 4102 Ougrée and Rue du Chêne, 200 – 4000 Liège and Technologipark 903a – 9052 Zwijnaarde – Belgium,
for **CRM asbl** *– Centre for Research in MetalSurgy asbl, and by*
Allée de l'Innovation, 1 B 37 – Quartier Polytech 3 – 4000 Liège and Rue Sompré, 1 – 4400 Flemalle – Belgium
for **ACACS scrl** *– Advanced Coatings and Construction Solutions scrl,*
has been examined on 2018-05-28 and found in conformity with the ISO 9001, edition 2015, standard for the following application field:

Industrial research and associatid activities such as testing, calibration and expertise.

This certificate has been issued by BQA in according to its quality manual concerning the certification of systems, and after concluding the contract of certification N° CER_SJ_QMS2015_31-05-2018_558_F under which the company accepts a regular control of its management system.

Certificate N° BQA_QMS_C_2006338
Valid until 2021-05-27

BELAC 9/9-QMS

D. SIMOENS
Director

BQA

Organisme belge d'Accréditation
Belgische Accreditatieinstelling
Belgische Akkreditierungsstelle
Belgian Accreditation Body

BELAC

Signatory to EA, ILAC and IAF Multilateral Agreements

Accreditation Certificate No. 267-CAL

In compliance with the provisions of the Royal Decree of 31 January 2006 setting up BELAC, the Accreditation Board hereby declares, that the calibration laboratory

CRM
CENTRE DE RECHERCHES METALLURGIQUES ASBL
Domaine Universitaire du Sart Tilman (p59) Avenue du Bois Saint-Jean, 21
4000 LIEGE - Belgium

has the competence to perform the calibrations as described in the annex which is an integral part of the present certificate, in accordance with the requirements of the standard EN ISO/IEC 17025:2005. The present accreditation is the subject of regular surveillance in order to confirm the compliance with the accreditation conditions.

The Chair of the Accreditation Board BELAC,

Issue date : **2017-12-07**
Validity date : **2022-10-27**

Nicole MEURÉE-VANLAETHEM

Original version of this certificate is in French.

.be

Organisme belge d'Accréditation
Belgische Accreditatieinstelling
Belgische Akkreditierungsstelle
Belgian Accreditation Body

BELAC

Signatory to EA, ILAC and IAF Multilateral Agreements

Accreditation Certificate No. 267-TEST

In compliance with the provisions of the Royal Decree of 31 January 2006 setting up BELAC, the Accreditation Board hereby declares, that the test laboratory

CRM
CENTRE DE RECHERCHES METALLURGIQUES ASBL
Domaine Universitaire du Sart Tilman (p59) Avenue du Bois Saint-Jean, 21
4000 LIEGE - Belgium

has the competence to perform the tests as described in the annex which is an integral part of the present certificate, in accordance with the requirements of the standard EN ISO/IEC 17025:2005. The present accreditation is the subject of regular surveillance in order to confirm the compliance with the accreditation conditions.

The Chair of the Accreditation Board BELAC,

Issue date : **2017-12-07**
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Nicole MEURÉE-VANLAETHEM

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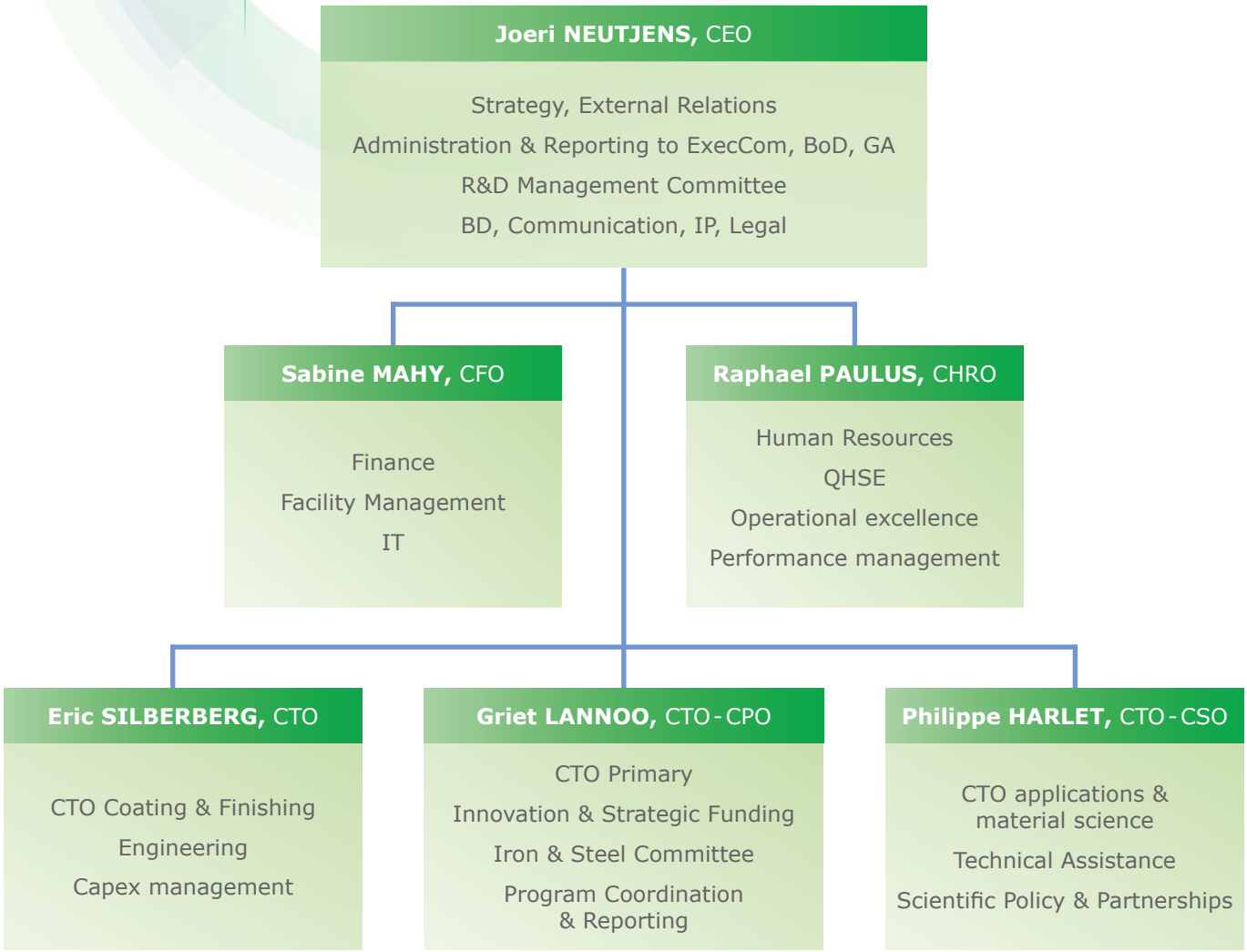
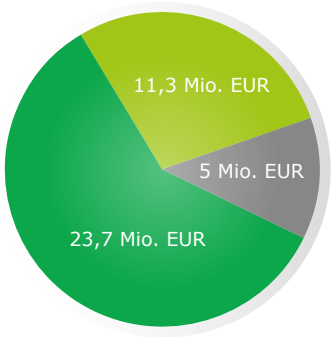
Leadership Team



CEO: Chief Executive Officer
CPO: Chef Program Officer
CFO: Chief Financial Officer
CSO: Chief Scientific Officer
CHRO: Chief Human Resource Officer
CTO: Chief Technical Officer

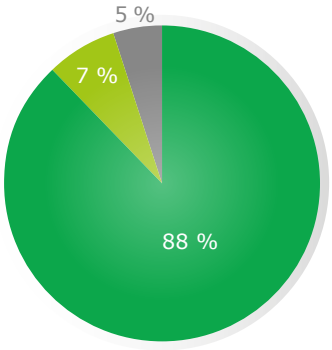
Key figures

Income by program



- Steel Collective
- Steel effective collaboration
- Other

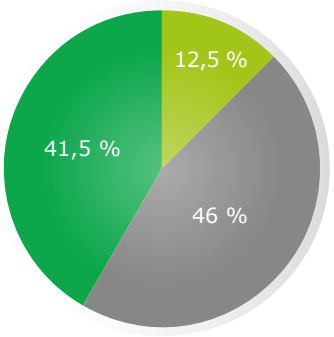
Income by financing



- Industrial collaboration
- National & Regional Grants
- European Grants

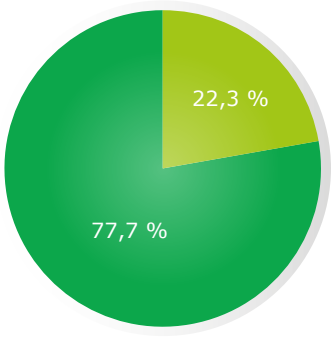
Total Income (CRM asbl): 40 Mio. EUR

CRM Group: 265 people



- Researchers
- Technicians
- Administrative staff

Gender balance



- Female
- Male

Report on R&D activities

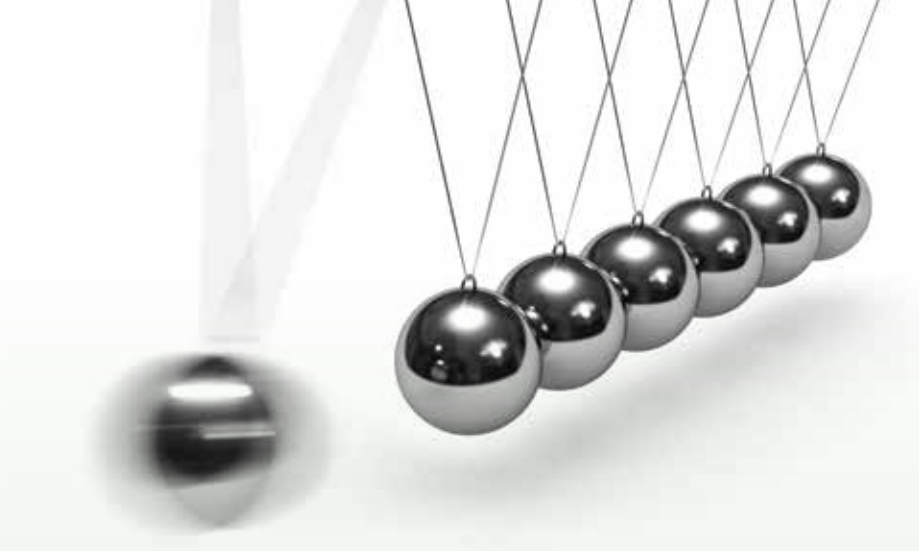
As independent, collective non-for-profit research organisation CRM Group offers since decades innovative technological solutions for the processing & manufacturing of metallic materials, from primary and secondary raw materials up to finished products, with a truly holistic process-product approach. CRM Group's outstanding expertise, competence and world-class equipment are at the service of Belgium and international member and non-member companies to provide them solutions responding to their industrial problems.

CRM Group continues, with its longstanding expertise, to offer to the metallurgical sector its innovative and industrial solutions for process, products as well as applications. In parallel it has further developed its vision for the future by developing know how, acquiring world-class equipment and bringing together transversal teams in order to be able to further address emerging industrial and societal challenges related to climate warming up, environment and the digital and energy transformation. Those technological platforms are now fully operational with multi-disciplinary teams and unique pilot simulators to provide cross-sectorial innovation in sectors from the metallurgical industry over OEM, the energy & construction sector, defence until aeronautics and aerospace on the following transversal topics:

Circular Economy dealing with recycling, closing the loop of metals, turning by-products & end-of-life products into valuable secondary raw materials

Energy transition dealing with low carbon steels, energy transition, reduction of pollutant emissions, renewable energy and the valorisation of waste into energy

Advanced Manufacturing on the integration of innovative and conventional manufacturing technologies for production, repair and coating of complex 3D parts



Digitalisation focussing on intelligent integrated manufacturing and the development of smart products.

This 2019 activity report highlights in particular the further development - in terms of extraordinary pilot equipment and activities - of those strategic technological platforms at CRM and presents furthermore a selection of noteworthy activities and results obtained at lab, pilot and industrial scale for the development of new processes, products & solutions and technical support.

