SUSTAIN

Future Steel Manufacturing Research Hub

Annual Review 2019-2020

Engineering and Physical Sciences Research Council

Swansea University Prifysgol Abertawe

The University Of Sheffield.

WMG THE UNIVERSITY OF WARWICK

Dr Richard Curry

SUSTAIN Programme Manager

Welcome

Dear SUSTAIN Network,

The SUSTAIN Hub was launched in April 2019 with unprecedented support and sponsorship from EPSRC, the UK's largest steel producing companies and the three academic partners: Swansea leading the Hub with Sheffield and Warwick forming the two initial spokes. Beneath this top layer of sponsorship and management, we have the aligned support of the UK's leading materials research and technology organisations, equipment manufacturers and applications experts.

We have now completed the first year of the project, with the last 12 months focussing upon maximising the industrial impact of our fundamental research, engaging with new companies and institutions and promoting the positive role of steel in a net zero carbon future. The SUSTAIN team are actively involved in many of the UK's steel, manufacturing and climate change conferences; some of which are highlighted in this report. Since our inaugural Engagement Event in December 2019, it has been fantastic to see the range of UK (and Global) interest in the project, both from regular steel collaborators and a host of new faces from a variety of areas including theoretical, applied and social sciences. The event helped to form the scope for the first future feasibility study call that will open in Summer 2020, inviting non-affiliated academics to apply for funding. The call will be preceded by sandpits to facilitate project development, align complementary research and facilities. We also look forward to the expansion of the Hub with two further spokes and additional opportunities for collaboration; calls for expressions of interest will be advertised in the near future.

This report contains an overview of the Hub's research Grand Challenges, Themes and Tasks. Many of the project Tasks have now started and a brief description of their progress is included. SUSTAIN strives to combine research excellence with solving the very real problems of climate change and sustainable recycling whilst maintaining the modern standard of living and profitable industrial sectors. We look forward to a not so far away future where the UK will lead the way with sustainable steelmaking – integrated steel plants processing wastes and providing green feedstock for the chemical, fuel and farming industries and renewable electricity powering low residual metal recycling, all with zero carbon dioxide emissions.

We thank everyone who has joined our network since April 2019 and invite new members to help us on our journey to a sustainable future.

Yours faithfully,
Richard Curry

Contents

Introduction

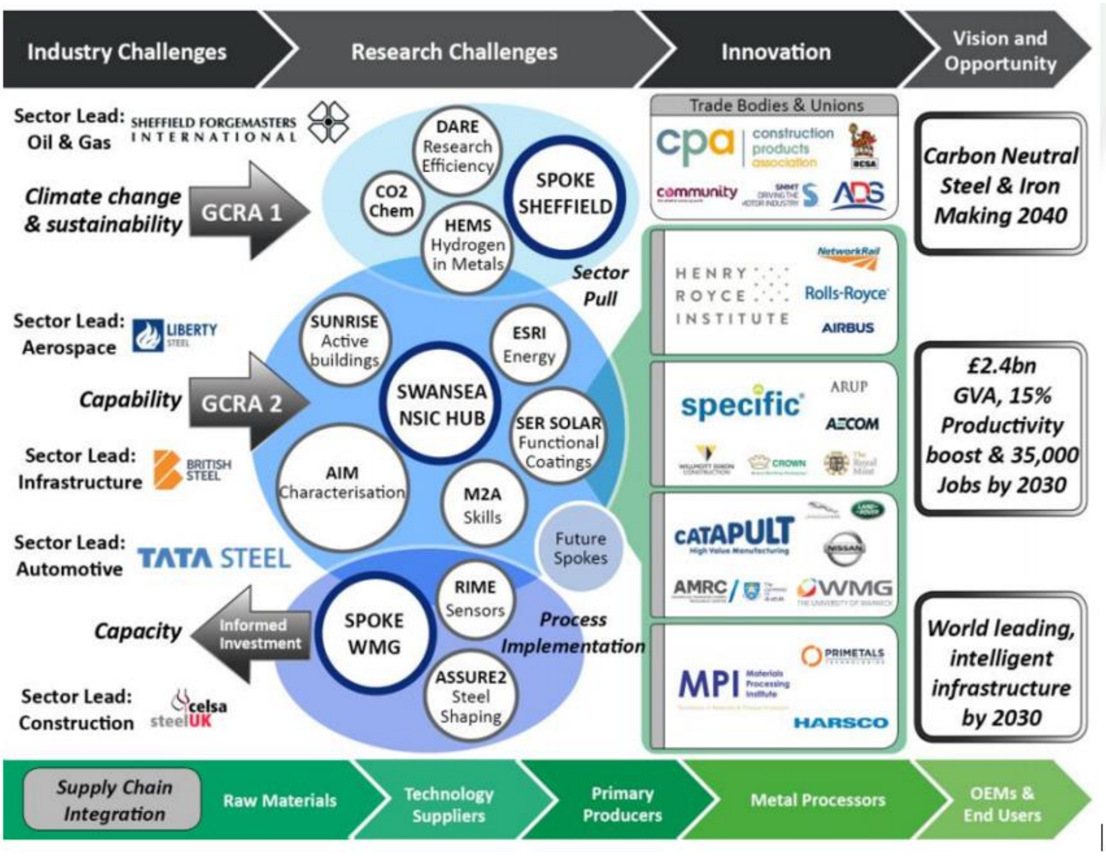
What is the SUSTAIN Project?

Steelmaking has been prominent in the UK for generations. The SUSTAIN Future Manufacturing Research Hub is a £35M project funded by £10M of EPSRC funds, as well as Universities, Trade Bodies, RTOs and Businesses over 7 years and aims to support the industry as we develop new, more environmentally friendly options to ensure the future of manufacturing in the UK.

