CRM GROUP

ANNUAL REPORT 2016

CLOSING THE VALUE CHAIN OF METALS

D/2016/0124/1

Contents

Foreword

CRM is a non-profit organisation providing R&D solutions, technology and innovation, in the scope of metal and steel production. It is entrusted with the mission of developing new processes, products and applications. Closing the gap between science and market, turning inventions into products and value creation are the main missions of CRM. It is supported by more than 45 industrial members: international steel groups (ArcelorMittal and TataSteel), metal producers and industries with a metal-related activity, like material or equipment supply and metal transformation.

At CRM health and safety remains the first priority. Despite the development and deployment of good practices in this area, four accidents with lost time occurred within CRM Group entities in 2016. From January 2017, an effective management structure is in place, in order to reinforce the positive health and safety culture, intensified by the visible and active leadership of senior managers.

In 2016 the total R&D budget was more than 35 Mio EUR, actively involving 244 researchers and employees. Over 80% of CRM activities were focused on steel. CRM is also developing new processes in transversal fields like energy, recycling, valorisation of by-products and new manufacturing technologies like additive manufacturing and 3D printing. These new activities are benefiting from favorable subsidy mechanisms from the regional authority in Wallonia, participating to the "Plan Marshall" with several major and challenging contributions that are highlighted in the present report.

At European level, CRM has continued to invest in partnerships with other 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 20 European projects.

To fulfil its mission, the CRM Group is organised around five R&D units:

- The production of metal, conducting research activities in energy, iron making, electric arc furnace, recycling, valorisation of by-products and environmental issues.
- The transformation of metal with activities in casting & solidification, hot and cold rolling, pickling, thermomechanical treatment & cooling, physical metallurgy and the development of new generic steels.
- The metal coating and surface functionalization technology with activities in metallic and organic coatings, surface conversion and the development of new advanced surface properties.

- The application of metal in various fields looking for application and new designs in construction and covering the development of new materials for a large field of applications.
- Operational engineering in charge of design, dimensioning, construction, automatisation with advanced sensors and implementation of new technical solutions on CRM pilot lines and in plants.

The R&D domains are supported by laboratories specialised in chemical analysis, metallography, surface analysis with large competencies in surface reactivity and mechanical properties.

The present annual report highlights the main achievements of the year 2016 obtained in the steel collective programme, shared between ArcelorMittal and TataSteel and in the regional R&D programme in partnership with our industrial members.

A selection of relevant activities and results gained during the year 2016 are illustrated through 4 thematic sections:

- Circular economy: how to valorise metals and end-of-life products into new valuables materials and energy sources.
- Innovative processing technologies: from raw materials to final shaped products.
- New advanced metallic materials and solutions with tailor-made properties.
- Technical support, valorisation & dissemination to industry and regional economy.

We take this opportunity to warmly thank all our members and partners who, year after year, have been continuously supporting CRM and enabling us "turning innovation into value creation".

Paul PERDANG
President CRM

Jean-Claude HERMAN
General Manager CRM

Company members

On April 19, 2017

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 DUDELANGE S.A. ..... G.D. Luxembourg
ARCELORMITTAL FRANCE S.A. ..... France
ARCELORMITTAL LUXEMBOURG S.A. ..... G.D. Luxembourg
ARCELORMITTAL RODANGE et 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
APERAM Stainless France S.A.S. ..... France
AURUBIS BELGIUM N.V. ..... Belgium
BEKAERT S.A. ..... Belgium
BIOCARBON INDUSTRIES Sàrl ..... G.D. Luxembourg
CARMEUSE S.A. ..... Belgium
CBR S.A.* ..... Belgium

CMI S.A.	Belgium
COMET TRAITEMENTS S.A.	Belgium
DE LEUZE S.A.	Belgium
DELEUZE GROUP-EMUREF S.A.*	Belgium
DREVER INTERNATIONAL S.A.	Belgium
EMG Automation GmbH	Germany
ERAMET S.A.*	France
EURAGGLO S.A.S	France
FONDERIES MARICHAL, KETIN & Cie S.A.	Belgium
GONTERMANN-PEIPERS GmbH	Germany
HARSCO BELGIUM bvba	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
JASCH Europe	Belgium
LHOIST Recherche & Développement S.A.	Belgium
MAGOTTEAUX INTERNATIONAL S.A.	Belgium
NDC TECHNOLOGIES S.A.	Belgium
NLMK CLABECQ S.A. – Plates	Belgium
NLMK LA LOUVIÈRE S.A. – Strips	Belgium
PAUL WURTH S.A.	G.D. Luxembourg
PHARMA TECHNOLOGY S.A.	Belgium
PRAYON S.A.	Belgium
PRIMETALS TECHNOLOGIES AUSTRIA GmbH	Austria
RECOVAL BELGIUM SPRL	Belgium
RECYDEL S.A.	Belgium
R-TECH S.A.	Belgium
SAFRAN AERO BOOSTERS S.A.	Belgium
THY-MARCINELLE S.A.	Belgium
TI GROUP AUTOMOTIVE SYSTEMS S.A.	Belgium
TMT sarl	G.D. Luxembourg
VMZINC S.A.*	France
WOW TECHNOLOGY S.A.	Belgium

* Approved by the General Meeting of April 19, 2017

Organisation

On April 19, 2017

Board of Directors of CRM

President

Paul PERDANG, Member of the leadership team of Global R&D, ARCELORMITTAL

Vice-Presidents

Pinakin CHAUBAL, Head of Process R&D and Americas labs, ARCELORMITTAL
Ernst HOOGENES, Director R&D Europe and Director Business Excellence, TATA STEEL

Directors

Ivan AERTS, Adviseur, Centrale der Metaalbewerkers van België
Vincent CHOLET, CTO, ARCELORMITTAL Europe – Long Products
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, CMI Industry
Marc FISETTE, Head of Performance Optimisation, ArcelorMittal Europe Flat Products
Matthieu JEHL, CEO ArcelorMittal Belgium
Leo KESTENS, Professor, Universiteit Gent
Greg LUDKOVSKY, Vice-President of Global R&D, ARCELORMITTAL
Stéphane PIRON, Secrétaire Fédéral – SETCa Fédéral
Mario SINNAEVE, R&D - Quality Control Manager, S.A. des Fonderies Marichal, Ketin & Cie
Gabriel SMAL, Secrétaire Général, ACV-CSC METEA
Sven VANDEPUTTE, Managing Director, OCAS N.V.
Wim VAN DER MEER, Director R&D Programmes, TATA STEEL RD&T
Olivier VASSART, Long Products Portfolio and Research Centres Leader, ARCELORMITTAL
Pierre VILLERS, Inspecteur Général, Direction Générale des Technologies, de la Recherche et de l'Energie de la Région Wallonne
Simone VOOIJS, Director Technical Tata Steel Downstream Operations, TATA STEEL
Pierre WOLPER, Professeur, Doyen de la Faculté des Sciences Appliquées, ULg

Observers

Jean-Claude HERMAN, Directeur Général, CRM
Yvon MASYN, Adviseur, Agentschap Innoveren en Ondernemen

Auditor

Dominique JACQUET-HERMANS

* Approved by the General Meeting of April 19, 2017

Iron and Steel Committee of CRM

Members

ARCELORMITTAL
Jean-Paul ALLEMAND
Michel BABBIT
Pinakin CHAUBAL
Marc DI FANT
Maïte RODRIGUEZ
Sven VANDEPUTTE
Olivier VASSART

TATA STEEL
Mark DENYS
Loes JANSEN
Wim VAN DER MEER

CRM
Jean-Claude HERMAN
Christian MARIQUE
Griet LANNOO

CERTIFICAT DU SYSTEME DE MANAGEMENT DE LA QUALITE

ISO 9001 : 2008

Par la présente, le BQA sa déclare que le système de management de la société ***CRM Group***

CRM GROUP

dont les sièges des sociétés sont établis
Avenue du Bois Saint-Jean, 21 – 4000 Liège et Technologiepark 903c – 9052 Zwijnaarde – Belgique pour
CRM asbl *– Centre for Research in Metallurgy asbl*
et Allée de l'Innovation, 1 – 4000 Liège et Rue Sompré, 1 – 4400 Ivoz-Ramet – Belgique pour
AC&CS *sarl – Advanced Coatings and Construction Solutions sarl*
a été examiné le 02-11-2015 et a été jugé conforme à la norme ISO 9001, édition 2008 pour le domaine d'application suivant:

Recherche appliquée et activités associées telles que les essais, l'étalonnage et l'expertise.

Ce certificat est délivré par le BQA sa conformément à son manuel de qualité relatif à la certification de système et après conclusion du contrat de certification N° CER_AI_QMS_02-11-2015_336_F aux termes duquel la firme accepte un contrôle régulier de son système de management.

Certificat N° BQA_QMS019_C_2006336
Valable jusqu'au 14-09-2018

BELAC
BQA N° 019-QMS

D. SIMOENS
Directeur

BQA

BELAC

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 NBN 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 : 2012-09-11
Validity date : 2017-10-27
Original version of this certificate is in French.