CRM gratefully thanks its industrial and research partners as well as the funding authorities for their collaboration and support.

Circular economy and materials preservation

Resource efficiency as main driver towards a sustainable metals industry

The circular economy is now a well adopted economic and industrial system in which resources are kept in use for as long as possible, the maximum value from them is extracted whilst in use and then products and materials are recovered and regenerated at the end of each service life. With its broad and unique set of competences and tools within its technological platform 'Circular Economy' CRM supports the metals industry to make the circular economy happen.

When striving towards a better use of resources and recycling of (by-)products, one has often to deal with materials and by-products under the form of wet sludge, fines, powder,… not compatible yet with the production process. The pre-processing and pre-conditioning of those materials is thus crucial to ensure their efficient recycling and therefore CRM has completed its already wide and unique set of tools for intensive mixing, pelletizing and agglomeration with a **stiff vacuum extruder**. This technology, already well established for clay processing, has recently proven its relevance in the metallurgical field thanks to its ability to process wet fines with less binder enabling the production of cold-bonded agglomerates with superior mechanical strength.

Stiff vacuum extruder

Remarkable recent achievements related to cold-processing of various types of materials in a wide range of applications are cited below:

- To ensure its competitiveness and sustainability, the European steel industry must use low quality ores and increase the use of recycled materials at the sinter plant. Solutions need to improve sinter quality and productivity at lowest possible environmental impact and energy consumption. CRM is coordinating the SinByOSe RFCS funded project aiming to develop and optimise pre-processing and selective granulation strategies allowing tackling these challenges.

- Tata Steel is developing a breakthrough ironmaking technology designed to produce low-CO_2 steel from fine iron ores and coal. When recycling zinc-bearing residues into the HIsarna process, its off-gas dust can be enriched to a high zinc concentration, enabling its economical valorisation as a secondary feedstock for zinc production. But this requires an adequate pre-processing of the zinc-bearing residues before injection, in order to avoid too much dust carry-over while allowing quick zinc evaporation and iron assimilation into the HIsarna liquid hot metal. In close collaboration with Tata Steel and with the financial support of EIT Raw Materials, metallurgical residues such as **BOF sludge and EAF dust** have been prepared into **micro-granules and/or briquettes** with satisfactory size and strength. The optimal recipes for micro-granulation and briquetting have been identified and validated by pilot scale trials. Some of the produced briquettes have been dropped into a 40l induction furnace with a hot heel of **HIsarna** liquid hot metal and slag. A high-temperature thermal camera and an on-line particle measurement device were used to closely monitor the iron dissolution and zinc evaporation phenomena.

Micro granules and briquettes prepared from BOF sludge and EAF dust for remelting in HIsarna furnace

Study of the dissolution of briquettes in the HIsarna process

- Another illustration of the CRM capabilities in the field of pre-processing waste and by-products deals with **the recovery and the treatment of various metallic wastes to be re-used in foundries** in collaboration with Revatech-Suez. The materials to be recycled are in powder form or

Agglomerates produced with the same mixture of MnO_2 and spent active carbon using 3 different technologies, for recycling into a Cupola furnace

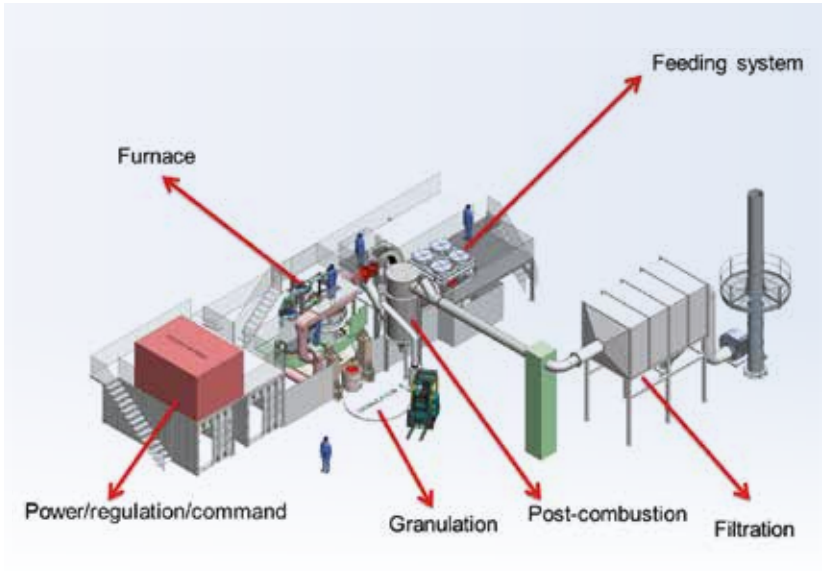
highly dispersed and thus need once more a pre-treatment to ease the handling and increase the metal yield in the foundries. Based on the large variety of by-products available for recycling, a specific mixture of several by-products has been made to define the optimal recipe for each foundry matching its chemical and/or process specifications. Consequently for each recipe the adequate preconditioning method is defined to produce the appropriate agglomerate for efficient feeding into the respective industrial foundry furnaces.

- The capacity of CRM to contribute to the **industrialisation of our solutions** in the field of circular economy has been well demonstrated in the EIT Raw Materials Go-4-0 project where CRM has **successfully produced 5 tons of briquettes with by-products from industrial partners** (Eramet - Norway, ArcelorMittal France, Comet Traitements - Belgium). CRM firstly developed the ideal formula combining a dozen of by-products with an organic binder before starting the production of 5 tons of briquettes that were subsequently used as alternative ore in the pilot submerged arc furnace (SAF) of Eramet Ideas for the production of Ferromanganese and Silicomanganese. For the production of the pilot lot of briquettes, challenges related to the hazardousness of the materials, the large volumes and associated logistics and the necessity to

Production of 5 tons of briquettes with by-products from industrial partners to be used as alternative ores

ensure the required quality and homogeneity of the briquettes had to be overcome. The pilot campaign was successful and set the path for an industrial implementation of the valorisation process.

De-Zincing of scrap in the thermal pre-conditioning furnace



Next to cold pre-processing, a **hot pre-conditioning** step might be mandatory for successful recycling of waste and by-products to purify or remove unwanted elements. Also in this field CRM continued to support its industrial members in their ambitions related to zero waste, resource efficiency and carbon reduction ambitions, as can be illustrated by :

- the use of the thermal preconditioning furnace in order to quantify the Zn content of the scrap fed as a secondary resource into the HISarna process. 50kg zinc coated scrap in various shapes and sizes received from Tata Steel has been treated in the thermal preconditioning furnace at 550°C for about 25 min under vacuum in order to evaporate the Zn. The weight loss of the scrap due to the **de-zincing process** was quantified at 0.6 wt%.
- in the frame of the 'Reverse Metallurgy platform': a **cutting-edge direct current plasma furnace** with a useful capacity of 125l and a power of 500kW allowing the treatment (remelting or fuming) of a wide variety of by-products and complex end-of-life products. This plasma furnace, that will be implemented in a Seveso site, will a.o. be used in collaboration with Hydrometal to test at pilot scale the volatilisation of high value metals present in complex by-products.

Process	EOL melting	Reduction melting	Slag melting	(Fuming)
Products				

Schematic layout of the plasma furnace and its applications

Light Al-packaging re-melting – Rotary tilting furnace – cast Al ingots from recycled Al

An excellent example of CRM's ability to **develop original and innovative recycling and valorisation routes that are industrially viable** is the project on recycling of secondary aluminium waste supported by the Walloon region in the frame of the 'Reverse Metallurgy platform'. The project focusses specifically on the collection, transformation and recycling of different secondary aluminium wastes including very light industrial and domestic packaging and products. This aluminium stream is currently not valorised at all for what concerns neither the value of the contained aluminium metal nor the positive impact of such a recycling on the energy and environmental point of view.

The original and innovative recycling and valorisation route has been developed and patented by CRM and has received the **Belgium Environment and Energy Award in the category Circular Economy**.

The concept includes the pre-processing of the broad panel of collected end-of life aluminium products into briquettes and medium size pieces to be subsequently melted in a tilting rotary furnace before casting and shaping in different ingot sizes. Thanks to this processing route **the waste is transformed into aluminium with a chemical composition, density and organic content well suited to be used in the steel industry and foundries in a first phase**.

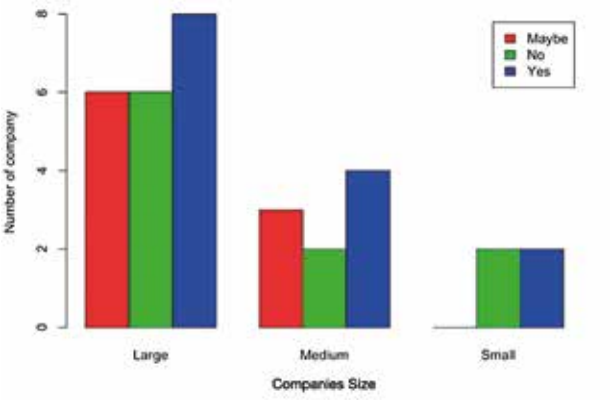
Through a partnership with John Cockerill, a complete pre-design of an industrial plant able to process 20.000 tons of aluminium wastes per year has been realised with the possibility to double the capacity of the plant for a very moderate additional investment. Discussions are in progress with potential stakeholders, industrial partners and regional investment funds to industrially implement the concept in Wallonia.

Another example of the valorisation of secondary aluminium is a maximised used **of recycled aluminium to produce aluminium powders for additive manufacturing** as studied in the 'CheapShape' project within the MANUNET Frame. In 2019, CRM has produced two aluminium alloys, AlSi7Mg and AlSi10Mg, from industrial and domestic aluminium scraps that meet the specifications of additive manufacturing. In partnership with Rina in Italy, the ingots were transformed into powder with a particle size of 20 to 80 µm for 3D printing. This product is currently being tested by our Walloon partner AnyShape to produce parts in additive manufacturing from the secondary aluminium.

Next to extensive research on processes to recover, precondition and recycle secondary material flows, CRM is also focussing on the **potential impact scrap evolution and secondary raw materials provisioning could have on final material properties.**

Through Flemish funded projects SMARTSCRAP and CLEANSCRAP we have mapped the current knowledge and susceptibility in different sectors to the use and procurement of their secondary raw materials. Specifically **for the cast iron production** a combination of on-site analysis combined with lab simulations have shown that the presence of specific elements is detrimental for the microstructure and in-use properties of the final products. Creating the necessary awareness on the risks associated to less-known elements such as Al, Ti, B and Mo and on possible options on how to handle them, provided through calculations, was strongly appreciated by the project User Committee.

Also **for the development of advanced steel grades** there is a huge challenge in the integration of these evolving scrap flows, therefore an extensive literature review has been made on the topic within the RESIDUALS project supported by ArcelorMittal and Tata Steel. It is obvious that the high quality work performed then will need to be complemented with new research work in view of the current societal challenges and recent steel grade developments.



Awareness of foundries to the European Steel Scrap specification

Energy transition

The pathway to a CO_2-neutral industry and renewable energy

Tackling climate and environmental related challenges is urgent and must be a top priority, as also stated in the recent Green Deal published by the new EU Commission. The transformation of our society into a resource-efficient, modern and competitive economy with a drastic reduction of greenhouse gas emissions is imperative. At CRM, the research for new steel production processes consuming less energy and fossil carbon, for ways to capture and sequester or transform the CO_2 produced by industrial processes, and for new sources of green energy with new ways to store it, has thus become a major concern for the safeguard of our planet. A technological platform dedicated to Energy Transition has been set-up within CRM to foster innovation, transversal actions and synergies on these essential topics.

As one of the main energy and carbon-intensive industries, the steel industry obviously requires significant developments and sound re-thinking to deeply cut its CO_2 emissions. Numerous mitigation options can first be developed in modern conventional steel plants and can potentially lead to very significant CO_2 savings on the short and medium-term. On the longer term, to reach near-zero carbon steelmaking in 2050, breakthrough technologies largely based on non-carbon energy vectors (electricity, hydrogen) have to be developed. CRM contributes to structure the efforts of the European industry within two EU-wide initiatives (the LowCarbonFuture and GreenSteel projects) which aim at the generation of consistent roadmaps for **'clean steelmaking'**, outlining further research needs, requirements, boundary conditions and timeline to achieve the 2030 climate and energy targets and the 2050 long-term strategy for a climate neutral Europe.