The SUSTAIN project aims to deliver cutting edge science and the engineering research required to create carbon neutral, resource-efficient UK steel supply chains. We can enable UK manufacturing sectors to deliver world-leading resilient solutions for tomorrow's transport, energy and building needs, whilst overcoming societal waste and energy challenges. With this we can bring high-value jobs and prosperity to the UK.

Our Vision

- Academic Leadership for Steel - A nucleus for broad multidisciplinary collaboration and influence the UK research agenda for steel
- 21st Century Workforce - Innovation cannot be divorced from skills training, our outreach programme aims to influence policy and set the agenda for future skills and generate exemplary content
- Carbon Neutrality and Zero Waste - This is the number one techno-economic challenge, we must create and commercialise solutions, influence policy and create opportunities for the circular economy within the supply chain
- Smart Processes for Smart Products - To secure and build these sustainability benefits into the future and to fulfil potential market opportunity, the UK industry must supply a wider range of markets with high quality products. We aim to investigate novel processes and data driven approaches that can deliver this goal



Management and Governance

Management Team

The Management Team will provide the Hub with a clear direction over its lifetime and beyond. It is comprised of representatives from each of the Spokes and the Programme Manager. The purpose of the Management Team is to evaluate submitted proposals for academic content, resource allocation, progress monitoring and dealing with arising issues.


Dr Richard Curry
Programme Manager


Professor Cameron Pleydell-Pearce
Deputy Director


Professor Dave Worsley
Director


Professor Claire Davis
Spoke Director, Warwick


Professor Mark Rainforth
Spoke Director, Sheffield

Advisory Board

With representatives from academia, industry and government, the purpose of the Advisory Board is to evaluate industrial and academic impact, provide a technical and scientific steer, provide strategic guidance and support on the influencing of policy and assess overall progress of the Hub against its objectives.

Dr Richard Bailey (Interim)	EPSRC
Dr Louis Brimacombe (Chair)	Consultant
Mike Greenall	NSG
Dr Robert Quarshie	KTN
Professor Dierk Raabe	Max-Planck-Institut für Eisenforschung GmbH
Gareth Stace	UK Steel
Dr Walter Stahel	Product Life Institute
Professor Sybrand Van Der Zwaag	TU Delft

Operational Committee

The Operational Committee members represent some of the main organisations involved in steel manufacturing in the UK. Its purpose is to review project proposals to ensure that there are opportunities for the research to be applied within the industry to confirm relevance.

The current members of the Operational Committee are:

Richard Bailey (Interim)	EPSRC
Dr Laura Baker	Tata Steel
Cathy Bell	Liberty Steel
Dr Phil Clements	Tata Steel
Dr Richard Curry	Swansea University
Professor Claire Davis	Warwick University
Chris Hagg	Celsa Steel UK
Dr Gari Harris	British Steel
Dr Simon Pike	Liberty Steel
Professor Cameron Pleydell-Pearce	Swansea University
Professor Mark Rainforth	Sheffield University
Alan Scholes	MPI
Professor Jesus Talamantes-Silva	Sheffield Forgemasters
Byron Tucker	Tata Steel
Chris Vaughan	British Steel
Richard Warren	Make UK
Professor Dave Worsley	Swansea University

The Committee meets quarterly and members are also involved in many events and workshops organised by the Hub and the individual tasks.

SUSTAIN Team

Theme Leads

Dr Enrico Andreoli
Dr Michael Auinger
Professor Andrew Barron
Professor Arnold Beckmann
Professor Claire Davis
Professor Jan Godsell
Professor Peter Holliman
Dr Zushu Li
Professor Jonathon Linton
Professor Giovanni Montana
Professor Eric Palmiere
Professor Cameron Pleydell-Pearce
Professor Mark Rainforth
Dr Martin Strangwood
Professor Peter Styring
Dr Richard Thackray

Researchers

Dr Matthew Burton
Dr Matthew Carnie
Dr Michael Dowd
Geraint Howells
Dr Ishwar Kapoor
Dr Ria Mitchell
Fawaz Ojobowale
Dr Karen Perkins
Dr Carl Slater
Dr Zakiah Syamra Suhaimi
Dr Eurig Wyn Jones
Dr Frank Zhou

Our Grand Challenges

GCRA 1 – Carbon Neutral Iron and Steelmaking

Carbon Neutrality and Innovative Steelmaking

Steel is ubiquitous in the modern developed world; its low cost and the highly developed industry that produces it, enable the standard of living we are accustomed to. From packaging to construction, transport and energy, steel plays a major part in our daily lives without notice. Although the steelmaking process is highly efficient, for every tonne of steel produced, twice the amount of CO_2 is liberated from fossil fuels to drive the process and its energy requirements. The first of SUSTAIN's Grand Challenges aims to develop innovative methods that will eliminate the carbon footprint of steelmaking and provide a sustainable method of production and carbon neutral industry that supports global needs.