Nicole MEURÉE-VANLAETHEM

.be

BELAC

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 NBN 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,

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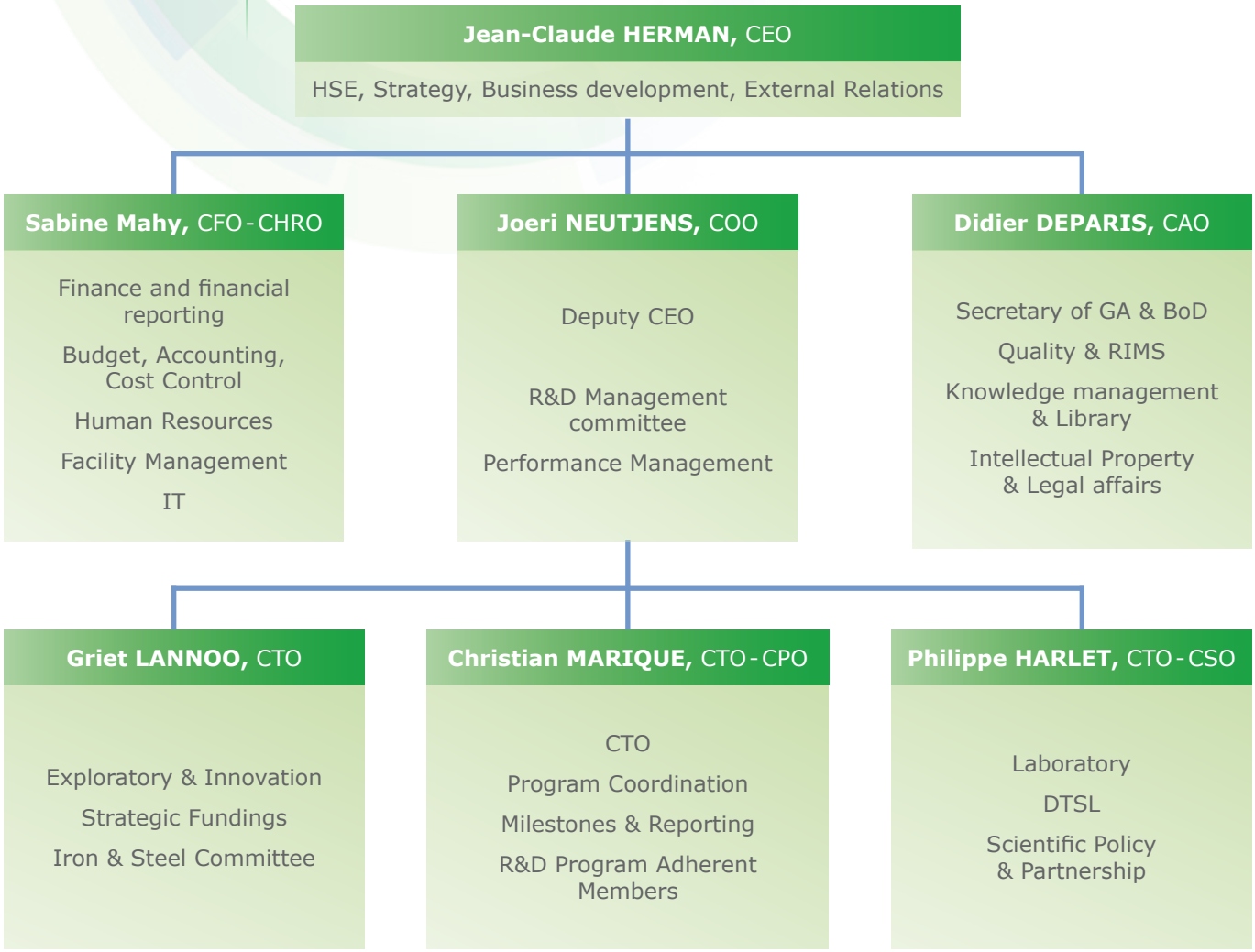
Nicole MEURÉE-VANLAETHEM

.be

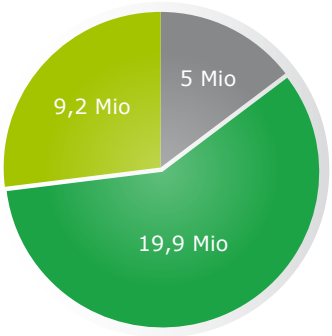
Leadership Team



CEO: Chief Executive Officer
COO: Chief Operational Officer
CFO: Chief Financial Officer
CHRO: Chief Human Resources Officer
CPO: Chef Program Officer
CTO: Chief Technical Officer
CSO: Chief Scientific Officer
CAO: Chief Administration Officer

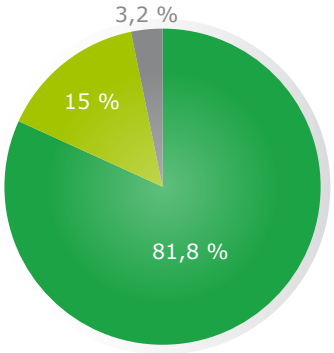
Key figures

Income by program



- Steel Collective
- Steel Private
- Other

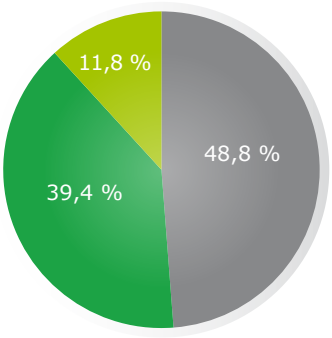
Income by financing



- Private
- National & Regional Grants
- European Grants

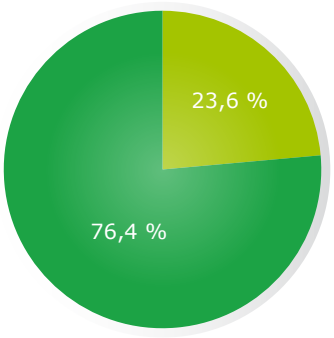
Total Income (CRM asbl): 34.1 Mio. Euros

CRM Group: 244 people



- Researchers
- Technicians
- Administrative staff

Gender balance



- Female
- Male

Report on R&D activities

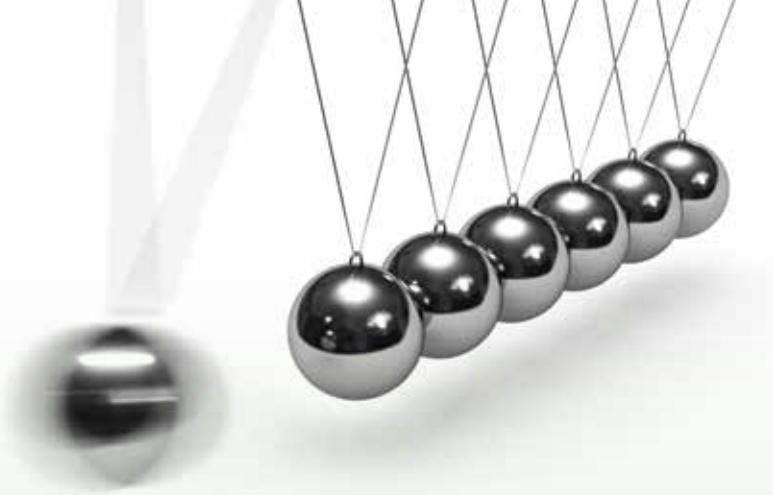
"Based on a long expertise and tradition in metallurgy and in metallic materials, gained during almost 70 years of existence, CRM Group is actively contributing to the recent evolution of the modern industry towards a larger integration of the circular economy approach, a more intense use and application of digital solutions in metal processing and products and the implementation of new manufacturing technologies for delivering innovative metallic products and solutions to the market"

One of the main missions of CRM is to provide its industrial members (45 in 2017) and customers with solutions in terms of R&D, process technology, product development and applications.

As its members are worldwide active in a broad range of technical/commercial domains and markets, CRM is also present to implement its own results and to disseminate/valorise its R&D results not only in Belgium and in Regional economy but also in Europe and in the World thanks to the efficient work of highly qualified teams covering a large scope of expertise and competences.

An aspect to be particularly pointed out is that CRM is operating big pilot facilities located in its laboratories at Liège and Gent (MPC partnership with OCAS) (sintering, melting & casting, rolling & thermal treatment, annealing & coating, metal shaping, forming and assembly). These facilities allow a faster and less expensive development and up-scaling of new process technologies, the testing and full assessment of new products, a shorter time to market of new solutions. A major objective of CRM is to keep all these equipment up to date and to continue to invest in new technologies in line with its development strategy and for the benefit of its members.

As the role of a research organisation is also to anticipate the needs of the economy and the industry, different initiatives, largely



supported by the Regional Public Authorities, have been engaged since a few years to build and promote new competences aligned with the concept of "Circular Economy" in which Steel & Metals are playing a key role, the development of "smart" products and technologies implying the use and applications of more sophisticated "digital" solutions, and the emergence of new manufacturing technologies nicknamed "3D printing, additive or hybrid processing" for supplying the market with new products and innovative solutions.

In 2016, the CRM Group was structured into five operational units:

- Metal production and recycling (raw material processing, melting & refining, by-products treatment & valorisation)
- Metal processing (casting & solidification, rolling & thermal treatment, product metallurgy)
- Metal surface and coating (metallic & organic coating, surface functionalization)
- Metal applications and construction solutions (building & structure, civil engineering, metal working & assembly, in-use properties)
- Industrial solutions (engineering & thermal technologies, industrial measurement & process control, pilot facilities)

To be mentioned that the CRM Group is certified ISO 9001 for all its activities whilst several measurement, calibration and analytical techniques are certified ISO 17025.

This report presents a selection of relevant activities and results gained during the year 2016 and open for communication that are illustrated through 4 thematic sections:

- Circular economy: how to valorise metals and end-of-life products into new valuables materials and energy sources
- Innovative processing technologies: from raw materials to final shaped products
- New advanced metallic materials and solutions with tailor-made properties
- Technical support, valorisation & dissemination to industry and regional economy

Circular Economy:
How to valorise metals & end-of-life products into new valuable materials & energy sources

"Steel and many other metals occupy a key position in the global concept of "circular economy" due to their economic and technical importance in numerous markets and application. As a recognised centre of expertise in metallic materials, CRM is actively working on the development and implementation of new recycling and production approaches."