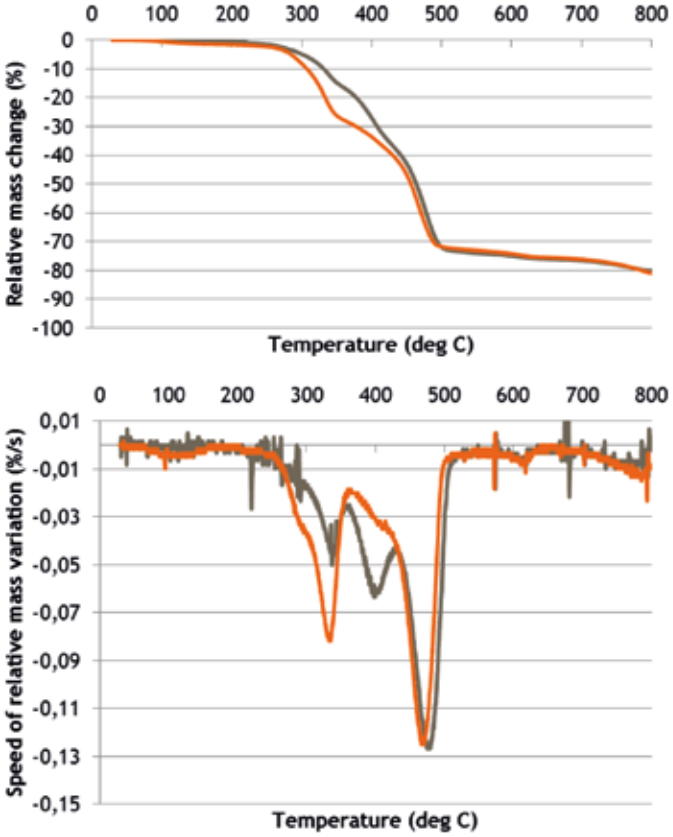
Among the CO_2 mitigation options under development for implementation in conventional steel plants, CRM is first working with its steel members in several projects aiming at **energy savings, energy recovery and re-use in production processes**. On heat recovery and re-use, CRM is also involved with regional partners in a more innovative project aiming at the direct generation of electricity from low-level heat sources (e.g. fumes and off-gases). The GTherm project is carried-out with 2 Belgian

universities (UCLouvain and ULiège) and is now testing a 1m-long heat pipe integrating low-cost Heusler-based thermoelectric modules in industry-like conditions, with promising initial results.

Thermoelectric testing unit (up: internal view, down: installed on an off-gas duct)

In the upstream steel production processes, another very attractive short-term option is to partly **replace fossil carbon by CO_2-neutral carbon** (forestry biomass, spent wood recovered from construction, agricultural residues, etc) **or with societal waste streams** containing significant amount of spent carbon, in the form of paper or cardboard residues, waste plastics, foams, etc. This option is mainly studied at CRM using the set of tools recently integrated at CRM-ETP, including the pyrolysis platform (operated with John-Cockerill), the HUGE fixed-bed facility, the TGA and the fuel analysis equipment. Many of these unique and exceptional tools have been further upgraded in 2019. Beyond their potential to study the pre-reduction of ores, the separation of volatile metals, the activation of carbon (for water or fumes cleaning purposes), the production of syngas, the carbonation of slags and minerals, the testing or regeneration of catalysts, the desulfurisation of mineral products, etc, these upgraded tools were

Pyrolysis platform: New big bag unloading station with conveyor (up), new filter (down)

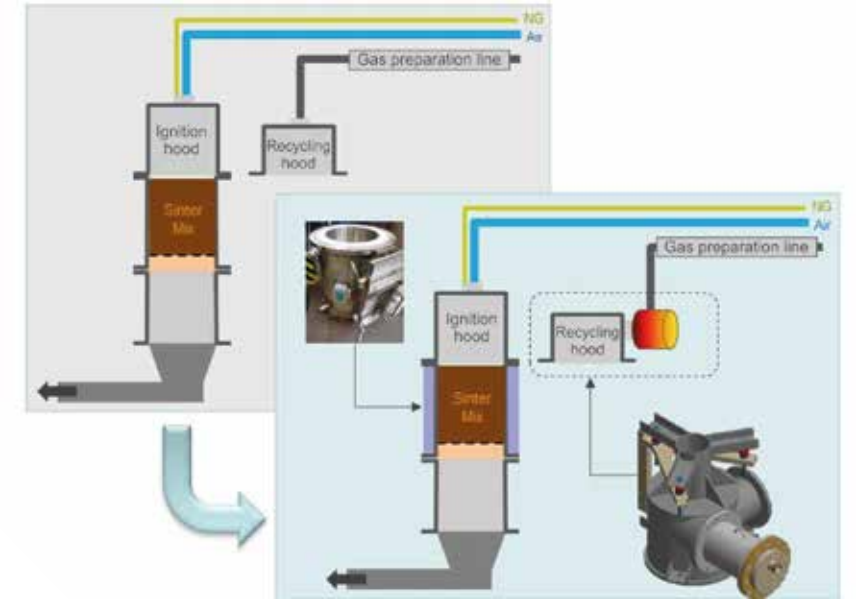


Pyrolysis of societal waste: pictures of various samples (left), TGA analyses (right)

intensively used in 2019 for the torrefaction and pyrolysis of CO_2-neutral or spent carbon resources. Series of basic tests have notably been performed for steel producers in order to identify suitable waste streams to produce alternative reductants for ironmaking. In this frame, a methodology for the characterisation of highly heterogeneous waste feedstock was first developed with a waste-collecting company. It includes the preparation of the waste samples (appropriate mixing, division, grinding and further mixing and sub-division), physico-chemical analyses (proximate, ultimate) and thermogravimetric measurements (TGA, DSC) on the reduced samples to understand the behaviour of the material under various thermal and gaseous conditions. Specific lab tests were then carried-out in larger crucibles to identify the best technology and processing conditions to produce suitable alternative reductants.

In particular for **sinter plants, drastic reductions up to -50% of reduction of CO_2 emission** are aimed for. This objective can be reached by making use of alternative solid fuels (from pyrolysis of wastes, see above) or by switching to alternative heat inputs, through gases. Options include Waste Gas Recirculation and innovative solutions integrating the production of hot fumes in an external combustion chamber. In order to meet the needs of this ambitious program, the **unique combination of CRM sintering tools are continuously upgraded**. It consists in a

mathematical model of the sintering process, a pilot station and a set of measuring devices (regrouped in a container) developed for full assessment of industrial sinter plants. The pilot station is currently being equipped with an external combustion chamber aiming at demonstrating the 50% reduction in CO_2 emissions.



Integration of external combustion chamber in sinter pilot

CRM is also active in the development of **breakthrough low-CO_2 production processes**, and involved with its steel members in running projects on HIsarna and on the reforming of steel plant gases using a plasma torch for the injection of hot reducing gas in the blast furnace. Moreover, as the use of green hydrogen is regarded by the EU steel industry as one of the main options for near-zero carbon steelmaking for 2050, the HUGE pilot facility at CRM-ETP will certainly be a tool of choice. This facility is a pressurised (up to 45 bar) refractory-lined fixed bed reactor with a capacity of 35 dm^3 of granular materials. It is equipped with external heaters, numerous gas injection lines (for air, O_2, CO, CO_2, CH_4, H_2O, N_2 and H_2) and exhaust

HUGE pilot facility: top of reactor (left), collection of by-products (right)

gas treatment and sampling lines. It is used for the simulation of various thermochemical conversion processes like pyrolysis, torrefaction, gasification, combustion or reduction, at ambient or high pressure. In 2019, various trials were performed: on ferrous sinter in order to reproduce real blast furnace conditions on a sample with full particle size distribution, pyrolysis of waste (aluminium packaging) in order to correctly characterize the gas produced during the intended melting of the raw material and pyrolysis and gasification of biomass (wood residue). In the frame of a running project, a new feeder and an inlet to the reactor are currently engineered for the injection of fine particles. This facility thus allows closely simulating breakthrough CO_2-lean iron and steelmaking options such as the operation of the blast furnace with massive injections of hydrogen or the fully hydrogen-based direct reduction of ores.

Pilot installation of thin film PV solar cells on roof new CRM building

Solar power as renewable energy is about converting energy from the sunlight into electricity using photovoltaic (PV) cells or concentrated solar power plants (CSP). CRM has also been active in both fields in the past year:

- In the field of development **of photovoltaic thin film solar cells** CRM group, in partnership with Solibro and ArcelorMittal, works in the H2020 project ARCIGS on the development and improvement of insulated steel as substrate compatible (roughness, insulation properties, high temperature resistance, no outdiffusion of detrimental elements) with the growth of flexible CIGS solar cell. **Solar cells and mini-modules were realized and led to efficiencies up to respectively 18.7% and 14%** (without antireflective coatings) which constitutes, to our knowledge, in the former case an unofficial world record for CIGS solar cell grown on insulated steel substrate. The cells have been produced **and BIPV (building integrated) modules are integrated in the roof of a new storage building constructed at CRM** for a long **duration demonstration** of the solution.
- In the field of **solar concentrator power plants**, CRM collaborated with John-Cockerill for the improvement of the paint of the solar receptor. Thanks to the new paint solution, with improved durability, the solar receptor captures as much energy as possible and release as little as possible. Another challenge lays in the selection of the materials to withstand the extreme conditions of high temperature variation and corrosion. The extensive testing capacities of CRM to test materials conditions of extreme and combined exposure are essential for the right material choice.

It is most certainly in a mixed energy vector that the global solution resides; such as the production of green hydrogen using intermittent energies (hydrolysis water), the recovery of this hydrogen via fuel cells or the storage of energy in chemical form (battery). The CRM develops electrochemical energy conversion systems for short and long term storage.

In the field of **fuel cells** the research is focussed on the **stainless steel bipolar plates development for Proton Exchange Membrane (PEM) Fuel Cell**. The substitution of graphite by stainless steel for this bipolar plates production offers great advantages in terms of cost and life time (corrosion resistance). The main challenge to overcome are related:

- to the development and upscaling of **innovative coatings** that fulfil combined specifications

Coated stainless steel bipolar plates for the use in fuel cells

Pilot line dedicated to development of coatings for bipolar plates

of durable low contact resistance, corrosion resistance and formability: an innovative PVD (Physical Vapour Deposition) coating on the stainless steel substrate has been applied and optimised in a dedicated pilot line.

Robotic spray (left) and wet roll-to-roll coating line (right) in clean room environment used for the upscaling of the battery production method without the use of toxic solvents

- the set-up of a characterization and forming platform to validate the developed bipolar plate in collaboration with the University of Liège: an original validation methodology has been set up that includes forming plates to evaluate the stamping resistance of the coating. Corrosion testing has also been defined to be as representative as possible to the real environment for a full understanding of the influence of parameters on the corrosion.

The research in field of batteries at CRM is focused on **Li-ion technology and its adaptation to produce greener and safer electrochemical storage solutions**.

The current production of Li-ion electrodes needs the use of a toxic solvent (NMP) that will not be allowed anymore in the future in EU due to REACH regulations. Driven by this REACH regulation, new electrodes and electrolyte solutions are developed. CRM is working on the **upscaling** of the innovative aqueous active materials formulations developed at ULiège to allow its deposition on steel based current collector by the use of **robotic spray or wet roll-to-roll coating line in clean room environment.**

In the field of **Water Hydrolysis and Hydrogen production**, CRM is contributing to the optimization of industrial electrodes and membranes for alkaline electrolyzers and to the development of characterization methodologies.

Advanced manufacturing

Innovative technology to improve products or processes

Advanced manufacturing makes use of innovative production technologies and opens up ways to improve production processes and products. It enables not only to produce products with new or improved functionalities but responds also to the need for a more efficient use of raw materials by reducing the material consumption and by extending the life time of the products.