Covers: Themes 1, 2 and 3 and Tasks 1, 2, 3, 4 and 5

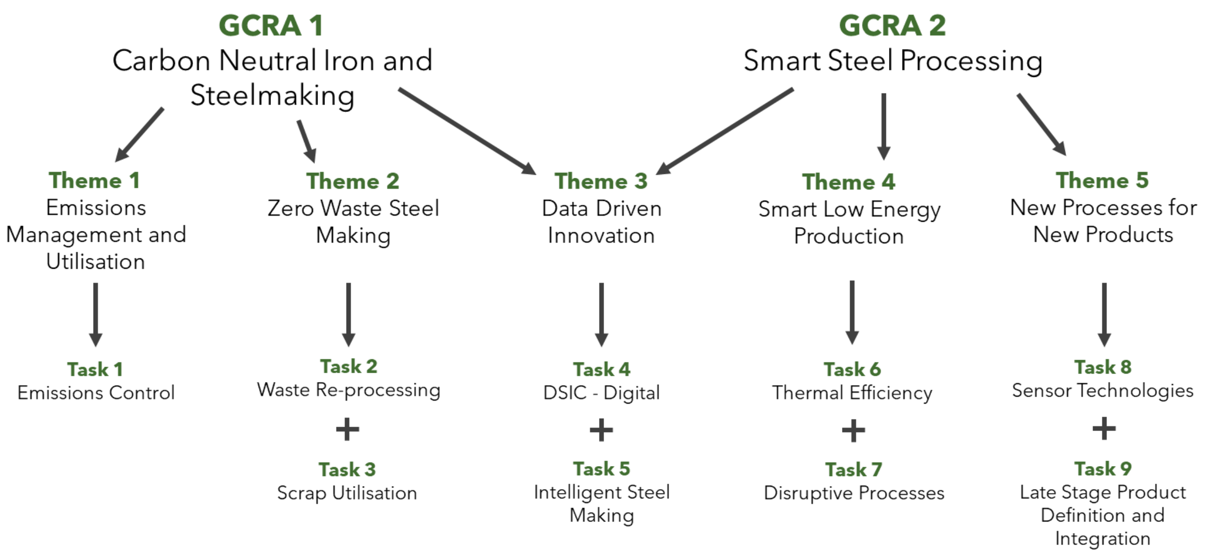
GCRA 2 – Smart Steel Processing

Metrology, Corrosion, Big Data, Industry 4.0, Alloy Processing

This Grand Challenge aims to revolutionise the steel industry through the development of steels with enhanced mechanical and physical properties, develop increased functionality and utilise the recent developments in sensor technology and digital systems. Focussing on production and supply chains, the Intelligent Steelmaking Grand Challenge is introducing concepts such as blockchain and tracking technologies into a mature supply chain and customer base that will explicitly describe the manufacturing process and sourced materials on a product by product basis. This gives the end customer and government bodies full confidence in the products performance, ethical raw material sourcing, production methods and carbon footprint.

Covers: Themes 3, 4 and 5 and Tasks 5, 6, 7, 8 and 9

SUSTAIN Workflow



Outreach and Engagement

Events Organised by the Hub

Inaugural Engagement Event December 2019

The SUSTAIN Steel project held its Inaugural Engagement Event at The Royal Society in London on 4th December 2019. The event was attended by over 70 delegates from industry, academia and government, and was launched by Professor Dave Worsley from Swansea University, followed by Gareth Stace from UK Steel. Both discussed how the industry has previously evolved but must now develop further in order to reduce carbon emissions in the face of climate change and update processes to embrace new technologies.

Academics from each task gave short presentations on their aims and objectives and how the different research areas can help achieve the Grand Challenges SUSTAIN aims to tackle. Delegates had the opportunity to view posters on each task and learn about the work being undertaken.

Grand Challenge workshops were held to delve deeper into the issues facing the industry, with high levels of engagement and enthusiasm. Many ideas were generated during these sessions, which will help shape future projects within SUSTAIN.

Events attended by Hub members

KTN Materials Research Exchange

SUSTAIN attended this event in February 2020, led by Professor Cameron Pleydell-Pearce as part of a larger display by 11 projects from Materials at Swansea. There was significant interest in the SUSTAIN project and several leads for potential collaborations were generated. Cam chaired the *Materials for Transforming Construction* Q&A session, where the panel comprised of academics and industrialists, who discussed the challenges of decarbonising on the UK economy and how materials can help solve some of these issues.

Make UK National Manufacturing Conference (February 2020)

Members of SUSTAIN attended Steel Sustainability workshops.

Global Steel Production Facilities workshop (February 2020)

Members of SUSTAIN team assisted the Alan Turning Institute on using satellite data for industrial carbon emissions.

Invited presentation

IoM3 50 Years of Alloy Development Conference, Sheffield

"Advanced Sensors for Microstructure Control" 7-8 Nov 2019 (Professor Claire Davis)

Other Engagement

Task Number	Activity
T2	Met academics from Sheffield and Cardiff and industrialists from MPI (13th Jan)
T2	Visit to Peel Jones – tuyere manufacturers (14th Jan)
T2	Meetings with Tata and N&P
T2	Invited to speak at next Iron and Steelmaking Tech Review at Tata
T4	Held workshop
T4	Discussions to organise workshop at Liberty Steel
T5	Organise workshop with UK steel partners. Participation discussions with Liberty Steel and Tata Steel
T6	Met with Vesuvius and arranged to visit their plant in Balborough

Community Outreach and Engagement

Becky Waldram, SUSTAIN's Outreach Officer is a key player in promoting and raising awareness of the science behind the SUSTAIN project to several significant school and community groups of all ages within the local South & West Wales area. The groups and activities include Discover Materials, Reaching Wider, Summer School Events, Science Family Fun Days, Swansea Science Festival, Super Science Swansea, EYST in Swansea, Climate Change Education Conference, CSI Style Science Evening, Women's Engineering Society, Women in Science and Engineering and Llanelli TeachMeet.

Online Engagement

SUSTAIN's project website (sustainsteel.ac.uk) was launched in September 2019 and has received more than 3,500 page views to date. This has been supported by the development of a profile on Twitter (@SustainSteel) and a company page on LinkedIn (/sustain-steel). To encourage audience participation, we plan to increase engagement on Social Media by launching #MetalMonday.

Future Engagement plans

SUSTAIN's initial call for feasibility studies is due to open soon. Due to the Covid-19 situation, this will be run as an introductory online webinar, followed by a virtual sandpit day. These online events aim for SUSTAIN to engage with prospective applicants and encourage the development of relationships with potential industrial partners.

We aim to grow our mailing list and deliver newsletter content on a quarterly basis, with separate subject matter for internal and external audiences.