In order to better explicit the concept of "circular economy", it can be meaningful to propose the following definition: the way to manufacture new added value products through the recycling, processing or re-use of by-products and end-of-life products coming from different industrial sectors inside a local, regional or more global economic closed loop.

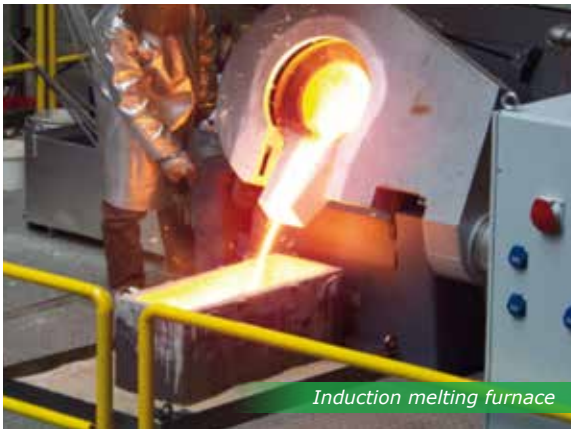
This definition perfectly fits with the activities managed by CRM around this thematic in different dedicated projects. As a first example, let us recall the program "Reverse Metallurgy", launched since two years now under the initiative and the strong support of the Walloon Government.

CRM is more especially focused on the development of pyro-metallurgical routes associating steel companies, foundries, recycling organisations and the manufacturing industry for covering different types of metallic residues issued from working shops and urban wastes collection.

• The recovery of high value alloying elements (Cr, Nb, V, Mo, …) can be illustrated through the recycling of metal chips generated during the machining of work rolls. These residues contain a high content in elements like Chromium and Niobium notably. They are compacted in a press available at CRM

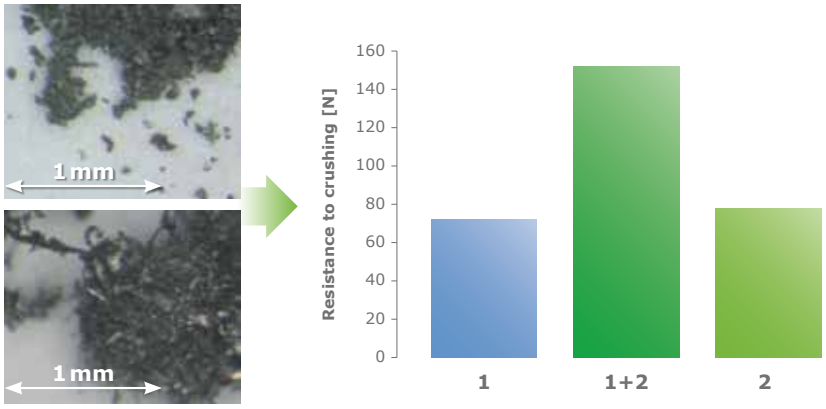
Machining of work rolls for hot strip mill

Compacted briquette made from metallic chips



Induction melting furnace

Pressing of grinding sludges



Higher briquette resistance when mixing different sizes of residues

Aluminium melting unit with post-combustion

for obtaining dense briquettes allowing their proper charging and introduction in an induction furnace. Several melting campaigns have been conducted at CRM to define the optimal operating window leading to an almost complete dissolution and adequate recovery of the ferroalloy components in the melt. This approach helps Marichal Ketin to enhance the internal valorisation of this type of residues and to reduce their consumption in ferroalloys. Another improvement concerns the briquetting and compaction of sludge produced during the grinding of work rolls with similar objectives than for the machining chips. Preliminary trials indicate the possibility to obtain coherent and resistant briquettes, a mandatory step for favouring a better valorisation of the grinding sludge.

- The synergy advantage to mix metallic residues coming from different workshops has also been demonstrated. An adequate mixing of different fine alloyed turnings favours their compaction and allows the production of higher resistant briquettes which simplifies their further handling and charging in furnace with no dust or fines formation.

- The recycling & melting of aluminium products. The equipment and ancillaries of the rotating furnace dedicated to the re-melting of aluminium products has been completed with the installation of a new fully regulated post-combustion burner, the implementation of a control room (camera

Control room

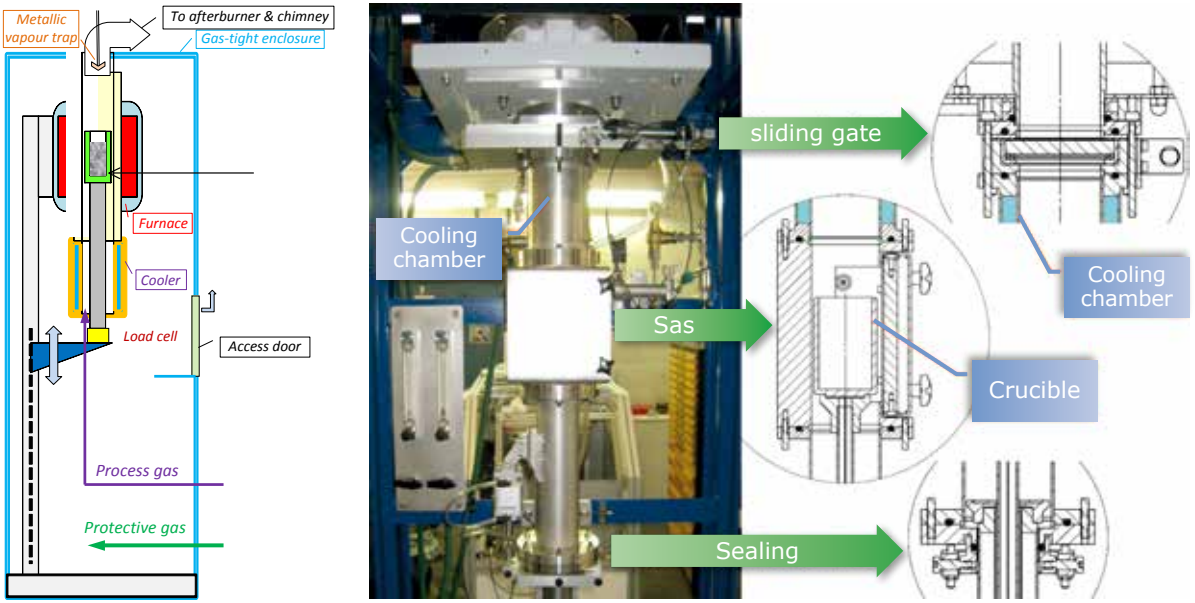
recording, temperature & data monitoring, …), the upgrading of the gas extraction and analysis system.

A large range of collected aluminium products have been processed to determine their chemical composition and assess their value-in-use as well as to fix the operating conditions and costs linked to this recycling route.

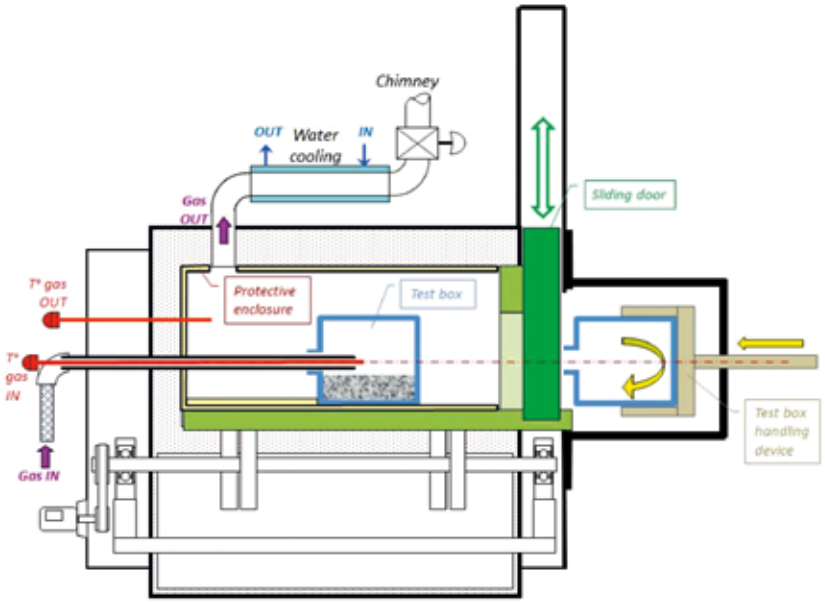
• A better valorisation of sludge, dust, scale, slag, …issued from the Steel industry and foundries is also part of the recycling activities with a focus on the development of new processing approaches.

Gas extraction circuit

Recycled aluminium products



New thermal treatment furnace fully instrumented



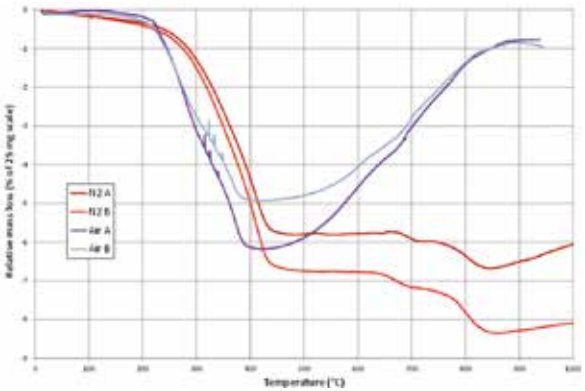
Thermal treatment furnace for processing large sample

- An original furnace has been designed by CRM to study the behaviour of these metallurgical by-products when thermally treated under controlled atmosphere to remove volatile elements and/or reduce oxidised elements. This furnace allows a continuous weighing of the sample and a monitoring of the off-gas emission when submitted to a defined thermal cycle. One of the objectives is to gain a better knowledge on the kinetic mechanisms acting on the de-zincing of metallic residues.

