ANNUAL REPORT
2019

CLOSING THE VALUE CHAIN OF METALS
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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 focusing 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
Industries 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
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
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

On April 15, 2020
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.
Leadership Team

Joeri NEUTJENS, CEO

- Strategy, External Relations
- Administration & Reporting to ExecCom, BoD, GA
- R&D Management Committee
- BD, Communication, IP, Legal

Sabine MAHY, CFO

- Finance
- Facility Management
- IT

Raphael PAULUS, CHRO

- Human Resources
- QHSE
- Operational excellence
- Performance management

Eric SILBERBERG, CTO

- CTO Coating & Finishing
- Engineering
- Capex management

Griet LANNOO, CTO - CPO

- CTO Primary
- Innovation & Strategic Funding
- Iron & Steel Committee
- Program Coordination & Reporting

Philippe HARLET, CTO - CSO

- CTO applications & material science
- Technical Assistance
- Scientific Policy & Partnerships
Income by program

- Steel Collective: 11.3 Mio. EUR
- Steel effective collaboration: 5 Mio. EUR
- Other: 23.7 Mio. EUR

Income by financing

- Industrial collaboration: 88%
- National & Regional Grants: 7%
- European Grants: 5%

Total Income (CRM asbl): 40 Mio. EUR

CRM Group: 265 people

- Researchers: 46%
- Technicians: 41.5%
- Administrative staff: 12.5%

Gender balance

- Female: 22.3%
- Male: 77.7%
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.
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.

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.
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-CO₂ 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.

- 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...
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
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.

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.

![De-Zincing of scrap in the thermal pre-conditioning furnace](image)

![Schematic layout of the plasma furnace and its applications](image)
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.

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.

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.
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.
Energy transition
The pathway to a CO$_2$-neutral industry and renewable energy

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.

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
intensively used in 2019 for the torrefaction and pyrolysis of CO₂-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 CO₂ 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
choice. This facility is a pressurised (up to 45 bar) refractory-lined fixed bed reactor with a capacity of 35 dm³ of granular materials. It is equipped with external heaters, numerous gas injection lines (for air, O₂, CO, CO₂, CH₄, H₂O, N₂ and H₂) and exhaust 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 CO₂-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.

CRM is also active in the development of breakthrough low-CO₂ 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...
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 **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
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
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.

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 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 its 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

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

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).

- 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.

Let us also recall that CRM has acquired an extraordinary 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** has been evaluated as an **alternative to electrolytic Cr 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
and propelled onto the workpiece surface by compressed air or gases (N\textsubscript{2}, 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 \textit{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 \textbf{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.
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
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 galvanized 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.
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.

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.

- 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.
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.

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.
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.

**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
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.
In the field of metallic coating, more particularly 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.
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.
Robotic laser beam welding of a cargo door demonstrator and door demonstrator after hot creep forming 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

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

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

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.

- 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,
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.
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  Advanced Coatings & Construction Solutions

• **AC&CS Ivoz-Ramet** > Flémalle
  Advanced Coatings & Construction Solutions

• **CEWAC** > Liège

• **CRM Gent** > Zwijnaarde
  Centrum voor Research in Metallurgie

• **CRM Sart-Tilman** > Liège
  Centre de Recherches Métallurgiques

• **EcoTechnoPôle** > Liège
  ETP

• **PiMW Sart-Tilman** > Liège
  Pôle d’Ingénierie des Matériaux de Wallonie

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