News Articles

BBC News	£35m research hub to make steel industry carbon-neutral
Green Car Congress	UK launches £35M research network to transform the steel supply chain
Henry Royce Institute	SUSTAIN: Working towards carbon-neutral steel and smarter production
Grantham Centre for Sustainable Futures	Smarter, greener, cleaner steel - £35 million boost for research to transform UK steel industry
The Manufacturer	£35m research network to SUSTAIN UK steel industry
Materials and Manufacturing Academy	Smarter, greener, cleaner steel: £35 million for Swansea-led research

Theme 1 – Emissions Management and Utilisation

Professor Andrew R Barron (Swansea) and Professor Peter Styring (Sheffield)

This theme focusses on the challenges of Carbon Capture and Usage for large point sources of CO_2 and management of other harmful gaseous and particulate emissions. Integrated steel plants create approximately twice the tonnage of CO_2 as steel product when considering the gaseous output through process (from Blast Furnace and Coke ovens through to the rolling mills). Electric Arc Furnace (EAF) plants output significantly less as part of the primary process, but may consume more fossil fuel down-stream due to inability to recycle up-stream gasses for product heating as part of rolling and deformation processes. This output would be even greater if steel plants were not already efficient at reusing the flammable process off-gasses for heating in down-stream processes such as hot rolling.

The first challenge is demonstrating a robust recovery and separation process to extract the CO_2 from a range of output gas streams that contain other gasses including nitrogen, volatilised compounds and particulate matter. Following this process a series of parallel activities will investigate the re-use of the captured CO_2 at the laboratory scale before upscaling to industrial scale throughput. This work will focus on novel Carbon Capture and Usage strategies to produce fuels, materials and foods.

Task 1: Carbon Conversion and Environmental Pollution

Theme 2 – Zero Waste Steelmaking

Professor Peter Holliman (Swansea), Dr Zushu Li (Warwick) and Dr Richard Thackray (Sheffield)

This theme concentrates on the reuse of domestic and industrial waste products within the steelmaking process. The projects within this theme currently focus on the substitution of fossil fuels with applicable land fill waste and the reuse of end of life ferrous materials within the steelmaking process. Non-Fossil Fuel Carbon source solutions for fueling the Blast Furnace and thermo-chemical pre-treatments will be studied together with investigations into the compatibility with existing fuel injection methods. High temperature elemental scavengers will be developed to selectively remove and partition blast furnace poisons into slag.

The UK currently exports approximately 10 M tonnes of scrap steel per year that could be locally recycled. The main challenge in the reuse of this material is the management of unknown elements inherited from a range of steel types, as well as non-ferrous materials entering the scrap steel supply, introducing impurities. This theme investigates novel management through processing methods that will maximize the performance of existing and newly developed metal sorting techniques. Additionally, this theme will investigate techniques to facilitate removal of residuals from liquid steel. The ultimate effects of residual elements on product performance, both in use and during the thermomechanical processing stages, will be mapped in terms of parameters on steel manufacturing and product qualities.

Process models will be developed to provide dynamic information of environmental impact, and Life Cycle Costing (LCC) will be used to test the technical data to provide auditable macro-economic data (e.g. cost benefits).

Task 2: Integrated Steelmaking to Reprocess Waste

Task 3: Scrap Segregation and Utilisation

Theme 3 – Data Driven Innovation

Professor Janet Godsell (Warwick), Professor Giovanni Montana (Warwick), Professor Jonathan Linton (Sheffield), Professor Arnold Beckman (Swansea), Dr Michael Auinger (Warwick) and Dr Richard Thackray (Sheffield)

The business model of UK steel manufacturing, both integrated and EAF route, needs to transition from a historical inwardly focused supplier/customer relationship to one that embraces the wider end-to-end supply chain and improves productivity more holistically. A number of enabling technologies, grouped under the umbrella term of 'Industry 4.0' or 'digital', have developed to a level of maturity that when combined could provide the basis for and facilitate a step change in the performance of the end-to-end steel supply chain.

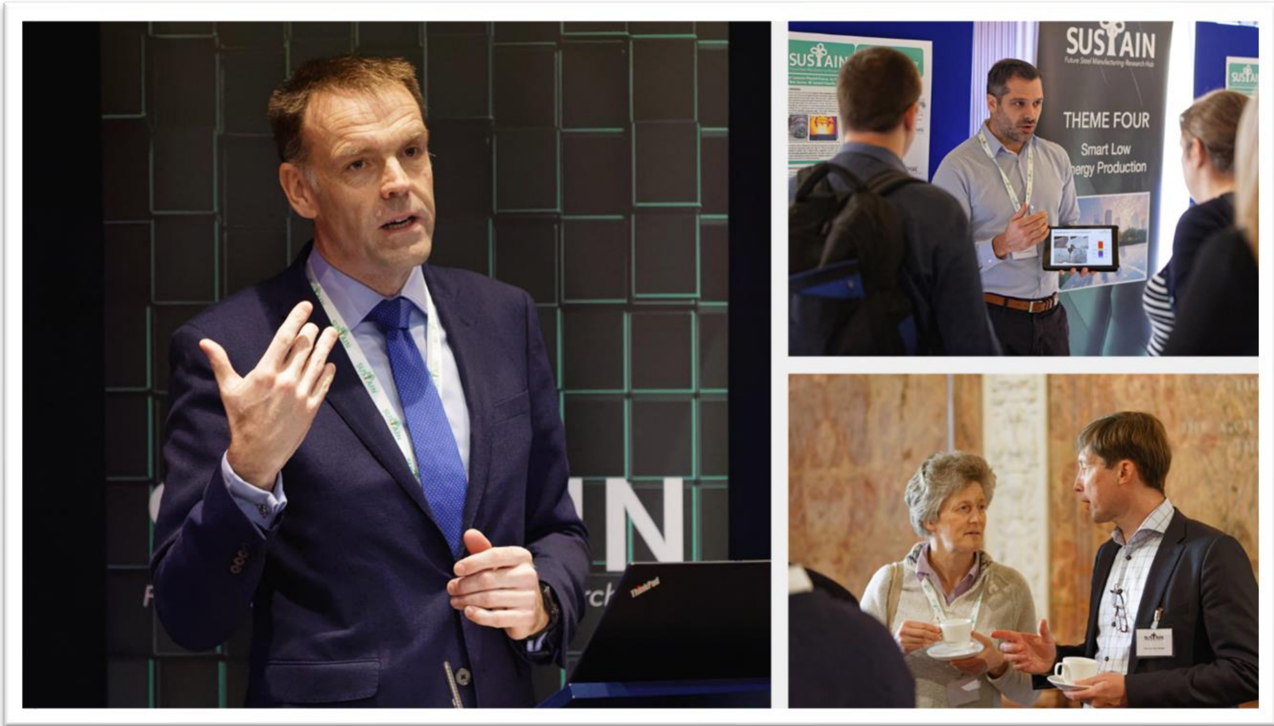
New approaches to process modelling and optimised fast-algorithm techniques will be employed to allow real-time simulation and prediction of complex thermodynamic, kinetic and mechanical processes. This will produce accurate data of the process and product that may be incorporated into complex product information databases and blockchain descriptors of product quality and process route.