- A second furnace has been revamped to process larger amount of material (without continuous weighing in this case but with the possibility to stir the mix) and to allow their further melting in order to assess the metal recovery yield and the quality of the final product.

- The treatment of oily by-products is also covered through a new thermal process for obtaining solid iron-oxide aggregates more easily recycled in BOF/EAF or in BF route as alternative iron

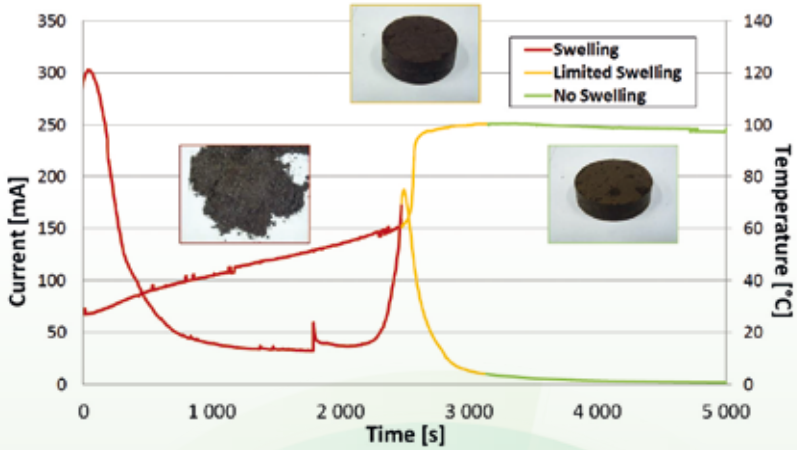
input. Using the TGA (Thermal Gas Analyser) recently acquired by CRM, preliminary trials with HSM (Hot Strip Mill) sludge collected at NLMK La Louvière have shown the possibility to produce good agglomerates whilst limiting the consumption of O2 used as combustible for the reaction. Next steps will involve the production of higher amount of compressed briquettes and their processing in the "Huge" reactor able to work at high temperature and under a high pressure (up to 50 bars).



TGA results on HSM sludges

- A dedicated action is conducted for Aperam aiming to enhance the recycling rate of the EAF dust. An original approach has been developed to produce self-reducing briquettes and to monitor the evolution of the free lime hydration prior briquetting in order to avoid any swelling and degradation risk when charging in the furnace.

A second example of large program dedicated to recycling is the initiative "KIC Raw Materials" managed under the umbrella of the European Institute of Technology (EIT). In this frame, a new project involving notably CRM, ERAMET, Comet Traitements and ArcelorMittal and named "Go 4.0" (From iron & manganese oxides wastes to valuable metal alloys using novel carbon sources materials) has been started in 2016. This up-scaling project aims to reduce the need for landfill deposits by



Control of the EAF dust hydration

turning waste streams from the metal industry into valuable products with a specific focus on:
- Carbon-thermic production of Silicon & Ferro-Manganese alloys,
- Metal & Carbon containing waste from steel & metal recycling activities. CRM is contributing by the application of high temperature pre-treatment in pilot facilities such as the Multi-Hearth-Furnace (owned by CMI) and the Rotary Kiln both available at ETP.

Rotary kiln

Multi-hearth-furnace (MHF)

Innovative processing technologies:
From raw materials to final shaped products

"Based on the competences developed after several decades of Research, Development and Innovation for the benefit of its Steel partners, a substantial part of the CRM activities remains devoted to improve the performances of the production routes and to propose new technology solutions prone to lower the energy dependence, the production costs, the quality issues,…"

Normal and high bed height sinter pot

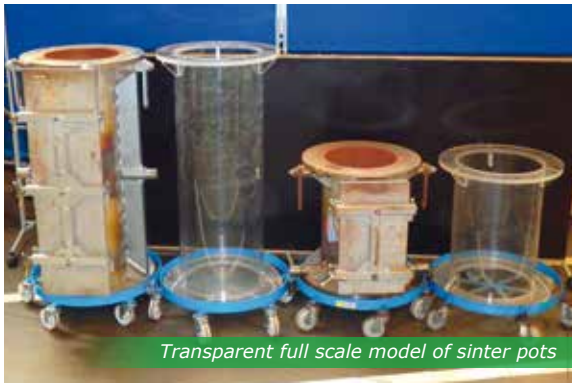
- One of the present challenges in the **sintering** area is the need to further improve the energy and raw materials efficiency due notably to their impact on the CO_2 emission whilst keeping a high productivity level and an excellent sinter quality.

To actively support its industrial members in this field, CRM continues to improve its competences and tools through the updating of the dedicated pilot facilities and the adaptation of the sintering simulation model.

As a recent example, let us mention the possibility to realise sinter pot trials with different bed heights, the pots being fully instrumented with thermocouples to evaluate the thermal profile of the sinter cake during the test. A total height up to 1m can be simulated.

Modifying the bed height is effectively one of the variables than can influence the heat consumption in the sintering process, even if other variables like the mix porosity or permeability have also a strong impact on the thermal distribution, the energy consumption (solid fuel), the productivity, …

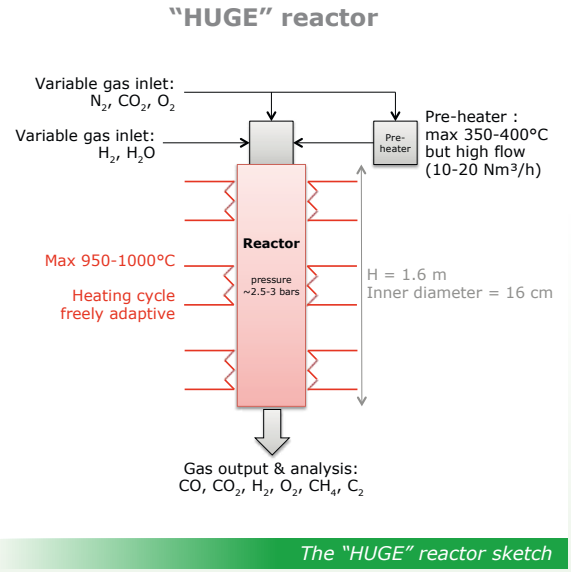
Transparent pot models of similar size than the real pots have been constructed to complete the set of simulation tools and to better assess the charging and behaviour of sinter mix with notably the vertical evolution of the mix density as a function of the bed height. This type of information is very helpful



Transparent full scale model of sinter pots

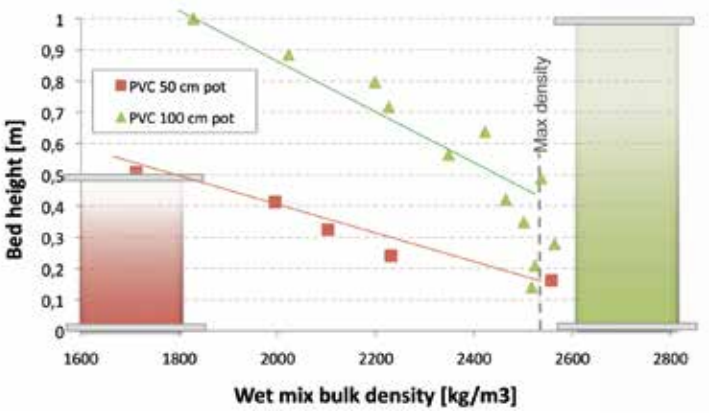
to improve the prediction of the sintering model and to propose, on a sound basis, solutions for adapting or modifying the charging phase at the entry of the sinter strand.

- A more realistic simulation of the behaviour of the ferrous burden inside the **blast furnace** is now feasible thanks to the "HUGE" reactor available at ETP ("Eco Techno Pôle" now owned by CRM). Large sample close to the industrial scale can be tested under thermal cycle, pressure and gas composition prevailing in different zones of the blast furnace.

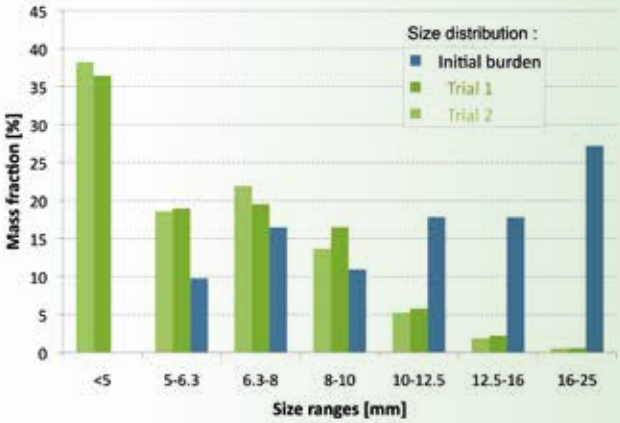


The "HUGE" reactor sketch

The degradation of the burden during its descent down to the blast furnace cohesive zone can hence be better assessed which allows a better tuning of the Mogador model used to control the blast furnace operation and also to derive good practice rules concerning the quality of the burden and its grain size distribution.