One of the cutting-edge technologies for advanced manufacturing is the additive manufacturing. Thanks to the freedom of design, unmatched complex shapes can be manufactured while using less raw materials and energy than traditional manufacturing. To support its industrial partners on **metal 3D printing** CRM has put the focus on additive manufacturing **of large scale parts by Wire Arc Additive Manufacturing (WAAM) or Laser Metal Deposition (LMD)** with the associated challenges to increase the productivity, to develop new alloys, to master the residual stresses and on the surface finishing of 3D parts.

The solutions find their application well beyond the metallurgical industry and also respond to the needs of the energy, construction, defence and aerospace & aeronautic, transport and OEM sectors.

In order to keep on responding to those needs of industrial partners active in various sectors, an unique equipment called Hymax **(Hybrid Manufacturing for XL applications)** has been commissioned in 2019. The equipment includes a 6-axis robot on which various Direct Energy Deposition (DED) heads can be mounted: a coaxial powder + laser (8kW), a coaxial wire + laser (5kW) and a wire arc head (WAAM), fully equipped with state of the art monitoring tools. Various handling

HYMAX Hybrid Manufacturing for XL applications

HYMAX Hybrid Manufacturing for XL applications

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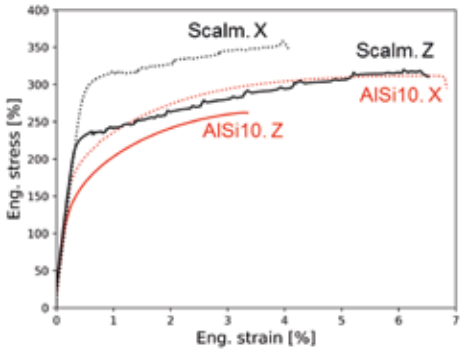
systems are also available: one turntable that can support 3300 kg, one 2-axis manipulator with a payload of 750 kg and a tower-type manipulator with a load of 600 kg which make the tool unique in his sort and especially suited to build or repair very large components.

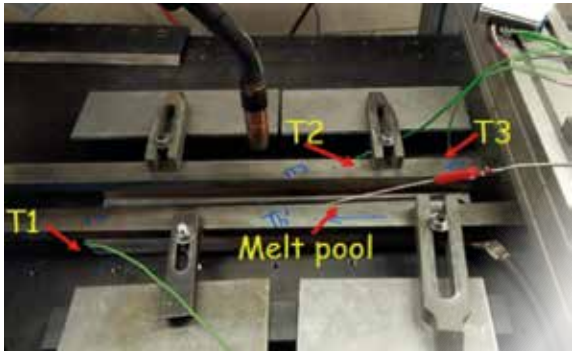
- In the European Space Agency (ESA) funded project LIRAM, in collaboration with SONACA, for example the **feasibility to print a large interface ring for space shuttles using Laser Metal Deposition** is studied. CRM optimises the printing parameters and heat treatments for 2 aluminium alloys: AlSi10Mg and Scalmalloy® and prints a demonstrator in its pilot installation. It also collaborates in the adaptation of the topologically optimised structure to be compatible with the LMD process.

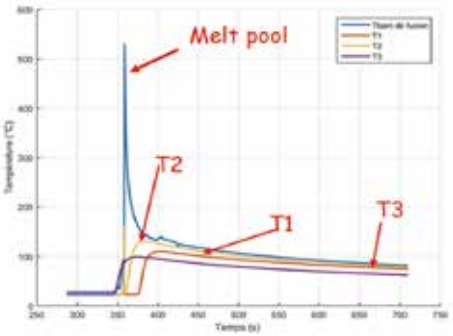


Tensile curves for LMD printed Scalmalloy® and AlSi10Mg in two building directions

Since the mechanical properties of a 3D printed part are highly dependent on the process parameters used: temperature, layer thickness, interpass time,… a **detailed monitoring during deposition and characterisation afterwards** is crucial to fully understand the impact of the parameters as well as to support numerical modelling in order to arrive at a 'first-time-right' production of parts by 3D printing.

- In particular for Wire Arc Additive Manufacturing

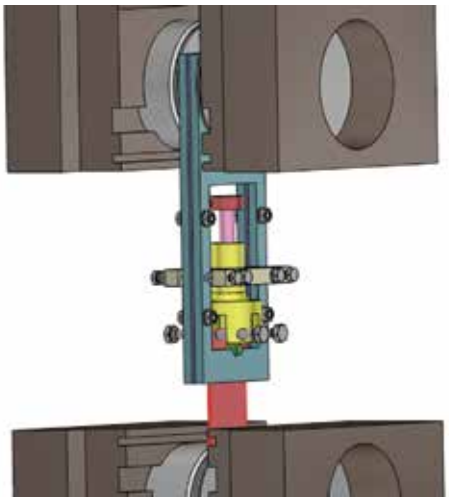




Extensive monitoring during WAAM deposition by thermocouples in the melt pool to feed and experimentally validate the numerical model of the WAAM process

of aluminium alloys, CRM is supporting the industrial partner Open Engineering with the **experimental validation of a numerical model**. Through an intensive test campaign varying a large set of process parameters in a wide range accompanied with an extensive monitoring during deposition and experimental characterisation of the properties afterwards data is generated to **feed and experimentally validate the numerical model of the WAAM** process.

- Another example of extensive characterisation concerns the **aerospace applications** in a project supported by ESA aiming at demonstrating the applicability of Additive Manufacturing processes for highly loaded primary **spacecraft and launcher structures**. An **extensive testing program** to check the process and to determine the mechanical properties of the materials is being performed in order to demonstrate that spacecraft and launcher structures can be produced in a reliable and repeatable manner. To do so, the CRM Group performs several tests such as **non-destructive inspections** (3D CT scan, X-ray 2D, etc), **mechanical tests** (bearing test, compression test) and **corrosion tests** (stress corrosion cracking test, salt spray test).



Bearing test to assess the applicability of Additive Manufacturing processes for highly loaded primary spacecraft and launcher structures

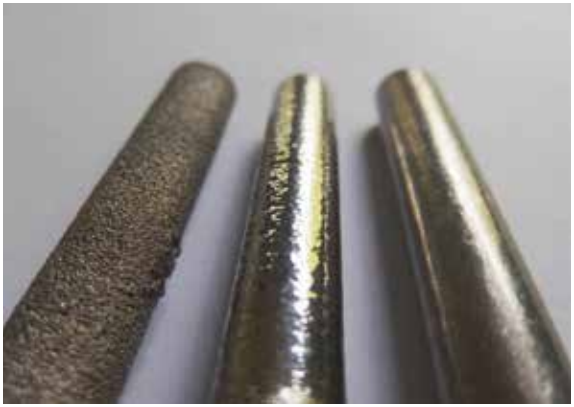
- To further promote the use and application of 3D printing for industrial applications, CRM is defining the optimised parameters for Laser Metal Deposition (LMD) and Wire Arc Additive Manufacturing (WAAM) for a set of selected high strength steels in the INSIDE MetalAM project supported by Vlaio (Vlaams Agentschap voor Ondernemen en Innovatie) and the Strategic Initiative Materials (SIM). The selected parameters will then be applied on demonstrator parts chosen in collaboration with the User Committee for applications in amongst others pumps, compressor rotors or valve bodies.

Definition of optimised deposition parameters for high strength steels with laser metal deposition (left) and WAAM (right)

In the field of **development of new alloys specially designed for additive manufacturing** required to take the full benefit of the new manufacturing processes, CRM is involved - thanks to the support of the European Space Agency (ESA) - in the development of new advanced aluminium alloys to deliver products with high end structural performance. Thanks to the development of innovative methodologies we are able to analyse the behaviour of new alloys under fast cooling conditions, close to those encountered in additive manufacturing processes without the need to produce the powder. Indeed,

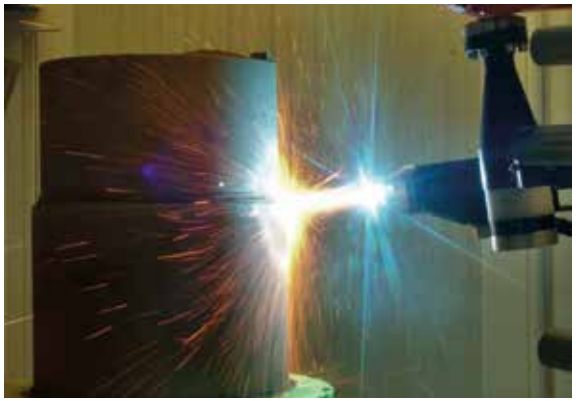
in the development phase, producing small lots of powder of a specific alloy to test its potential is costly and time consuming. With our unique methodology we have screened a series of new alloys in the fast cooling conditions without the need to produce the powder and identified by this the most promising alloys that are going to be tested in 2020.

Parts produced by Selective Laser Melting show a certain roughness of the surface in as-built stage. This surface roughness is detrimental for mechanical properties in particular fatigue and thus a surface finishing is required to polish the surface and to obtain the required properties. CRM has been active for several years in the research on **surface post treatment** in order to find the optimal surface finishing treatment. Several factors have to be taken into account: the alloy type, the initial and aimed roughness, cost, treatment time and impact on environment (linked to use of chemicals). One example that can be cited in this field is the surface treatment of Ti6Al4V and Carpenter C465 alloys for **metal structural aerospace components manufactured by powder bed additive manufacturing** in the frame of a project supported by the SIM and Vlaio led by ASCO. Electro-chemical surface finishing methods are being evaluated as well as chemical polishing and tribofinishing.



Surface finishing of coupons for aerospace applications. From left to right : reference sample, surface processing 1 and surface processing 2

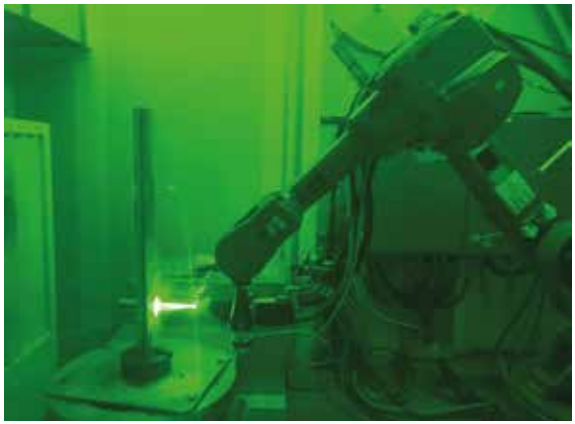
Let us also recall that CRM has acquired an extra-ordinary thermal spray coating booth in the frame of the 3D Coater ERDF (European Regional Development Fund) project. This equipment meets industrial needs thanks to its capacity allowing the treatment of parts up to 1 Ton. Next to the plasma torch and HVOF (High Velocity Oxygen Fuel) processes already available, the spraying booth has been completed with a twin arc spraying system. We have now a complete set of spraying systems available to provide robust coatings for the finishing of parts aiming at for instance wear and corrosion resistance:



Thermal spray of NiCr coating on 3D parts as alternative to electrolytic Cr treatments

- Thermal spray has been evaluated as an **alternative to electrolytic chromium treatments for gear shafts**. Nickel-Chromium coatings deposited by **HVOF (High Velocity Oxygen Fuel) and electrical arc-wire** have been compared. The coatings deposited by arc-wire show the best adhesion and a high compatibility with the post-machining operations. This method, which avoids using solvent and chemical baths could then be further considered for the treatment of real parts.

- With **Twin Arc Spray** two electrically opposed charged wires comprising the spray materials are heated and melted by forming a controlled arc between them. The molten metal is atomized



Twin wire arch torch demonstration

and propelled onto the workpiece surface by compressed air or gases (N2, Ar…) to form the coating. Metal wire feedstock materials are generally sprayed but dissymmetric wires or core wires can also be used for the deposition of complex alloys. The ability to process metals at high spray rates on large areas and to coat the pieces by keeping the substrate temperature low convinced CRM of the opportunities opened by this equipment in the development of coatings.