The ambition is to create a data-driven step change improvement in the competitiveness of UK steel supply chains. This will ensure that the UK maximises its opportunity to contribute to the global network of steel supply chains in a sustainable and valuable way. In turn this will secure future competitiveness of companies within the UK steel supply chains.

This will require UK steel supply chains to be effective, efficient and harness the opportunities enabled by recent technological developments. To be transformative, the industry will have to be disruptive. The goal of this task is to ultimately generate disruptive technologies for 21st Century supply chains and business models.

Task 4: UK Digital Steel Innovation Hub (DSIH)

Task 5: Intelligent Steel Production



Theme 4 – Smart Low Energy Production

Professor Cameron Pleydell-Pearce (Swansea), Dr Zushu Li (Warwick), Professor Claire Davis (Warwick) and Professor Dave Worsley (Swansea)

This theme focusses on using smart techniques, enhanced material properties and non-carbon sourced reactants to reduce the net carbon usage and energy required throughout the steelmaking process. Thermal energy lost as heat throughout the steel manufacturing process is considered together with both the use of new novel materials to convert conducted and radiated heat into useful electrical energy, as is the performance and durability of existing and future refractory materials. Processing and re-use of refractory material is also considered and the impact that this will have on in-service longevity, reduction in mining of materials for refractories and financial value to industry.

This theme also investigates the use of hydrogen in the production of iron which is currently produced using fossil fuels such as natural gas. Direct Reduced Iron (DRI) is used extensively in Electric Arc Furnace (EAF) steel plants to mitigate the concentration of impurities introduced from the processed scrap metal by dilution. Greater use of DRI in the UK will allow current EAF plants to expand their product mix to include higher quality low alloy products and enable integrated plants to incorporate or move to EAF technology and maintain a large amount of their existing products in the process. Reduced processing manufacturing will also be investigated, focussing on near net-shaped casting and minimised energy input and processing of existing products.

Task 6: Thermal Efficiency

Task 7: Disruptive Processes: Direct Reduced Iron (DRI) and Near Net Shape Casting

Theme 5 – New Processes for New Products

Professor Claire Davis (Warwick), Professor Eric Palmiere (Sheffield) and Professor Mark Rainforth (Sheffield)

This theme looks at the potential of using novel chemistries, processes, and measurements to produce new products or improve the efficiency and consistency of existing high value steels. Application of electromagnetic sensors to provide improved monitoring of the steel production processes allows for greater digitalisation and control, leading to more efficient, less energy intensive manufacturing. Improved monitoring of processes is a key part to sustainability, growth and modernisation for the steel industry. Great improvements have been made for real-time monitoring and feedback control, but several areas have been highlighted where insufficient information is currently available requiring new and improved sensing approaches.

One area of focus is microstructural monitoring during processing. Research here will focus on modelling and practical experimentation of advanced microstructure measurement and control using electromagnetic sensors. Close measurement and control of microstructures during heat treatment and rolling will enable favourable microstructures to be formed and maintained, maximizing the potential properties of steel alloys for given chemistries and designs. Another area of focus is the development of ultra-high-performance steels for improved processing efficiency, reduced process energy requirements, ultra-high strength for equivalent lighter weight products and novel processes which enable late differentiation of the steel into a range of diverse products.

Task 8: Smart Sensors for Real-time Measurement: Electromagnetic Sensors

Task 9: Product Development, Late Stage Definition and Integration

Task 1 – Carbon Conversion and Environmental Pollution

Professor Andrew Barron (Swansea), Dr Enrico Andreoli (Swansea) and Professor Peter Styring (Sheffield)

Introduction

The overall aim of SUSTAIN Task 1 is to reduce steelmaking carbon emissions by capturing and converting the CO_2 into high value-added products. This approach is essential since steelmaking processes will continue generating CO_2 even in the long term; other tasks within SUSTAIN consider the development of technologies with lower carbon footprints.

Valuable products made from CO_2 will lower the overall cost of carbon capture and sequestration. CO_2-derived chemicals and fuels are particularly interesting for their added value and in some cases large market scale, allowing a future circular economy based on the recycling of carbon dioxide.

Key Aims

- Carbon dioxide separation from steelmaking relevant gas mixtures using pressure and/or temperature swing adsorption with purposely made amine-based solid-state porous sorbents and ionic liquid cellulose sorbents.
- Carbon dioxide conversion to value-added products using thermocatalytic conversion of CO_2 to CO and/or designed C-based fuels, and electrocatalytic conversion of CO_2 to ethylene and alcohols.
- Biorefinery for algae feeding and harvesting using industrial CO_2 emissions. Algae processing to high value chemicals for the food, pharmaceutical, personal care and home products industries.

Planned Impact

Providing the UK steel industry with designed scalable options for carbon dioxide valorisation.