Evolution of the sinter mix density across the pot height

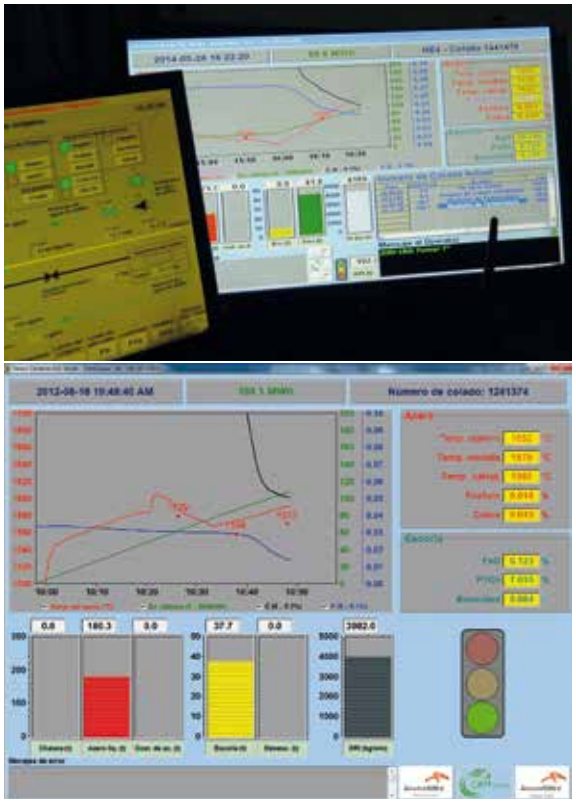


Assessment of the BF burden degradation through "HUGE" tests

- The dynamic model developed by CRM to control the **EAF operation** is now implemented on-line at ArcelorMittal Lazaro Cardenas in Mexico. This plant is operating four furnaces with a full continuous feeding of DRI (Direct Reduced Iron)

As a guidance tool for the operators, the most significant model results are displayed in the control room (temperature and carbon evolution, weight of steel and slag) as well as indications of specific events (temperature and CELOX measurements, steel and slag sampling, …)

After almost 2 years of application, substantial savings have been realised on the reduction in the number of thermocouples and probes per heat and on the decrease of the tapping temperature leading to a lower electrical energy consumption. Most of the heats are centred in a dispersion band of ± 20°c (between aimed and realised temperature) and 25% of the heats stay in a narrower band of ± 2°C which is a remarkable result.

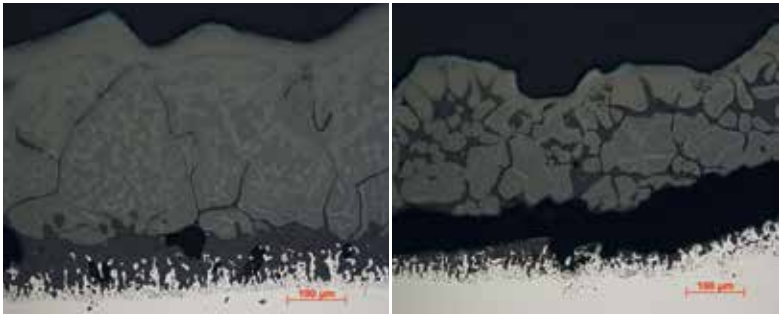


EAF dynamic model implemented at ArcelorMittal Mexico

- In the **metal processing** area, an activity requiring a particular attention is the protection of the products against oxidation at high temperature. In the frame of a project financed by the RFCS program, different protective coatings able to reduce the slab oxidation in the **reheating furnace** before entering in the rolling mill are tested. Their efficiency depends on the application temperature (cold or hot application), the applied thickness and the steel grade. Tests on high-Silicon steels have shown the possibility to reduce by 50% the oxide thickness formed after reheating. Nevertheless, the use of this kind of water-based coatings does not yet avoid the formation of Fayalite. Further developments are continuing in this field.

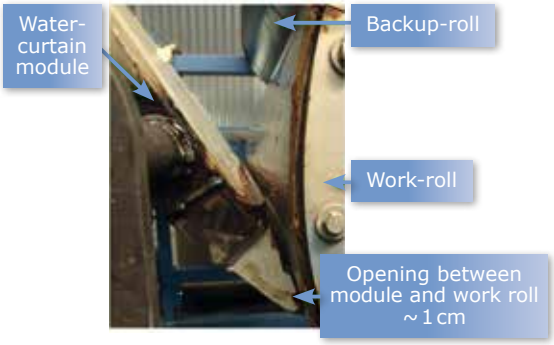
Cross section oxide formed during reheating at 1180°C **without** coating

Cross section oxide formed during reheating at 1180°C **with** coating



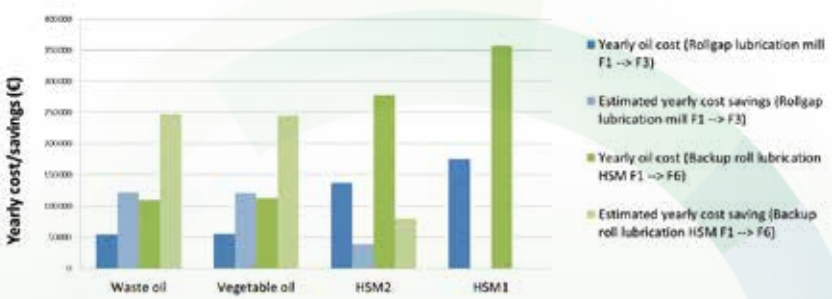
Oxide reduction during slab reheating

An enhanced lubrication of the strip during **hot rolling** whilst keeping a high efficiency for the roll and strip cooling is another important axis of development. In order to avoid as much as possible interferences between the oil and the cooling water, different design options are considered such as the modification of the entry cooling system with the replacement of the cooling ramp by nozzles and the placement of a water curtain header.



Modified entry cooling system in HSM

Projected savings if an alternative rolling oil is used, reflected on the highest oil cost



Cost savings in HSM when using alternative oils

Another approach considers the use of alternative oils such as low cost green oils or recycled waste oils coming from other processes. Hot rolling tests have indicated the possibility to drastically reduce the operating costs, compared to custom made commercial oils whilst keeping the rolling forces at the same level or even reducing them. Cost savings up to 250 k€/year could be made in industrial plants by applying or recycling these oils. Furthermore, the environmental impact will be lowered due to the higher biodegradable properties of these oils without additives.

- Improving the strip cooling performances and the lubrication are also major targets in the **cold strip mill** in particular to suppress product defects associated to excessive temperature increase during rolling. Let us recall the successful implementation of a new concept of strip cooling header based on the water pillow cushion designed by CRM in a tin plate mill of Tata Steel at IJmuiden.

Another challenge for the cold strip mill is to progressively prepare the replacement of the hard chrome plating to condition the surface of the work rolls. Several options are searched for by testing alternative coat materials. One of the substitution options studied by CRM relies on the use of electroplated Ni-based cermet coatings. Surface flash annealing of the cermet coat using an induction heating allows improving their wear resistance while preserving the mechanical properties of the bulk roll material. Even if it appears really promising, this solution needs further investigation before moving to an industrial implementation.

Whatever the substitution solution that will be implemented, these new coatings present the risk to be less wear resistant than the hard chromium plating and to lead to a downgrading of the strip surface quality through the formation of more iron fines for example. As a consequence, complementary actions to overcome this possible degradation of the strip cleanness have been launched in parallel. Among the various possibilities, CRM is more especially looking to the application of high pressure water jet to remove contaminants

Induction heating of coated roll

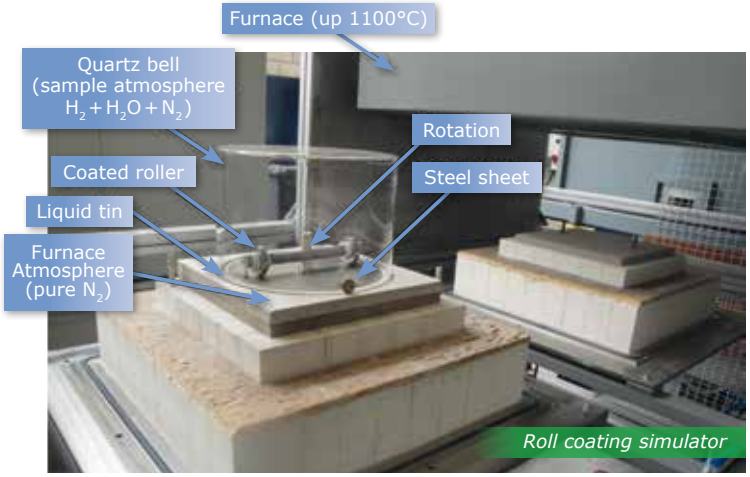
Industrial testing of the high pressure cleaning

(iron fines, oil residuals) from the strip. After tests realised on a pilot installation, industrial campaigns have been conducted in the cold rolling mill at ArcelorMittal Gent by implementing two high pressure nozzles on the top side of the strip. The positive effect of this cleaning method is clearly visible with a decrease of the iron fines by more than 40%.

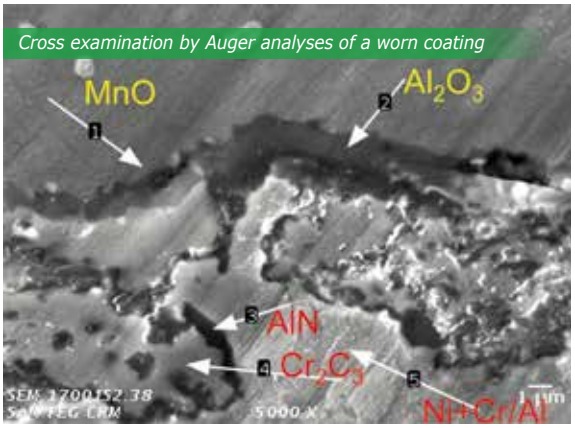
- In the **finishing & coating** area, a major challenge for the **annealing & galvanizing** lines is the processing of larger volume of high strength steels containing a high amount of alloying elements. The presence of these elements and their selective oxidation during the process can induce pick-up problems on the furnace rolls due to the interaction between these oxides and the roll material leading to sticking problems, a faster roll degradation and strip product defects.

In order to better apprehend the interaction between these different components and to propose adapted solutions, a dedicated simulator has been designed and built by CRM.