In the frame of another ERDF project, CRM got the opportunity to acquire a remarkable rotary bell **electrostatic spray mounted on a 6 axes robot**. This pulverisation technique is used in the automotive industry to paint cars on the production lines, providing the best coating finish with high productivity and yield. This technique used all over the world for paint application was tested at CRM **with sol-gel products**. Sol-gels are known to have a low pot life and curing sensitivities due to internal stresses during solvent evaporation. Different formulations like glassy coats or ceramic based ones were sprayed relatively easily on various metallic substrates (steel, stainless steel, aluminium, …). The formulations tested gave good finishes with glossy aspects and low roughness without orange peel effect. Concerning adhesion or cracks, the coating showed similar results than the ones applied by dip drawing or roll-coating.

Electrostatic spray

Sol-gel coating on metallic substrate applied by electrostatic spray

Digitalisation and industry 4.0

Smart production and smart products

Industry 4.0 is about linking of digital systems, models and objects, about data collection and data processing, assistance systems and networking & integration. The digital transformation impacts every industrial sector and is furthermore closely connected to advanced manufacturing, circular economy, construction and the energy shift.

Smart production

Essential elements in the **digitalisation of industrial manufacturing processes** are the **sensors** to capture and process data. CRM is for many years developing sensors for the steel industry with a special focus on sensors to be implemented in harsh environment and to measure on or with surrounding metallic objects. The further evolution of these sensors in terms of their miniaturisation, connectivity, integrated artificial intelligence is ongoing to make them industry 4.0 proof and ready to be transferred to application fields outside the metallurgical industry such as metal construction, defence, energy sector and other industrial sectors operating in severe conditions (high temperature process, corrosive environment, …).

Recent CRM developments contributing to the digitalisation of the steel industry processes are highlighted below:

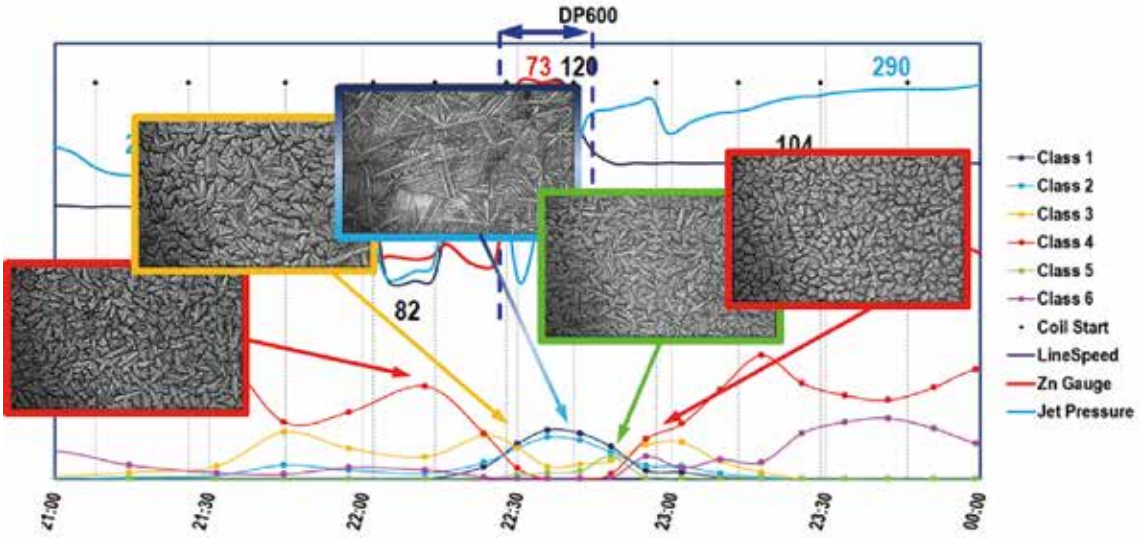
- Controlling the austenite fraction during the final thermal cycle in continuous galvanizing and annealing lines is a key parameter with respect to the end-user properties of high strength

Prototype of the austenite measurement system installed in industrial galvanising line

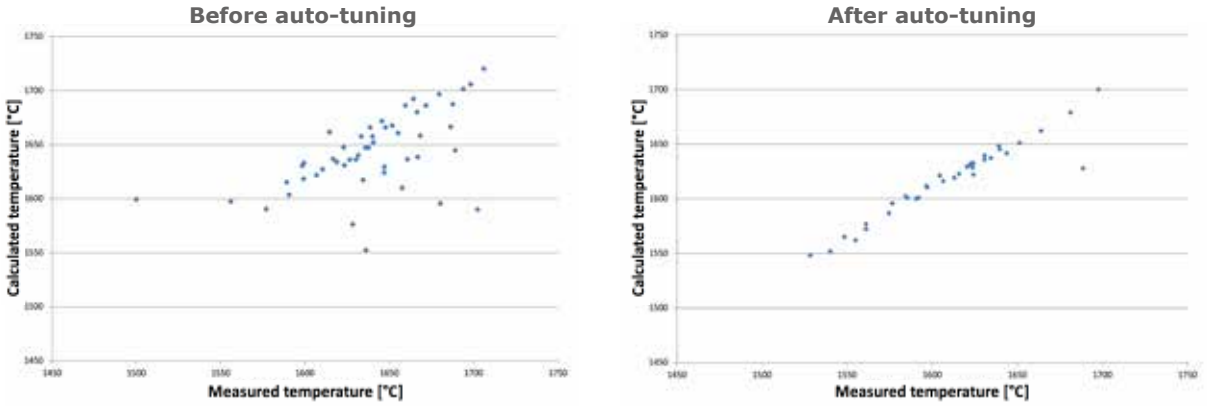
steel strips. For such an **on-line and in real time measurement of austenite fraction on moving steel strip** during annealing, an industrial prototype of a new electromagnetic sensor is under development. This very cheap sensor allows the measurement at low or high temperature and at a distance of several tens of millimetres of the strip while keeping a sufficient sensitivity and is also able to work above and below the Curie temperature. The whole system has been modelled with a finite element method in order to optimize the sensor and a first industrial prototype has been installed in continuous galvanizing line for first industrial trials.

- The miniaturised low cost and compact On-Line Microscope (OLM) of CRM has been applied to **characterize the coated surface at microscopic level during industrial production of galvanised steel**. Clear and high quality pictures have been grabbed. To study the evolution of the **zinc-grain size and morphology in function of the process parameters**, image processing has been applied with the help of a **deep-learning algorithm**. The model output consists in 6 numbers, corresponding to the probability of the image to belong to one of the 6 classes predefined for the learning. A promising classification of the images has been achieved and the link with process parameters like line speed and jet pressure can also be established.

- The CRM **EAF model** is a key tool on the way to zero-emission iron & steel production. It is a dynamic metallurgical model that continuously solves mass and thermal balances for scrap, liquid steel, slag, gases and furnace. In addition it calculates scrap melting evolution. The model is already running in the control room of 3 industrial plants at ArcelorMittal and supports the operators in taking the right measures as soon as a drift is detected during production. In order to further improve the model and ease further roll-out it has now been completed with **self-learning models for auto-calibration** of the model constants.



Automatic classification of the microscopic images of the Zn-coating obtained by industrial measurement campaign with the OLM and link with process parameters



EAF-model results: Correlation between T measurements and simulation without / with auto-tuning of parameters

- The **smart monitoring of the work roll degradation** in the hot strip mill by means of dedicated software on a **tablet** is continuously being upgraded. Let's remind that the tool has been integrated in the daily operation at ArcelorMittal Ghent since several years. All data coming from the tablet is connected with the mill network and is being used together with production and maintenance data to follow impacts on the degradation phenomena.

Tablet for smart work roll evaluation

The tablet tool is also under implementation at Tata Steel Ijmuiden. Within the frame of the European RFCS project 'Mastering work roll degradation II'; the principle of "gamification" has been added to the software for increasing the interaction with and the motivation of the operators. In cooperation with Tata Steel the software has been completed with a news feed, an interactive quiz on roll degradation, as well as with the visualization of statistics concerning the usage of the tablet per team and the results of the degradation over the last period.

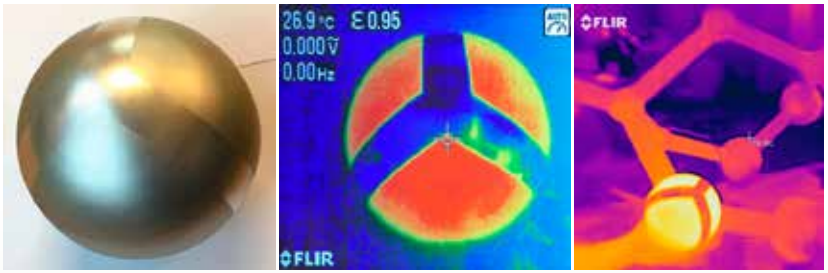
Smart products and solutions

Printed electronics in combination with advanced material development offers tremendous possibilities for new markets and businesses for flexible, stretchable and large area electronic. This technology becomes an integrated part of the Internet of Things (IoT), Industry 4.0 and digitalisation by making smart system displays, sensors and active functional surfaces. Most of these **printed devices** are currently integrated on plastic foils, papers and textiles. Nevertheless, **metallic substrates** appear to be also a promising alternative for several reasons. First, metal can overcome important arising technological difficulties due to the shortcomings in durability, moisture barrier properties (particularly for organic material), heat dissipation and severe environment (high temperature, high pressure…). Moreover, electronic integrated metal solutions will allow very innovative smart applications for all sectors using metals like in building, appliance, automotive, aeronautic, defence….

Printed electronics technology opens the door to innovative and thin film active functions. A large field of applications are covered at CRM, from printed tracks, wireless antenna (NFC, RFID) to printed sensors (temperature, pressure, constraint gauges, gas sensors) and lighting.

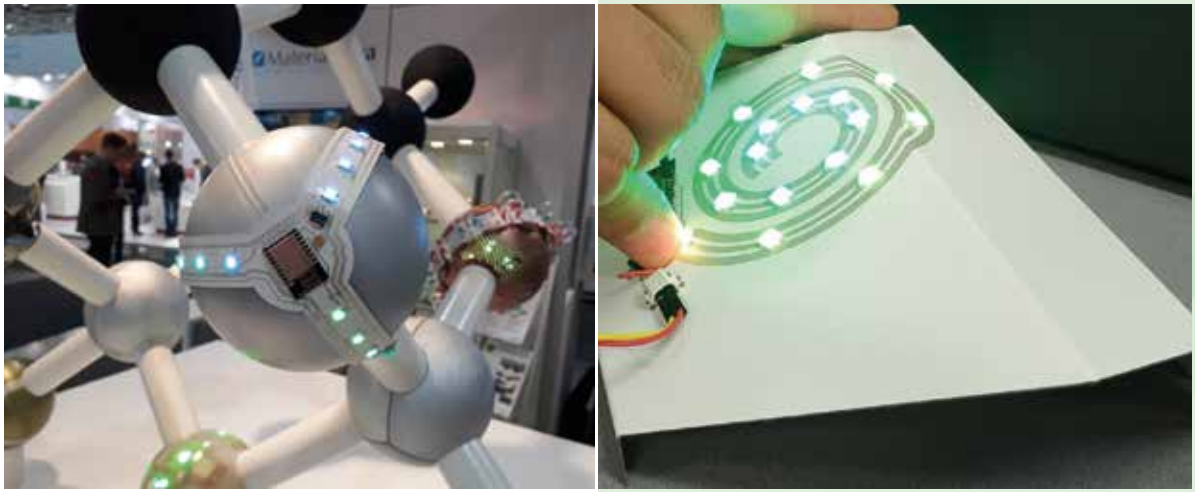
Although printed electronic is mainly dedicated to 2D surfaces, it also offers nice opportunities to address the 3D world. In this context, CRM contributed to the joint demonstrator "Wallonium" aiming at illustrating the industrial valorisation of research carried out in Wallonia. CRM demonstrated two smart products on "Wallonium":

- A first sphere demonstrates a **printed LED tracking on flexible metallic surface**. The metal is first electrically isolated by a convenient polymer or ceramic layer. The circuit is then printed by screen printing, flexography or inkjet technology. The electronic components like LEDs are then connected via standard techniques (e.g. pick & place). The substrate being deformable, it is possible to give the desired shape after forming and assembly without altering the electronic functions. The LED lighting is controlled at distance by Wi-Fi connection to a chip.