Progress to Date

Task 1 has completed the hiring process of two postdoctoral research assistants (PDRAs), with the posts due to start in June and October 2020. This start date has been delayed to reduce the Impact of Covid-19 on recruitment and laboratory/trial work. The work at Swansea will progress with focus on amine-based sorbent synthesis and testing once the laboratories reopen.

Work on CO_2 electrolysers will start in October with the development of gas diffusion electrodes to deliver industry relevant rate of CO_2 conversion.

The bio-refinery demonstrator is almost deployed at Vale's Ni refinery. Once Covid-19 restrictions are lifted we will have the demonstrator operational within 1 month. The work at Sheffield will start with the design of the pressure swing absorber, CO_2 conversion reactors, ancillary systems and control system. This will be done remotely in the early stages and move to workshop and laboratory once the university re-opens. It is not envisaged that this will have a major impact in the early stages of the project.

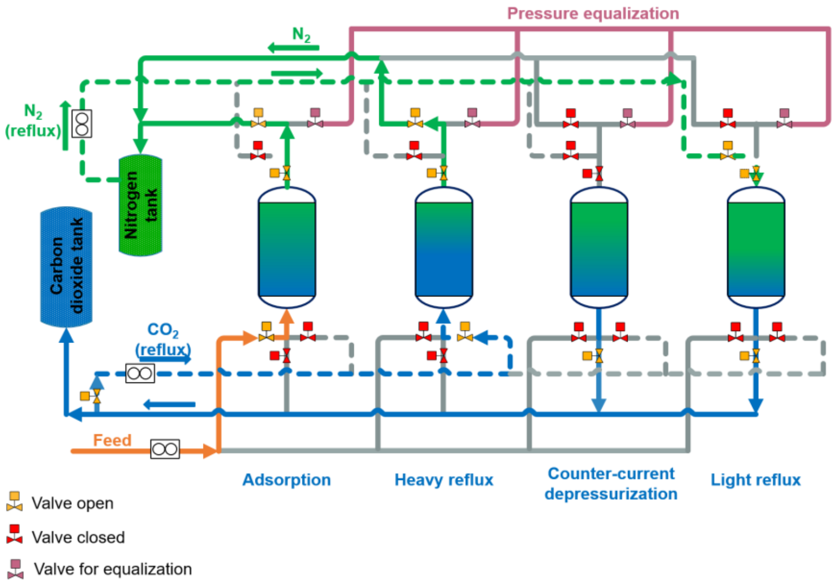


Figure 1. Schematics of operation of a 4-bed PSA unit designed and built at Swansea University for the separation of CO_2 from industrial flue and process gases, including steelmaking gas mixtures.

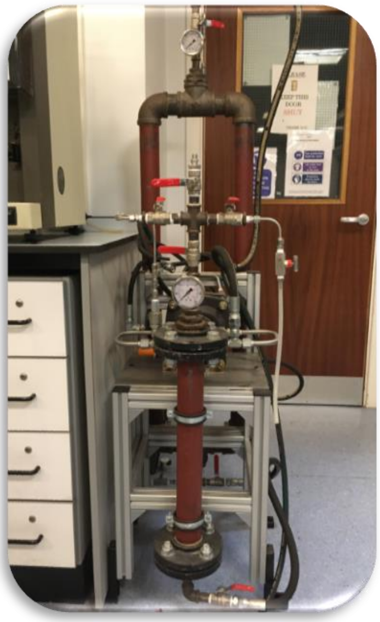


Figure 2. Single-bed PSA unit developed and built at the University of Sheffield for CO_2 separation from gas mixtures.

Figure 3. Porous copper monolith electrodes developed and tested as gas diffusion electrodes for carbon dioxide conversion to hydrocarbon in Swansea University

Figure 4. Reactor for the thermochemical conversion of CO_2 to added-value products developed at the University of Sheffield.

Outputs

There will be continued interaction with RICE operation to maximise synergy of research & innovation efforts. Sheffield will talk to potential end users.

Task 2 – Integrated Steelmaking to Reprocess Waste

Professor Peter Holliman (Swansea), Dr Eurig Jones (Swansea) and Dr Richard Thackray (Sheffield)

Introduction

Blast furnace ironmaking uses significant fossil fuel carbon. Changing to non-fossil fuel carbon sources, including wastepaper and plastics presents significant technical challenges to understand the influences of differing material handling, elemental composition, thermal chemistry and by-products. This project will test feasibility and develop understanding and control of these alternative raw materials.

Key Aims

- Characterise non-fossil fuel-carbon (NFF-C) and study the ultra-fast and slower thermal chemistry of NFF-C
- Develop catalysts and element scavengers to control NFF-C chemistry
- Study the formation and potential end-uses of NFF-C by-products
    - Study "green" coke production from NFF-C/coal blends and BF reactivity
    - Life cycle analysis of NFF-C in the BF

Planned Impact

To displace fossil fuel carbon in the blast furnace to decarbonise this.

Progress to Date

Excellent progress has been made since the PDRA started in December 2019. This is despite equipment issues introducing challenges to sample preparation and measurements. Work has progressed well on material processing (milling, sieving and flowability) to optimise this process for "pure" raw materials. Material characterisation (elemental analysis, materials chemistry) have progressed well and we are developing better understanding of key parameters.

Thermal chemistry has been studied to develop fundamental understanding (kinetics and evolved gases) of initial materials. We are developing a model to describe raw material behaviour in the BF context.