The objective is to reproduce industrial annealing conditions (atmosphere composition, temperature) and to submit samples representing the strip and the coated roll to a mutual friction contact. More precisely, two small rolls (Ø40mm) coated with different materials rotate on a high strength steel sample. The speed difference between the 2 sides of the rolls induces a friction between the roll and the steel. A quartz bell (Ø300 mm) is put over the system to allow a separate control of the atmosphere composition around the samples and inside the furnace. The hot furnace (±950°C) is moved from its parking position over the bell for realising the thermal cycle. The system is equipped with a gas analysis and temperature control. A test campaign can reach a total duration of more than 6 days. A subsequent fine analysis of the coating layers by electronic microscopy allows to deduce the potential causes or mechanisms of the degradation and to identify methods for reducing the sticking and wear issues.



Roll coating simulator

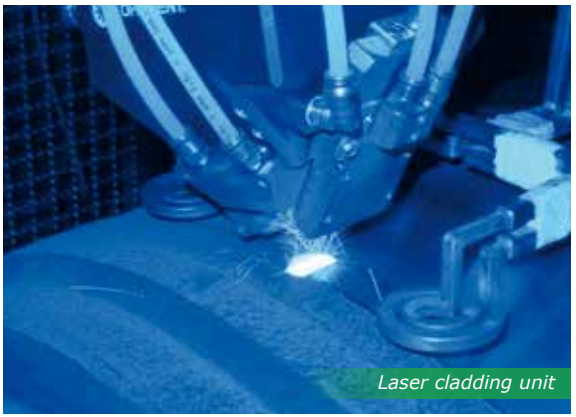


Cross examination by Auger analyses of a worn coating

New advanced metallic materials and solutions with tailor-made properties

"Whilst the existing production routes continue to offer a large potential to develop new products with improved properties, the emergence of new manufacturing technologies is another opportunity to be explored to prepare the products of the future and supply the markets with innovative solutions."

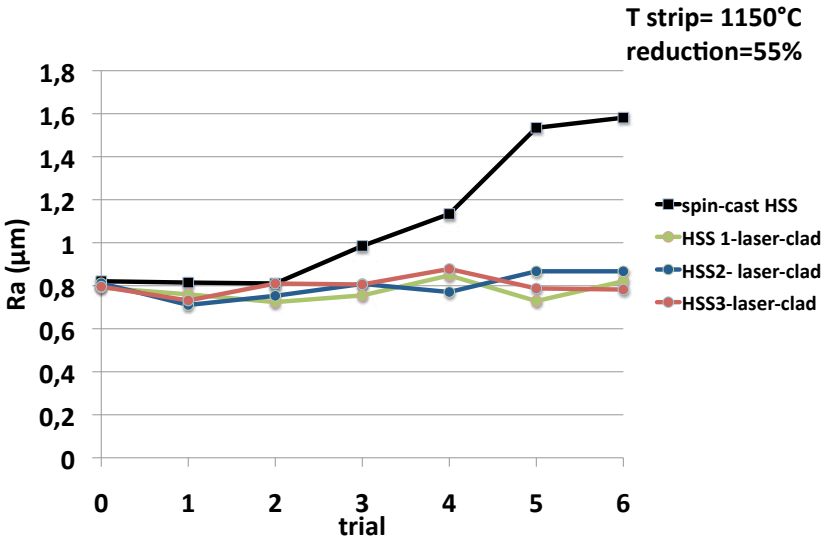
• The application of the laser cladding process is a first example of new technology that could be implemented to produce the work rolls used by the Steel industry in the hot strip mill. A pilot equipment able to process large industrial rolls has been installed in the facilities of Marichal Ketin at Liège. The basic concept is to overlay a re-usable steel arbor with a thick layer of HSS steel material. This development associates CRM, ArcelorMittal, Tata Steel and Marichal Ketin. In parallel to the set-up of this new technology and the definition of the optimal operating parameters, pilot rolling tests with the clad roll materials have been launched to assess their performances in use.



Laser cladding unit

Continuous hot rolling trials have been carried out in the pilot line at Gent with work rolls containing laser-clad inserts. Several HSS grades have been compared to a reference spin-cast HSS material.

Hot rolling test with laser-clad inserts



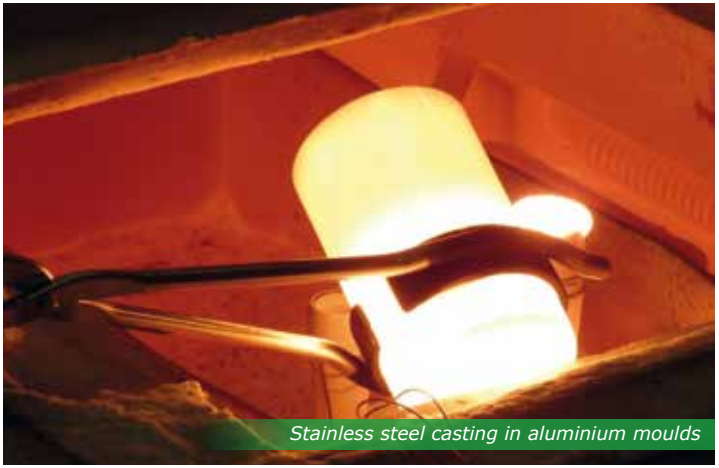
Roll surface degradation along successive rolling campaigns

Whilst the reference spin-cast materials exhibits a steadily increased roughness (from 0.8 to 1.5 µm) , the laser-clad materials show a strongly improved resistance to surface degradation as their surface roughness remains very stable evolving between 0.7 and 0.8 µm. This improved resistance to thermal fatigue and wear is linked to the refined microstructure obtained with the laser-cladding manufacturing process.

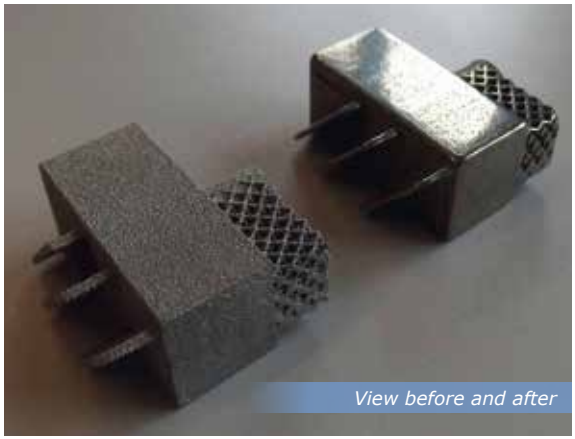
• A second example of activity where CRM was involved in collaboration with the Belgian centre specialised in refractory & ceramic materials (INISMA-CRIBC – Mons) concerns the 3D printing of ceramic moulds for foundries manufactured with the selective laser melting technology. The aim of this project was to produce ceramic moulds by additive manufacturing for the casting of low and high melting point metal alloys in order to speed up their preparation time (10 to 40h instead of 120 to 150 h) and to reduce their manufacturing cost. Alumina moulds manufactured by INISMA-CRIBC have been tested at CRM for casting aluminium and stainless steel alloys. Complex shapes such as turbine blade or valve body have been successfully cast with a small wall thickness ranging from 2 to 10 mm without problems of thermal shock resistance. The surface quality of the products is similar to that obtained with the sand casting approach.

• As a third example of CRM activities in this field, let us mention the project realised for ESA (European Space Agency) on the post-surface processing of parts produced by additive manufacturing. In this collaborative project associating Walopt, Sirris, Thales Alenia Space and CRM, three metallic materials are studied: Aluminium AlSi7Mg, Titanium Ti6Al4V and an Invar alloy. One of the targets is to smooth the surface aspect of the pieces after

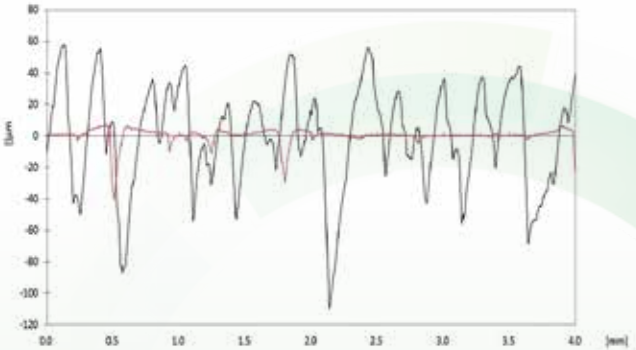
Double turbine blade ceramic mould produced by additive method



Stainless steel casting in aluminium moulds



View before and after



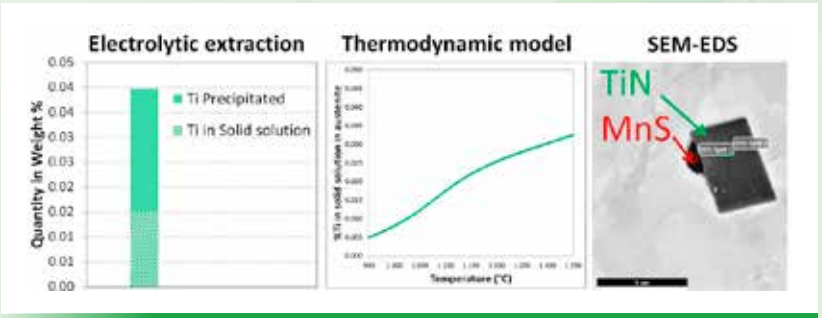
Roughness profile before and after

Post-finishing of additive manufactured parts

additive fabrication through the application of tribo-finishing and electro-polishing methods. An effective decrease of the roughness profile can be observed when combining these techniques.