IR cartography of sphere covered with coatings having different emissive properties

- A second sphere demonstrates **the possibility to change the aspect of an object observed by IR detectors** (detection in dark for example). It offers applications in IR stealth solutions for the defence sector for instance. The sphere has a homogeneous metallic aspect in visible range but is composed of 2 kinds of coatings with different emissive properties: a 3 branches pattern of low emissive material has been printed on a higher emissive coating. So when the sphere is heated, the image coming from an IR camera (8-14µm) shows a strong colour contrast between the 3 branch pattern and the rest of the sphere.



3D Printed circuit of electrical LED tracks on flexible and structured metallic substrate

From lab scale over pilot lines to industrialisation of our process solutions

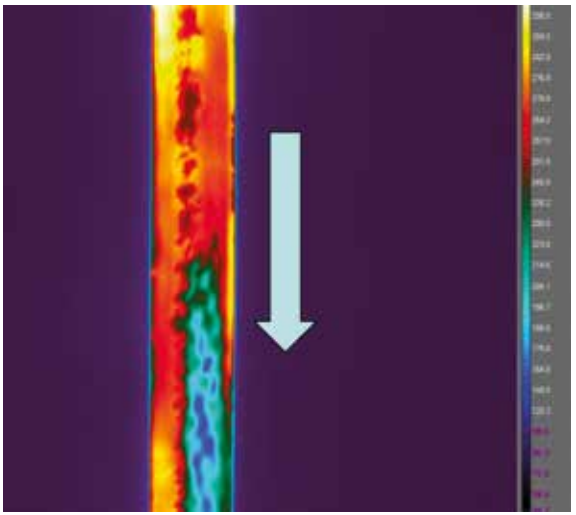
Turning applied research into value creation

CRM is renowned already for many years to turn its research ideas into industrial reality thanks to its profound knowledge of the industrial environments and constraints and its remarkable and unique pilot installation simulating in lab situations close to the industrial reality.

Smart cooling actuator tested on pilot line

Developing industrial cooling systems remains a key competence of CRM and has again led to some successful results in 2019:

- A **smart cooling actuator** combined with a dedicated control model, aimed to adjust the temperature profile over the length and width of the transfer bar or strip has been **validated on the pilot rolling line**. To proof the concept of local cooling to correct temperature heterogeneity, a small part of the strip section has been cooled with the new developed actuator and the response of the actuator was clearly monitored by thermal camera. This test demonstrated the aptitude to perform selective cooling on zones of 50mm width.



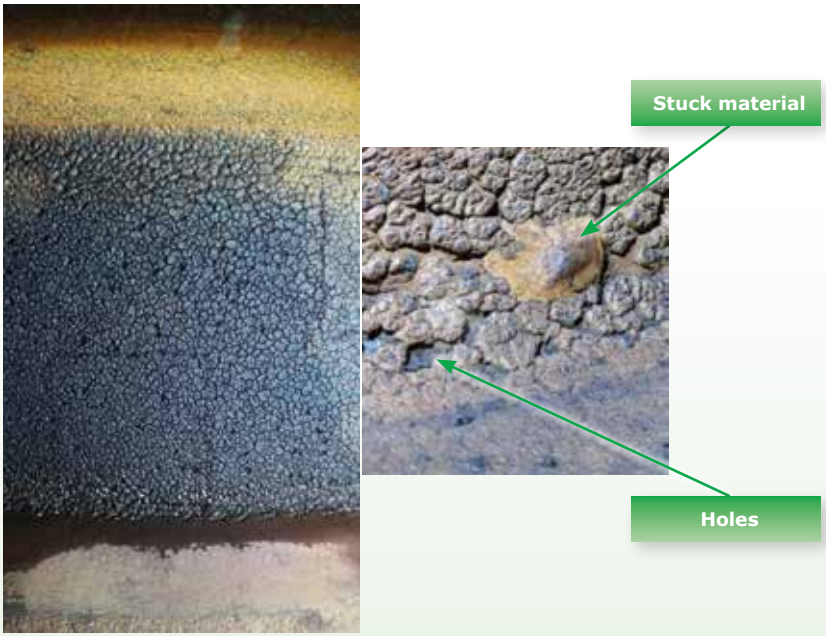
Thermal camera response validating the concept of smart selective cooling

In the field of hot rolling, minimising the **work roll degradation** is of prime importance to assure the product surface quality and to reduce the roll cost.

- Specifically for the edger rolls, a detailed investigation has been done in order to understand the degradation and the use of this width control actuator. Ultimate objectives of this project are to reduce edge defects occurrence by an improved understanding and application of rolling actuators (e.g. roll design, roll grade, cooling, lubrication, pass design), to increase the roll performance and suppress associated edge defects and production losses due to roll change. **Edger rolls degradation was studied on site in 5 plants** (Tata Steel IJmuiden and ArcelorMittal Gent, Dunkerque, Hamilton, Fos-sur-mer, Eisenhüttenstadt). It was concluded that edger rolls degrade similarly in the plants: thermal fatigue and wear in the vertical flange and mainly abrasive wear in the top flange sometimes combined with thermal fatigue. Sticking of product particles and the removal of roll particles are also main contributing actuators to the formation of product defects.

- In the European funded project MasteringRolls II, one of the objectives is the development of an **absolute and fully non-destructive roll oxide thickness measurement**. In this frame, oxidation trials following thermal cycles of a roll in a mill have been reproduced on both HSS and HiCr materials. Oxidation conditions have been varied (quenching water composition, amount of cycles) to achieve different oxide thicknesses on the roll materials. Measurements with a handheld XRF have been performed, combined with GDOES and cross section metallography. All those analysis are on-going to set the calibration curves for the new non-destructive measurement of the roll oxide based on XRF technology.

Handheld XRF device used for (roll) oxide thickness measurements



Typical roll degradation of edger roll during on-site inspection

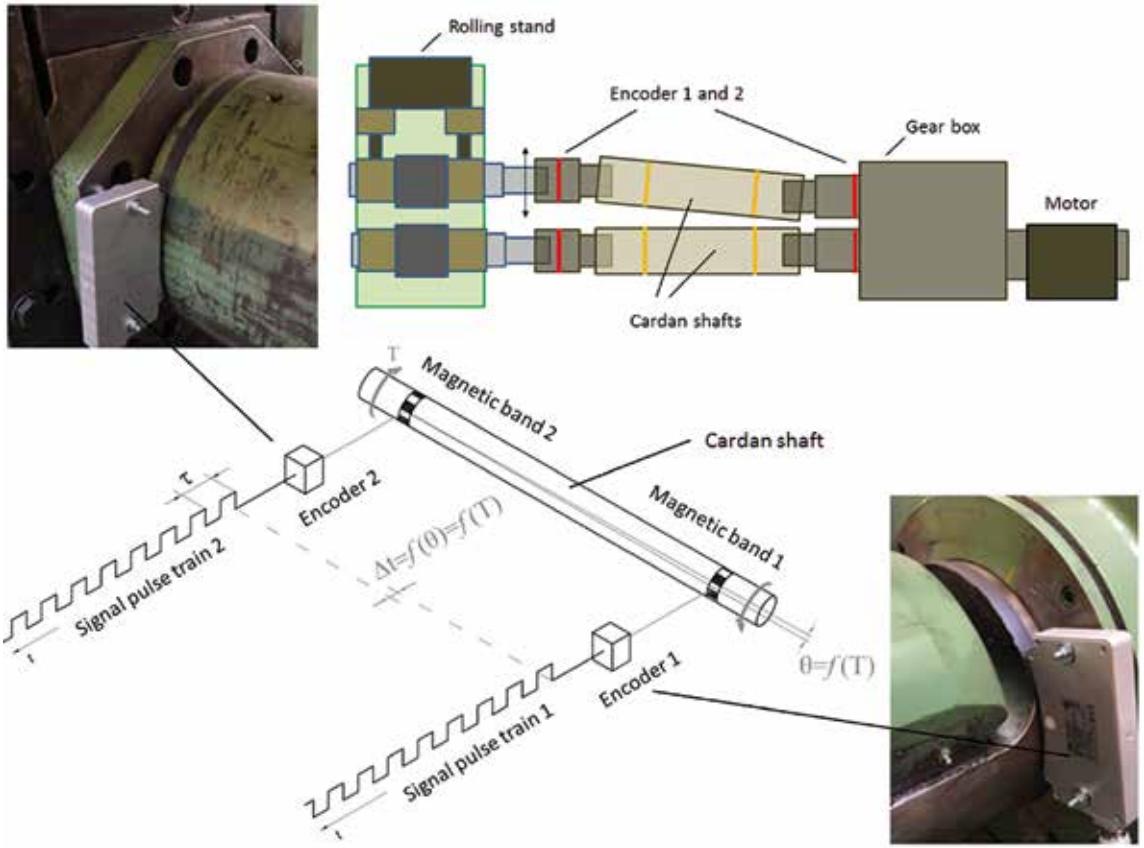
Lubricant application in the hot and cold rolling mill is commonly used to reduce the friction and decrease the rolling forces. Direct benefits are the reduction of surface defects, the reduction of roll degradation and the increase of the rolling campaigns. Friction control will become even more important for the rolling of future harder grades. Therefore, reliable lubricant application systems are a necessity.

- During the past year an **industrial representative lubrication simulator** named 'FUSLUS' has been developed to evaluate mixing conditions (including industrial emulsion flow rates and nozzles) and clogging behavior in long duration trials. Based on representative simulations, guidelines can be provided to the mills on how to use, maintain and rinse the emulsion application installation. Future

Full scale lubrication simulator

lubrication concepts can also be tested to assess the feasibility of the lubricant in combination with the application technology.

- In order to accurately control lubrication and to avoid steering and flatness issues or spindle breaks, the spindle torque is one of the most important parameters. CRM is therefore looking for a **robust and low cost torque measurement system** based on the measurement of the twist of top/bottom spindle linked with the total motor torque. Different measurement system, avoiding electrical rotating parts, wireless transmission and use of sensitive strain gauges are being tested on the pilot hot rolling line.

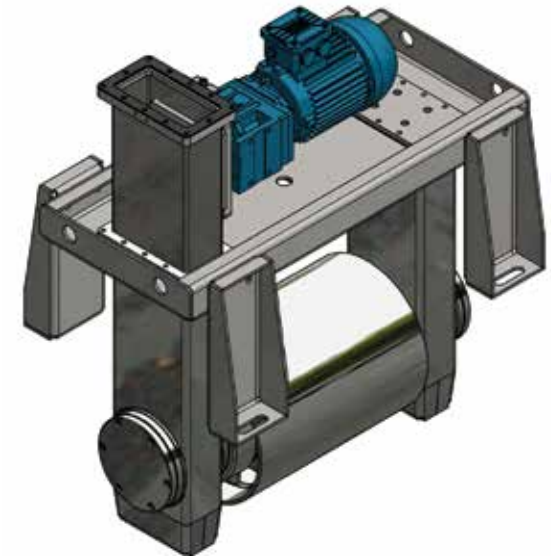


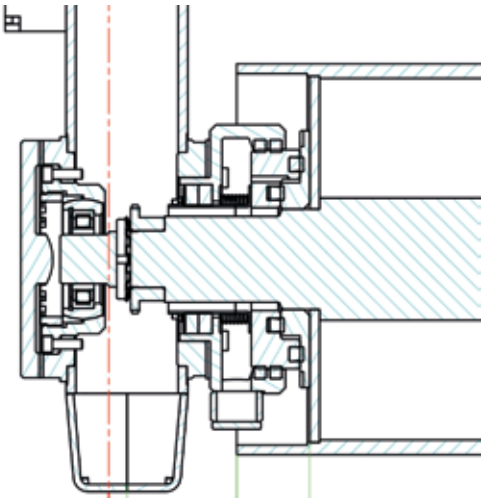
Robust torque encoders implemented in pilot rolling mill

In the field of metallic coating, more particulary of galvanizing:

- **Increasing the galvanizing line speed** is mandatory for reducing production costs, however line speed above 200m/min is challenging and not current practice because of issues with stabilizing wiping, bath immersed hardware and intensive skimming. The RFCS project "HighSpeedGalvanizing" focusses on these aspects for enhancing galvanizing line speed. Amongst key factors investigated, CRM works on the use of "tight" bearings meaning without contacting liquid zinc which should overcome the above mentioned issues. A roll equipped with tight bearings is being prepared to be tested first in a simulator and subsequently on the CRM pilot galvanising line.