Figure 5a. Left - cutting mill for sample preparation and 5b. Right - pyrolyser

Outputs

- Initial paper using the GCms equipment on plastic analysis - G.L. Sullivan, J. Delgado Gallardo, E.W. Jones, P.J. Holliman, T.M. Watson, S. Sarp, Chemosphere, 2020, 249, 126179
- Meeting with MPI, Sheffield and Cardiff Uni, 13 Jan 2020
- Presented to Tata meeting with N&P, 13 Feb 2020
- Meeting with Celsa, 17 Feb 2020
- Towards Low Carbon Steelmaking. E.W. Jones, F. Ojobowale, P.J. Holliman, Royal Society of Chemistry Twitter poster competition, Feb 2020
- Presented to Iron & Steelmaking Technical Review (online) with Tata Steel, 7 April 2020
- Working on new paper on NFF-C concept

Task 3 – Scrap Segregation and Utilisation

Dr Zushu Li (Warwick), Dr Ishwar Kapoor (Warwick), Professor Claire Davis (Warwick) and Dr Richard Thackray (Sheffield)




Introduction

Significantly increasing the use of UK-generated scrap in steel production has become a strategic direction for the UK Steel industry. This task investigates the effects of residual elements inherited from steel scraps on material processability and the properties of typical products. It will provide a fundamental understanding and the technological developments to maximise scrap utilisation for manufacturing high quality steel products at an economical cost. This work will help achieve the government's compulsory target of reducing CO_2 emissions by 80% before 2050, and net-zero emissions for the steel industry whilst maintaining the sustainability and profitability of the UK steel industry.

Key Aims

- To reveal the effects of residual elements on steel processability and product qualities for typical steel grades by advanced characterisation and testing
- To discover the effects of processing parameters on the tolerance of residual elements in steel
- To explore or implement the knowledge/technologies developed in the project in industry
- To develop a framework to assess the economically feasible removal limits of the residual elements and the recovery rates of valuable alloying elements from scrap during processing

Planned Impact

To provide an in-depth understanding and the technological developments for maximising the utilisation of UK-generated steel scrap in the production of high-quality steel products at an economical cost, whilst ensuring the sustainability and profitability of the UK steel industry and minimising the environmental impact.

Progress to Date

1. We are carrying out a critical literature review on the effects of residual elements and processing parameters on steel processability and product properties. This will enable the steel community to understand the state-of-the-art of this topic, reveal knowledge/ technology gaps, and prioritise our research activities. This ongoing literature review focuses on the downstream process of the steel manufacturing route, from casting through hot-rolling, cold-rolling and annealing to assessing mechanical properties.
2. We have been extensively engaging with industry partners to define the key steel grades to be studied, their processing routes (parameters) and their current specification of residual elements. We are also asking the industrial partners to provide production samples at different stages as benchmarking materials.
3. Accordingly, we are designing the experimental layout and chemistry. We are using the melting and casting facilities at WMG of the University of Warwick to make typical steel grades in the laboratory; the first steel grade we are making is Low Carbon Free Cutting Steel (LCFCS) with increased levels of the residual element copper.
4. We are investigating the as-cast microstructure in EBSD. Particles were investigated in SEM-EDS and STEM-EDS. This is helping us understand the effect of copper associated with MnS particles, on copper enrichment at grain boundaries.

It should be pointed out that the activities 2 to 4 have been affected by the COVID-19 pandemic. Industrial sampling and sample delivery have been postponed and the researchers are unable to access the laboratory and office since mid- March 2020 (e.g. reduced resources in industry and university closure).

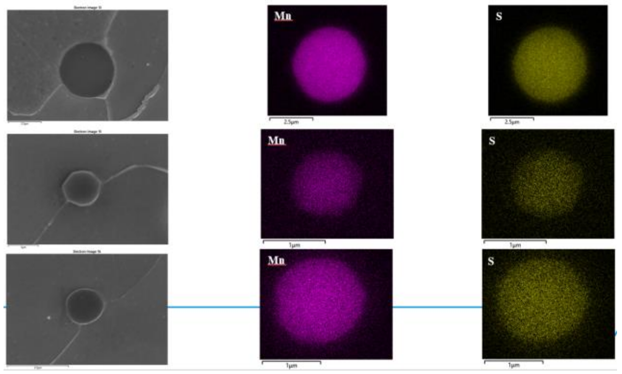


Figure 6. MnS particles in the as-cast low carbon free cutting steel (LCFCS) manufactured at WMG (SEM-EDS)

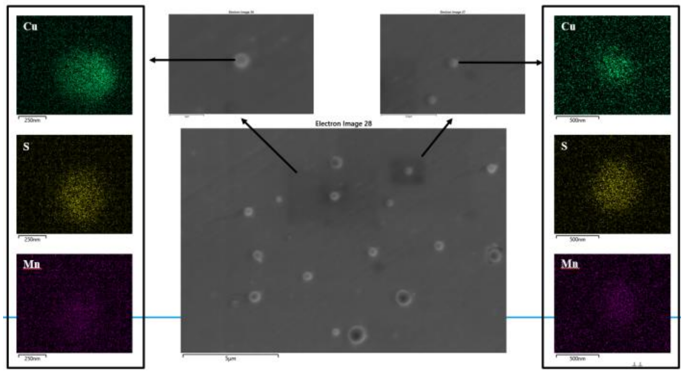


Figure 7. Copper rich MnS particles in the as-cast low carbon free cutting steel (LCFCS) manufactured at WMG (STEM-EDS)

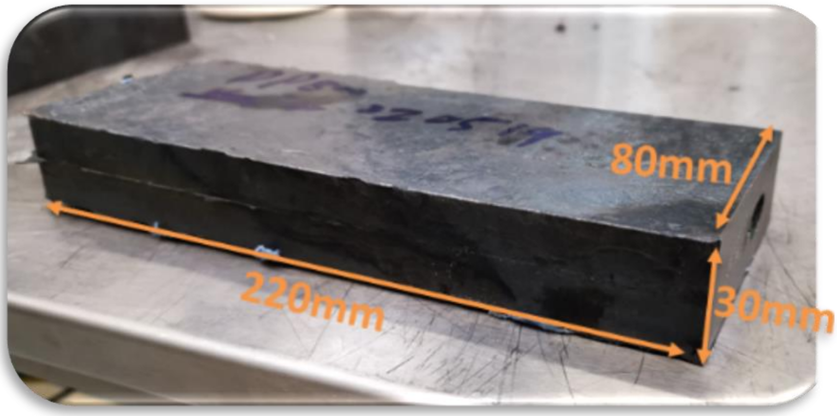


Figure 8a. Left – Vacuum induction melting (VIM) furnace for melting/casting steel in lab, and 8b. Right – an ingot casted from VIM melting.