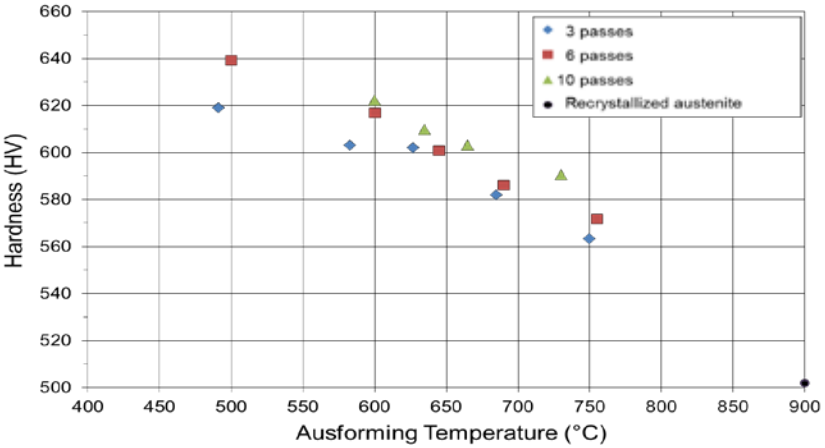
The expertise of CRM in **physical metallurgy** and process-products interactions is applied for developing or improving new generic concepts of advanced steel grades and their associated applications.

As an example, for the manufacturing of "yellow goods" such as earth-moving, equipment cranes, portal frames or applications such as truck chassis, trailers, agricultural equipment, a new generation of hot rolled HSLA steels with a resistance higher than 700 MPa and a thickness in the range 6-12 mm is searched for. Considering the severe service conditions of these applications: high loads, shocks, cold climate, the steel has to combine high strength, toughness and fatigue resistance. The addition of Titanium associated with other micro-alloying elements appears to be the best metallurgical option in order to more accurately control the grain size and the hardening precipitates of the microstructure. Several sophisticated analytical techniques are applied to study and quantify the precipitation states during the different stages of the hot rolling process. Electrolytic extraction tests coupled to SEM-EDS analysis allow a fine quantification of the formed Ti-based precipitates, with some heterogeneous nucleation occurring on existing oxides or sulphide. This information will feed in-house metallurgical models aiming to better describe the thermo-metallurgical behaviour of these HSS grades during hot rolling.



Characterisation of the Ti precipitation state by different approaches

With the target to produce super high strength steel grades (TS>2Gpa), novel approaches mixing dedicated chemical compositions and existing metallurgical routes are screened inside a project supported by the RFCS program. Ausforming rolling trials have been performed between 500°C and 850°C under variables deformation rates. A high deformation of the metastable austenite leads



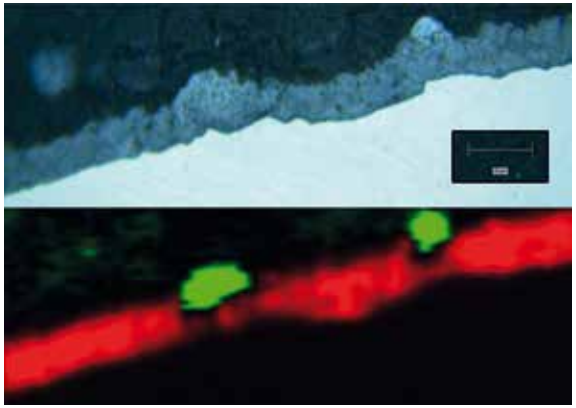
Impact of the forming process on the resistance of high strength steel

Electrochemical plasma process at CRM

to a strengthening of the microstructure. The hardening mechanisms results from a combination between the refinement of the resulting martensitic structure (when rolling at low temperature) and the inheritance of the dislocations accumulated in austenite before its transformation in martensite. This processing route allows an increase in hardness close to 140 HV (or 200Mpa for the tensile strength) without affecting noticeably the elongation. Thanks to the sophisticated in-situ measurements realised with the high resolution diffraction unit at Grenoble, more precise relationships have been established between the dislocation density inside the martensitic microstructure and the tensile strength.

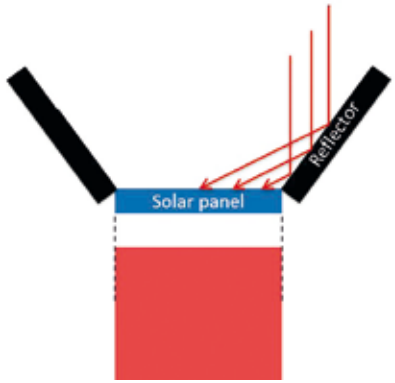
New technologies for the deposit of **hard coating** on metallic materials are also explored. In the frame of a project supported by the Walloon region (DGO6) and named "PlasmLiq", a pilot facility dedicated to develop an electrolytic plasma coating process has been implemented at CRM. It is equipped with a latest generation of 50kW pulsed current rectifiers

Stainless steel sample after plasma electro-polishing

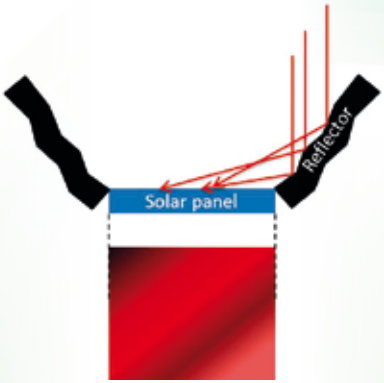


Cross-section aspect of a TiO2 layer built by plasma electrolytic oxidation

Perfect solar concentrator
➔ Homogeneous solar illumination



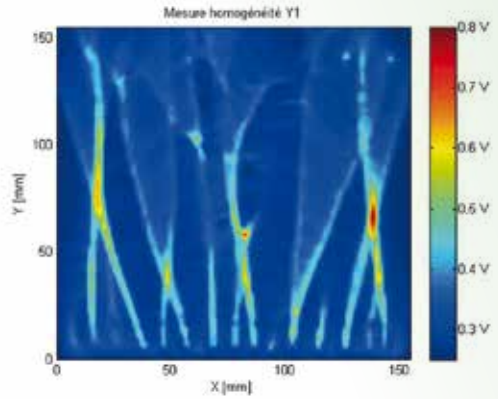
Non-perfect solar concentrator (wrinkles)
➔ Non-homogeneous illumination



Wrinkles on a solar reflector can affect the light transmission

that allows to cover a broad range of plasma surface treatments. Among the different tested approaches, let us illustrate the deposit of a fine Titanium oxide layer on a stainless steel substrate. Through a fine analysis of the surface by Raman microscopy, it is possible to identify the nature of the formed Ti-phases.

In collaboration with Walopt and ONERA, CRM is contributing to the development of a low cost concentrator solar array for ESA (European Space Agency). The tasks devoted to CRM include parts of the design of the solar panel (reflector film and its supporting structure, deploying system) and the development of a laboratory scale optical bench. This measurement unit must characterise the effect of the wrinkles on the solar reflector and their associated effects on the homogeneity of the light transmitted to the photo-voltaic receptor. As illustrated, a very good assessment of the wrinkles impact can be obtained.



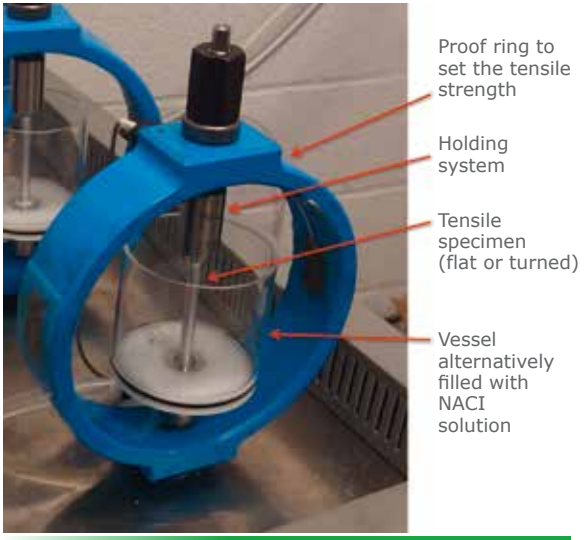
Assessment of the light homogeneity on a solar reflector

Technical support, valorisation & dissemination
to industry and regional economy

"One of the missions of a collaborative and certified research centre is to offer to its member, but also to the industry and the regional economy, its expertise to support their technical needs. The dissemination of the acquired knowledge and the promotion of its own development at the regional and international level are other important tasks."

As an introductory information, it is helpful to recall the financial support granted by the Walloon region to SME's for their development studies ordered near a certified research centre like CRM. This initiative called "Chèques technologiques" is managed by AEI (Agency for Enterprises and Innovation).

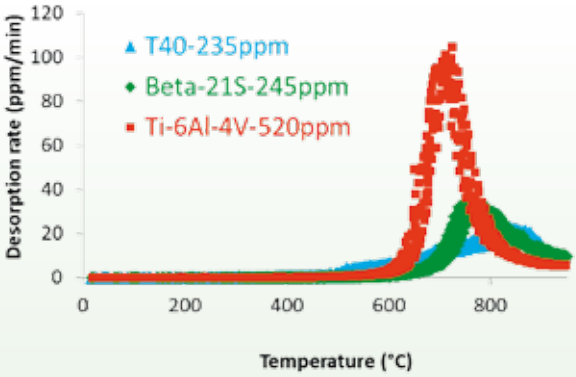
• One of the regular problems observed in several industrial situations is the cracking of components by stress corrosion. The Stress Corrosion Cracking (SCC) is difficult to detect until extensive corrosion has already taken place, leading to catastrophic failure (ex. aircraft structure, boilers, liquid or gas transmission pipes, …). In order to better apprehend this problem and to determine the susceptibility of metallic materials to the combined action of tensile stress and corrosion, a new test has been developed at CRM. The test is performed under alternate immersion of sample into a NaCl diluted solution. The sample is immersed in the solution 10 minutes every hour during 30 days. During this period, the sample is set under constant load and a large range of metallic materials can be tested (aluminium alloy, magnesium alloy, steel, stainless steel, maraging steel, titanium,...). The test is performed in accordance with the ESA norm ECSS-Q-ST-70-37C and ASTM norm G44 – 99 (2013).