- Both modern **batch and continuous galvanising processes** conduce to the production of large amount of dross leading to downgraded products, loss of productivity due to frequent line stops for dross removal and safety issues for operators who clean the bath. The **improved removal of drosses** polluting the galvanizing baths (continuous strip and wires, batch) is therefore a key factor and CRM is studying, with the support of the RFCS, the dross removal by **melt centrifugation**. The study and the development of centrifuge equipment in small liquid metal baths (40 x 40 x 150 cm, 700°C max) as well as the safe handling of ingots (1t max) are in progress.





Roll equipped with tight bearings enable high speed galvanising

New products & solutions

And their dissemination to industry & regional economy

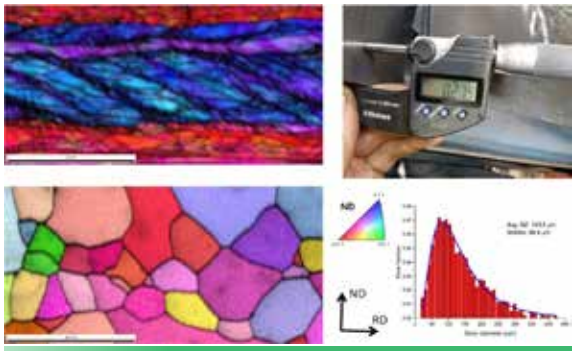
As independent collective research centre in metallurgy, CRM offers for years services and knowledge towards the metallurgical industry as well as to a great variety of customers active in different other sectors. Next to the technical assistance, the development of new processes for producing metals, the development of new metallic products and their coating, the characterisation of metallic or related materials, the offer has now been completed with advanced manufacturing, solutions related to digitalisation, circular economy and energy shift as already illustrated in previous sections.

In this section examples are given to further illustrate the variety of solutions and services that CRM offers to a wide range of customers and sectors.

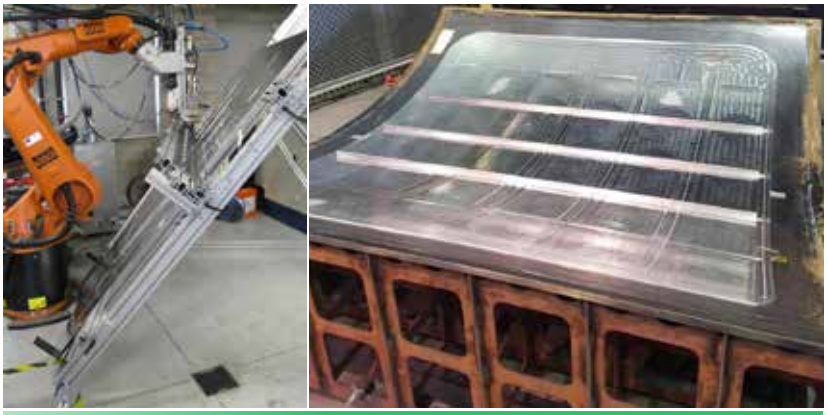
For the **steel industry**, we continue to support our members to develop future high-performance product:

- In collaboration with our associate member NLMK and thanks to the support of the Walloon region, we managed to define the optimised composition and the process window for **a new type of plate product**. The first industrial trials are running successfully since December at the mill of NLMK Clabecq. It was a challenge to find the good balance between concept and industrial reality that was achieved thanks to a combination of laboratory investigation, pilot plant simulation and demonstration on industrial site.

Industrial test of the production of a new plate grade



Microstructures of cold rolled (top) and annealed (bottom) electrical steel samples, measured by electron back-scatter diffraction (EBSD) technique. Thickness of the two samples are similar (280 µm) but microstructure scales are 10 times different.



Robotic laser beam welding of a cargo door demonstrator and door demonstrator after hot creep forming

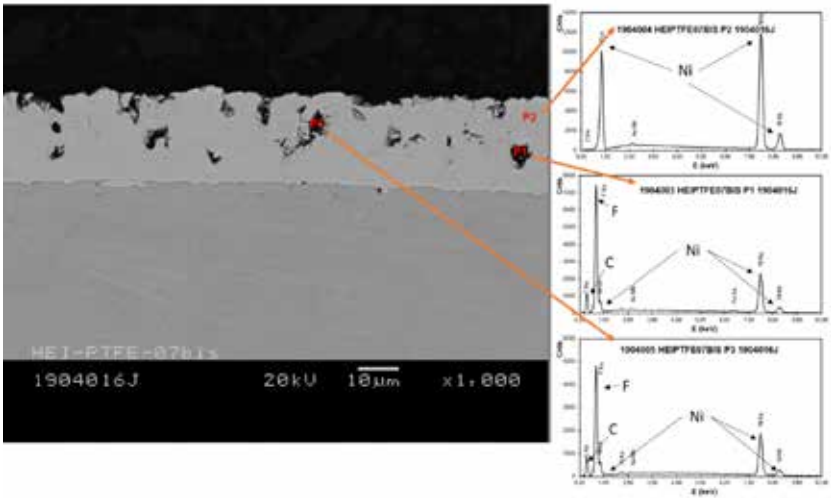
- CRM with its twelve partners of the H2020 ESSIAL project explores and optimizes properties of soft magnetic materials by advanced laser technology. Driven by the need to reduce CO_2 emission and to increase efficiency of energy conversion to electricity and vice versa we are searching **to improve the performances of soft magnetic cores in electric machines** (i.e. generators and motors). We succeeded to reproduce the production of fully finished non-oriented electrical steel sheets with insulated coating layers: steel sheets of 200-300 µm thick have been produced, allowing reducing the energy loss by Eddy current, as compared to conventional materials, with 20%.

In complement to the many examples already given in the section on advanced manufacturing on our offer towards aeronautic and aerospace industry we can cite another example related to

- a **metal cargo door application:** in the search for replacing chemical milling during aircraft manufacturing and for reducing manufacturing costs associated to conventional assembly, new manufacturing routes have been looked for and compared. CRM investigated one of them being a vacuum formed door skin (by hot creep forming) with integrated stringers that are welded. A series of preliminary laser welding tests have been performed first on smaller samples of the Al-Mg-Sc alloy for definition of the welding parameters. Those settings have then been used for the welding of a real scale demonstrator model that – after non-destructive inspection - was given its final geometry by hot creep forming.

Many sectors are looking for **alternatives to hexavalent Cr-plating** to comply with the REACH regulations.

- One of the many applications concerns the substitution of hard chrome plating for the

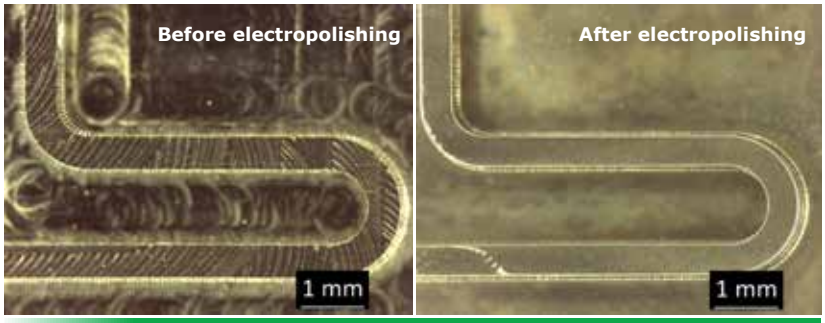


Cross-section view of a low-friction composite coating for hydraulic applications

protection of the shafts of hydraulic cylinders. For this application, CRM investigates low-friction **composite coatings applied by electroplating**, which combine a **metal matrix and self-lubricant particles** to ensure solid lubrication and corrosion resistance of the coating. This year, a lab-scale pilot facility was designed and constructed at CRM for the investigation of composite electroplating process.

Surface quality requirements for high-end applications become increasingly stringent while the complexity of component shape increases.

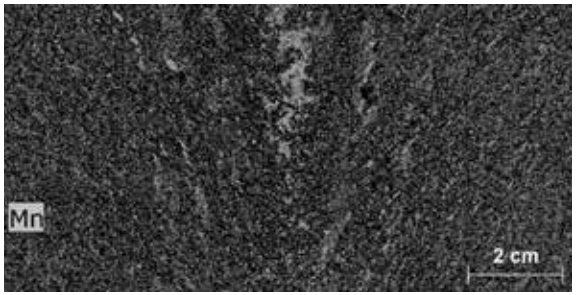
- In the AdEPT project CRM focusses on the investigation and evaluation of **advanced electropolishing technologies** and strategies to meet those requirements. Advanced bath chemistry, electrical parameters and configurations have been tested and selected for electropolishing tool steel parts **for application in injection moulding**. Demonstration mould inserts polished at CRM will be tested for injection trials by the project partner Hahn-Schikard.



Improved of the surface quality by advanced electropolishing of injection moulds with micro-machined features

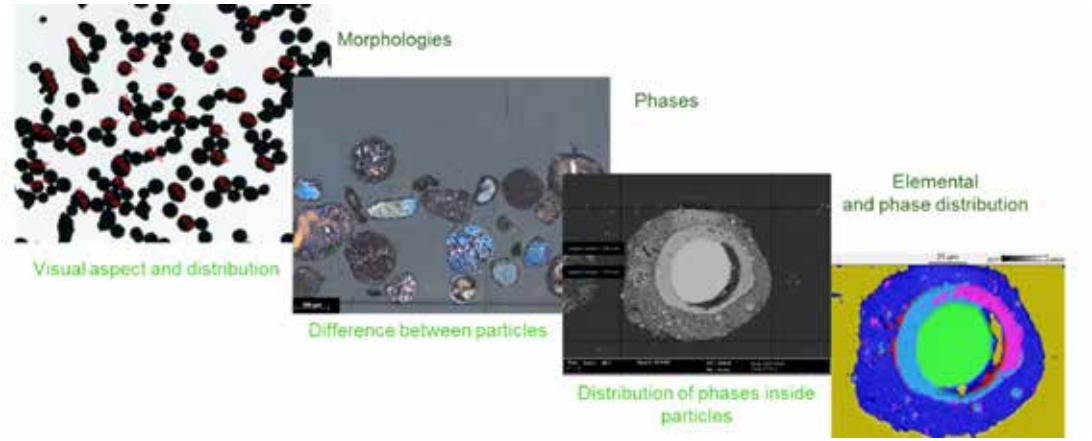
CRM has further extended its offer of its already complete panel of characterisation tools with:

- A **micro-XRF (X-Ray Fluorescence) to enlarge the chemical local analysis and large scale imaging** for complex applications, such as quantitative analysis of metallic multilayer stacks for composition and coating thickness. Such technology is well placed between portable XRF and SEM local analytical capabilities and has been used for example to deeply characterise macro-segregation in as-cast product on a scanned area of 190x160mm² with a beam resolution of 20µm.



Mn segregation pattern by micro XRF

- Enhanced knowledge and adapted procedures combined with a set of characterization methodologies with a multiscale approach for **powder characterisation**. Indeed powder characterization is required for applications in a great variety of domains (circular economy, additive manufacturing, environmental topics…). From the global size and morphologic characterization based on laser and optical granulometers (granted through SinByOSe RFCS project), light optical microscopy is used to determine quickly and efficiently the particle-to-particle homogeneity and some quantification can be given through image analysis. The internal particle homogeneity can be further characterized with Scanning Electron Microscopy combined with local elemental analyses based on Energy-dispersive X-ray spectroscopy (EDX) at a µm scale and at a few 10nm with the Scanning Auger Microscope. With Raman microscopes,



Multi-scale approach for powder characterisation

the compounds or phases present inside each particle can be determined at a few µm-scale. The global analysis of powders can be complemented with more classical techniques such as chemical analysis (combustion for light elements or Inductive coupled plasma (ICP) for the others) and X-ray Diffraction for phase determination.