The stress corrosion cracking test (SCC)

SCC installation at CRM

• In relation with the cracking in service of metallic pieces, the problem induced by the hydrogen embrittlement has also to be mentioned. CRM has developed during the last decade a great experience in this field through notably the construction of an home-made equipment for measuring the hydrogen contained in the products, its diffusion and the risk of delayed fracture. This Thermal Desorption Analyser (TDA), initially designed for measuring hydrogen (0.1 to 10 ppm) in steel products, has been recently adapted to characterise non-ferrous metals such as titanium alloys largely used in the aeronautic industry. With these alloys, the level of hydrogen that can be absorbed reaches up to 10000 ppm in certain conditions. As a matter of fact, the characterisation unit has been adapted with changes in the sample preparation procedures for hydrogen charging, in adapting the size of the sample and in selecting a different atmosphere used in TDA measurements. The measurements on Ti-based alloys are now fully reliable and in agreement with the usual standards.



Hydrogen measurements by TDA in Titanium alloys

• The assessment of the fatigue behaviour in service of metallic components is more and more requested for a lot of various applications. In order to offer the access to top class equipment, a full revamping of the CRM fatigue machines has been realised with the installation of a new hydraulic group and of a modern control unit. This upgrading offers more possibilities in the applied frequency range during the test (from 2/3 Hz up to 30Hz) and in the programming of complex stress-strain cycles.

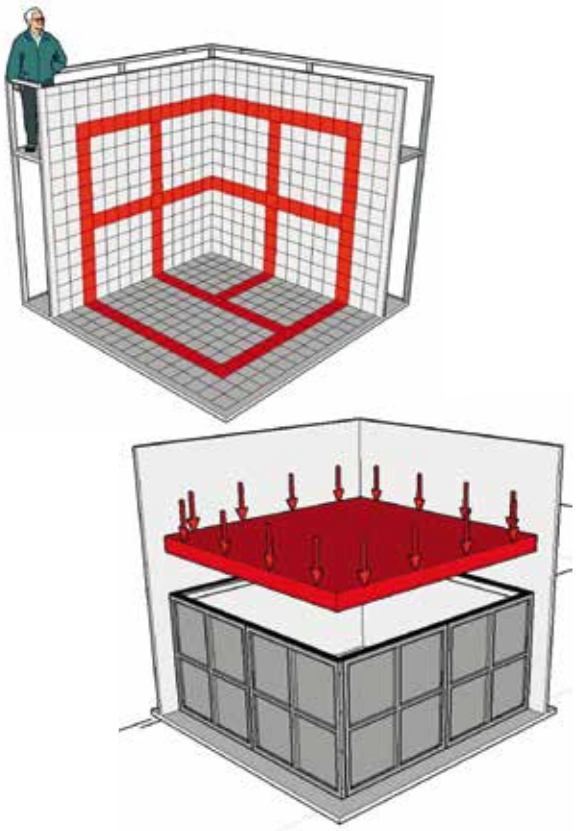
fig. 3 - Thermal Desorption Analyser (TDA)

the test machine and new control unit

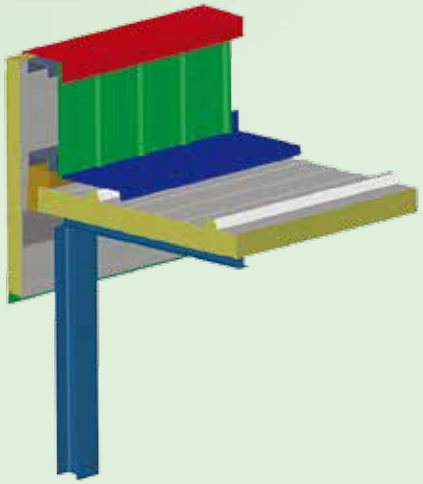
The hydraulic group

Fatigue testing equipment

• In a totally different application field dedicated to the building performances, it is of interest to present the 3D test bench designed by CRM to measure and control the airtightness ability of metallic assembling, joint or envelope structures integrated in office or industrial building and in domestic housing. With the new regulations aiming to drastically reduce the energy consumption of the buildings and housings across Europe, insulation measures have to be promoted to reduce the conductive losses through the building and house envelope by reaching a very high airtightness level. One of the goals is to eliminate the thermal bridges to drastically prevent corrosion and condensation effects in the envelope. To allow a full assessment of real structures components, CRM has designed and built a full scale test bench where it is possible to evaluate the behaviour of components like double skin and sandwich panel roofs or facades, complex joints, … Complex interactions between thermal, airtightness and hygrothermal related effects can hence be monitored on a real structure. The results of this type of test are a mandatory step to define and select robust adapted solutions. Such a platform is also helpful to train professionals and to enhance their skill linked to airtightness issues and new techniques prone to enhance the building performances.



Sketch of the 3D airtight test bench



Example of complex metallic assembly in building

View of the 3D test bench

During the year 2016, CRM has participated to different seminars, congresses, workshops or fairs.

To be particularly pointed out are:

• On October 6, 2016, CRM welcomed in Liège the seminar "Circular Economy, Reverse metallurgy and Eco-Fabrication organised by TechniFutur with representants coming from France, Luxemburg, Germany and Belgium.

• On November 21, 2016, CRM has actively contributed to the event "Recycling Valley: Innovative Reverse metallurgy in Wallonia and in Europe".

Recycling Valley

• On November 24, 2016, the participation to the exhibition "Design" organised at Liège by SPI+.

• Since several decades, CRM Group is actively participating to associations, organisations and networking aiming to exchange and share experience at the National and International level where its expertise and competence in the manufacturing and processing of metallic materials are largely recognised.

• As a collective research centre recognised by the Belgian and Regional Authorities, CRM is member of:

UCRC (Union of Collective Research Centres): The association representing at the Federal level the Belgian collective research organisations.

Wal-Tech: An association regrouping the 22 collective research centres certified by the Walloon Region. Several platforms have been created to share experience and coordinate activities.

VLOOT (VLaamse Overkoepelende Organisatie van Technologie- & Innovatieverstrekkers). It is a structural overall collaboration between more than 20 technological and scientific innovation actors in Flanders.

Examples of recycled products

CReSus (Centre for Resource Efficiency and Sustainability): A common initiative of CRM and ULg/GeMMe aiming to strengthen collaborations at regional level as well as in the European initiatives such as Horizon 2020 and EIT/KIC on (primary and secondary) raw materials.

MATERIALS RESEARCH CLUSTER GENT

MRC (Material Research Cluster Gent) is an initiative in which seven partners (OCAS, Gent University, Sirris, BIL, Clusta, CRM, SIM and its division Flamac) share commun laboratories with a strong focus on metals. This cluster has at its disposal state-of-the-art equipment for characterisation and testing from the nanoscale to large-scale industrial components and structures and more than 200 scientists and technicians under one same roof.

- At the European level, CRM takes actively part to the following organisations and platforms:

The **European Steel Technology Platform (ESTEP)** brings together all the major stakeholders in the European steel industry (steel manufacturers, universities and research institutions active in steel research, major users of steel, and public bodies like the European Commission and national governments).

Together with ULg and over 120 other European industrial, academic and research partners, CRM is since 2015 a member of the KIC (Knowledge and Innovation Community) **"EIT Raw Materials"**, covering a wide range of themes like exploration, mining, efficient use of raw materials in process manufacturing industry, recycling and substitution of critical raw materials. More info : https://eitrawmaterials.eu/

In the frame of EIT Raw Materials, a **European Pilot Plant Network for Extractive Metallurgy and Mineral Processing (Metnet)** has been created, offering to customers an access to pilot plants in order to bring ideas or concepts into industrial use. Besides CRM, the current members are Swerea MEFOS (Sweden), BRGM, CEA & ERAMET (France), GTK (Finland), ELKEM (Norway), IMN (Poland) and MPI (UK). More info : www.metnet.eu

The four independent European steel research institutes (CRM, CSM, Swerea MEFOS and VdEh-BFI) joined forces in 2011 to found **RIES**, a network that pools the complementary research areas of these institutes.

Legally formed in July 2012, **SPIRE (Sustainable Process Industry through Resource and Energy efficiency)** is a European Public Private Partnership (PPP), dedicated to innovation in energy and resource efficiency and created to meet and participate to the Horizon 2020 Framework Programme of the European Community.

Let us mention that CRM is also member of:

WorldSteel: *the International Institute of the Steel Industry,*

EUROFER: *the European Federation of the Steel Industry,*

UWE: *Union of the Walloon Enterprises*

Publications & Conferences

AWARDS

- Investigation on Work Roll Corrosion and Oxidation Mechanisms in a Hot Strip Mill has been selected to receive the 2016 AIST Rolls Technology Best Paper Award.

- 2016 Institute Medal, the highest technical award of the American Iron and Steel Institute (AISI) awarded to six industry researchers for their winning paper, "Implementation of High-Turbulence Roll Cooling at ArcelorMittal Dofasco's Hot Strip Mill."
  Authors John J. Fitzpatrick, manager, product characterization – research and development; Ghassan Gebara, business unit manager of hot mill technology; Andrei Ianos, senior specialist, hotrolling; Zafer Koont, senior research leader - all from ArcelorMittal Dofasco in Hamilton, Ontario; Patrick Van Poecke, support manager, mechanical maintenance, ArcelorMittal - Gent — and Hugo Uijtdebroeks, activity manager, process technology, metal processing, from the Centre For Research in Metallurgy in Liege-Gent, Belgium

M. Dormann,
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de Wallonie
> Liège






T +32 (0)4 254 62 11
F +32 (0)4 254 64 64
info@crmgroup.be

www.crmgroup.be