- A complete new state of the art tensile test machine for the measurement of the yield strength, tensile strength, elongation, reduction of area and anisotropic coefficient of texture. The equipment allows performing tensile test under stress, deformation and displacement control. Extraordinary and unique features are available to perform tensile tests, relaxation and compression tests at room or at high temperature (up to 950°C). The room temperature test can be performed under the accreditation ISO 17025.

For the dissemination of its results and to promote its developments, CRM has participated to different events, seminars, congresses, workshops and fairs.

- 1st seminar of the **LowCarbonFuture project**, 1st of April in the frame of the EuroSteelMaster conference in Brescia (Italy)
- The **Materials Market** on the SIM User Forum in Gent where the activities on additive manufacturing and recycling have been presented on May 22nd, 2019
- Event **"Get inspired by the latest technological advances in materials for additive manufacturing"** organized on October 15th in Liege. CRM presentation on *« CRM : New aluminum alloys »*
- The **Automotive Day** organised in the frame of the INTERREG 'Grande Région' by ULiège and Technifutur on September 24th, 2019 in Liège.

Award, publications & Conferences 2019

AWARD

Belgium Environment & Energy Award 2019 in the category "Circular Economy"
"La seconde vie des déchets d'aluminium"

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Metal processing & product metallurgy

P. HUYGHE, M. CARUSO, J.-L. COLLET, S. DE PINOY, S. GODET
In Situ Quantitative Assessment of the Role of Silicon During the Quenching and Partitioning of a 0.2C Steel
Metallurgical and Materials Transactions, May 2019

T. NGUYEN-MINH
Organizing committee member & Co-editor Conference Proceedings
The 7th International Conference on Recrystallization and Grain Growth (Rex&GG), 04-08 August 2019, Ghent

S. FLAMENT, O. LEMAIRE, G. WALMAG, M. SINNAEVE
Prevention of contact fatigue damage occurrence in reversing roughing mills
Proceedings 11th International Rolling Conference, 1st to 4th October 2019, Sao Paulo (Brazil)

P. GELTEN, G. SCHIPPER, H. UIJTDEBROEKS, P. ADRIAEN
High-Turbulence Roll Cooling in Tata Steel IJmuiden Hot Strip Mill 2
Proceedings 11th International Rolling Conference, 1st to 4th October 2019, Sao Paulo (Brazil)

Finishing & coating

D. MERCIER, A. NICOLAY, A. BOUDIBA, X. VANDEN EYNDE, L. LIBRALESSO, A. DANIEL, M. OLIVIER
Mechanical properties and decohesion of sol–gel coatings on metallic and glass substrates
Journal of Sol-Gel Science and Technology, 93, pages229–243 (2020) (December 2019)

O. HUBERT
The influence of diffusible hydrogen on the tensile properties of model high strength steels
PhD Thesis (UCLouvain), 2019

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On the interactions between atmospheric hydrogen sources and 22MnB5 steel
PhD thesis (UCLouvain), 2019

M. MANDY, C. GEORGES, T. STUREL, P. DRILLET, P.J. JACQUES.
On the analysis of the simultaneous uptake and desorption of different isotopes of gaseous hydrogen by advanced high strength steels
Scripta Materialia, 161 (2019), 84–87

Additive Manufacturing

F. DUMINICA, N. NUTAL, S. LE CRAZ, J.-F. VANHUMBEECK, C. ARCHAMBEAU
Finition de surface des pièces métalliques issues de l'additive manufacturing
VOM Magazine, February 2019

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Finition de surface des pièces produites par fabrication additive
Techniques de l'ingénieur, October 2019

PAPERS ON CONFERENCES 2019

Metal Production & Recycling

J. BORLÉE
Low Carbon Future Steel Industry – Process Integration pathway
Seminar LowCarbonFuture @EUROSTEELMASTER 2019, 1st of April 2019, Brescia (Italy)

L. DO VALLE, O. HAVELANGE, C. MATHY, F. VAN LOO, S. SERRE
A successful industrial application of selective waste gas recirculation for NOx mitigation with positive impact on productivity at ArcelorMittal Fos-sur-Mer
4th ESTAD (European Steel Technology and Application Days), 24 - 28 June 2019, Düsseldorf (Germany)

S. BORN, A. BABICH, J. VAN DER STEL, H.T. HO, D. SERT, O. ANSSEAU, C. PLANCQ, R. GEYER, D. SENK, V. PRIDHIVI
Formation of char by coal injection and its behaviour outside the blast furnace raceway
4th ESTAD (European Steel Technology and Application Days), 24 - 28 June 2019, Düsseldorf (Germany)

C. PLANCQ, G. MOREAS, F. VAN LOO
Raceway Instrumentation
4th ESTAD (European Steel Technology and Application Days), 24 - 28 June 2019, Düsseldorf (Germany)

F. BLAFFART, M. DORMANN, T. MARCON
Synergistic use of by-products in the production of FeMn alloys
4th ESTAD (European Steel Technology and Application Days), 24 - 28 June 2019, Düsseldorf (Germany)

B. KLEIMT, R. S. NICK, M. DE SANTIS, J. C. PIERRET, M. JEMSON
EU supported research projects on secondary metallurgy technology with focus on on-line measurement and control -

Evaluation of results and outlook to future developments
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C. MARIQUE
L'économie de demain sera circulaire – recyclage de l'aluminium
Think Circular – Les afterworks d e l'économie circulaire, 19 Sep. 2019, Naxhelet

B. VANDERHEYDEN
Contribution of circular steel production to a sustainable automotive sector
Automotive Day, 24 sep. 2019, Liège

C. KECH, D. GAROT, C. NADIN, C. FRIPPIAT
Optimization and economic assessment of an environment-friendly in situ enzymatic biodiesel production method from urban sewage sludge
Poster at the 5th European Conference on Sludge Management (ECSM), 6-8 October 2019, Liège

B. VANDERHEYDEN
RECLAiming valuable METals from process residues through HIsarna ironmaking (RECLAMET) - focus on pre-processing
Prometia Seminar, 21-23 Oct. 2019, Kristiansand (Norway)

L. FRAIKIN, C. MARIQUE, M. DORMANN, A. RASSILI
La transformation et valorisation des produits usagés à base d'aluminium
Salon Métamorphoses, 5 Nov. 2019, Marche-en-Famenne

M. DORMANN
Recovery of a new type of secondary zinc oxide from the innovative ironmaking technology HIsarna
67th zinc experts meeting of the GDMB Society of Metallurgists and Miners, 20-22 Nov. 2019, Liège

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S. FLAMENT, G. WALMAG, O. LEMAIRE, M. SINNAEVE
Optimization of Hot Rolling Roughing Mill rolls to prevent premature contact fatigue damages occurrence
AISTech 2019, Pittsburg USA May 2018

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Advanced sensors for Industrial process control in the steel industry
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L. KESTENS, T. NGUYEN-MINH
The enigmatic recrystallization texture component {311}<136>
The 7th International Conference on Recrystallization and Grain Growth (Rex&GG) 4-8 August 2019, Ghent

T. NGUYEN-MINH, I. TOLLENEER
Effects of laser treatments on evolutions of microstructures and textures in electrical steels
The 7th International Conference on Recrystallization and Grain Growth (Rex&GG) 4-8 August 2019, Ghent

E. A. LOPEZ-COVALEDA, S. GHODRAT, L. A.I. KESTENS
Semi In-Situ Measurements of Thermomechanical Fatigue in Cast Iron
The 7th International Conference on Recrystallization and Grain Growth (Rex&GG), 4-8 August 2019, Ghent

O. MALOBERTI, M. NESSER, J. FORTIN, P. DASSONVALLE, J. DUPUIS, C. PINEAU, T. NGUYEN
A zero-field energy minimization principle to understand and control the magnetic domains refinement in GO SiFe – comparison between laser irradiation, scribing and ablation
The 24th Soft Magnetic Materials (SMM) Conference, 4-7 September 2019, Poznan (Poland)

O. MALOBERTI, M. NESSER, E. SALLOUM, S. PANIER, J. FORTIN, P. DASSONVALLE, C. PINEAU, T. NGUYEN, J-P. BIRAT, I. TOLLENEER
The tensor phase theory for volume magnetic structures of soft magnetic materials – Frequency dependent vector permeability and magnetic losses with time harmonics
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H. MILAN, B. VERVAET
Cooling efficiency of various emulsions during cold rolling
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P. GELTEN, G. SCHIPPER, H. UIJTDEBROEKS, P. ADRIAEN
High-Turbulence Roll Cooling in Tata Steel IJmuiden Hot Strip Mill 2
11th International Rolling Conference, 1st to 4th October 2019, Sao Paulo (Brazil)

E. A. LOPEZ-COVALEDA, S. GHODRAT, L. A.I. KESTENS
Semi in-situ Observation of Thermo Mechanical fatigue in Compacted Graphite Iron
International TMF-Workshops 4th Workshop on Thermo-Mechanical Fatigue, 13-15 Nov. 2019 Berlin (Germany)

T. NGUYEN-MINH, R. PETROV, L. KESTENS
Reconstruction of austenite microstructures in steels by global optimization of misorientation functions
The 22th Meeting Materials – M2i Conference, 10 December 2019, Noordwijkerhout (The Netherlands)

Finishing & Coating

H. MYALSKA, A. DENOIRJEAN, H. AGEORGES, P. DENOIRJEAN, L. PAWLOWSKI, R. PILEGGI , M. TULUI, A. L. MARINO, S. LIONETTI, J.-F. VANHUMBEECK, D. BERNARD, M. DETHIER
Tribological behavior of CerMet cold spray coatings used as a replacement of hard chrome coatings
International Thermal Spray Conference (ITSC 2019) 26-29 May 2019, Yokohama (Japan)

S. DETRICHE, J.-F. VANHUMBEECK, J. DELHALLE, Z. MEKHALIF
Influence of alloying elements on stainless steels electropolishing: an electrochemical impedance spectroscopy study
International Conference on Applied Surface Science, 16-20 June 2019, Pisa (Italy)

R. HARZALLAH, M. LARNICOL, C. LECLERCQ, A. HERBEIN, F. CAMPANA
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AdEPT : Une étude des techniques d'électropolissage avancées au service de l'industrie du moulage par injection
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S. REUTER, C. GEORGES, M. DUPORTAL, D. MERCIER, A. OUDRISS ET. AL.
Optimisation of the corrosion rate of iron-based alloys for bioresorbable stent applications by surface acidification
International Symposium on Surfaces and Interfaces for Biomaterials, 22-25 July 2019, Québec (Canada)

L. SAMAIN, S. PACE
A versatile and flexible roll-to-roll vacuum pilot line tailored to industrial needs
Proflex 2019 – Roll to roll coatings of flexible materials, 4-6 November 2019, Dresden (Germany)

Industry 4.0 – Sensors

G. MOREAS
Industrial applications of on line and real time microscopy
4th ESTAD (European Steel Technology and Application Days), 24-28 June 2019 - Congress Centre Düsseldorf (Germany)

L. GILON, G. MOREAS
Sensors and measurements towards industry 4.0
4th ESTAD (European Steel Technology and Application Days), 24-28 June 2019 - Congress Centre Düsseldorf (Germany)

O. HERBIET, G. MOREAS
Austenite measurement
4th ESTAD (European Steel Technology and Application Days), 24-28 June 2019 - Congress Centre Düsseldorf (Germany)

Additive Manufacturing

D. MERCIER, J. JIMENEZ, MARTIN, N. NUTAL
On the selection of Invar alloy for aerospace applications : as-cast vs additive manufactured samples
Colloque réseau national de la métallurgie, April 2019, Nancy (France)

G. LANNOO
Metal additive manufacturing is not only a question of printing
Material- Eurofinish, May 2019, Leuven

N. NUTAL, J.-F. VANHUMBEECK, S. LE CRAZ, C. GEORGES, F. DUMINICA
Finition des pièces métalliques issues de l'additive manufacturing
Technifutur® - Formations - Additive Manufacturing - Finishing de pièces fabriquées par AM – 20-21 Juni 2019


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