Outputs

- Experimental (SEM-EDS and hot-ductility) investigations on LCFCS are on ongoing which will result in research findings for a Journal
- Meeting with industrial collaborators (Liberty Steel and British Steel) – exchanging new research ideas
- Working on a project proposal for summer internship 2021 programme with WMG and IIT Guwahati – Combine experimental techniques (in WMG) with FE-modelling (in IIT Guwahati)
- Attended Designing Alloys for Resource Efficiency (DARE) conference held in Sheffield (11th-12th Feb. 2020)
- Attended SUSTAIN Engagement Event The Royal Society London (4th December 2019)
- Organised and held a Residual Workshop

Task 4 – UK Digital Steel Innovation Hub (DSIH)

Professor Arnold Beckmann (Swansea), Professor Giovanni Montana (Warwick), Professor Jan Godsell (Warwick), Dr Zakiah Suhaimi (Warwick) and Professor Jonathan Linton (Sheffield)

Introduction

The Digital Steel Innovation Hub is a dynamic network that provides industrial partners with the opportunity to rapidly identify promising data driven innovations and funding for further development. This enables industry (through problem driven proposals) and academia (through capability driven proposals) to share promising ideas for such innovations.

Key Aims

- To improve effectiveness and efficiency of processes within UK steel supply chain
- To improve value added and productivity of products and processes of UK steel supply chain

Planned Impact

To improve productivity of end to end steel supply chain through digital technologies.

Progress to Date

The project's initial PDRA was recruited In September 2019 to begin the first stage of the task and commence discussions with Industrial partners (British Steel, Liberty Steel, Forgemasters and Tata Steel). Industrial and academic partners have discussed and defined DSIH governance and next steps. A series of workshops were organised where industrial partners shared their key challenges as well opportunities and potential projects that could be explored within T4. Academic partners presented their approach and a buy-in was obtained for Ops and SCM area. For other areas, generalisation of the projects is required.

The agreed next step for further projects is to work with both commercial and technical leads of a chosen company on a project brief. Once finalised, each academic partner will need to receive the appropriate buy-in from the other industrial partners. Within Data Science, a PhD candidate has been identified, whereas for the PDRF re-advertisement is necessary. For Computer Science, the PDRF post has been advertised.

As part of the Operations and Supply Chain Management approach, an engagement event with top management level was carried out at Liberty Steel, Stockbridge. Positive feedback was received and a work plan has been discussed to move forward.

Outputs

- T4 July 2019 workshop
- T4 January 2020 workshop
- Engagement event with Liberty Steel

Task 5 – Intelligent Steel Production

Dr Michael Auinger (Warwick) and Dr Richard Thackray (Sheffield)

Introduction

Many existing process models for steel production do not allow for process alignment and are too complex for meaningful real-time predictive use. The primary aim of Task 5 is to take a different view on steel production in its entirety by not seeking to improving product qualities, but by focussing on decreasing energy usage and building links across the entire process chain. This will be achieved by the development and optimisation of process level models supported by experimental verification, analysis of process data, and by benchmarking current process routes to quantitatively assess how efficiently industry currently uses both energy and materials.

Key Aims

- Inventory of Existing Process Efficiency and Resource Flows
- Analytics of Process Data
- Optimisation of the Building Blocks
- Life Cycle Assessment to Quantify Efficiency Gains

Planned Impact

Delivery of coherent process level model and assessments for fast and efficient optimisation of the process chain with respect to cost, energy flow and material usage.

Progress to Date

The project has received significant input from both industrial and academic partners and has identified state of the art historical process simulations within the industry that are of relevance to project. This, together with SUSTAIN's robust project assessment process has strengthened the proposal and opened up new exciting areas of research within this task.

An industry partner workshop to identify specific areas of interest in this task has been planned but is postponed due to the availability of key industrial researchers and technologists who have been furloughed in the wake of the COVID19 pandemic. However, the academic partners have begun to review existing relevant literature and detailed discussions will begin with industry partners as soon as possible.

Recruitment of two PDRAs to work on this task began In Q4 of the project but will now be delayed by the COVID19 pandemic.

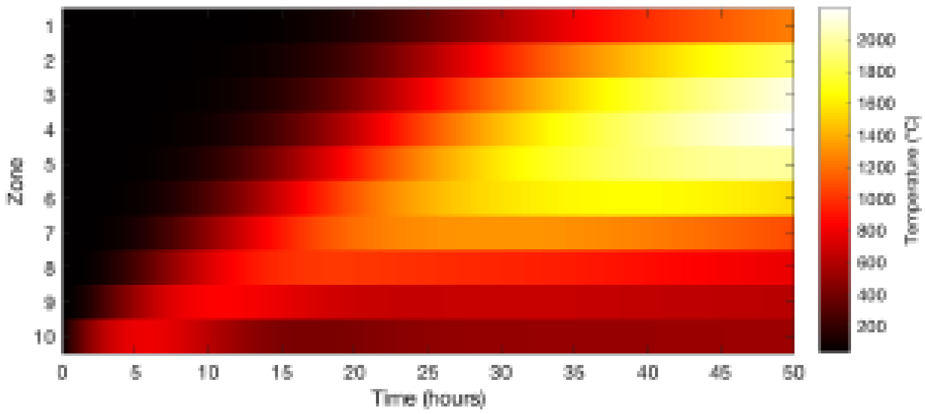


Figure 9. Evolution of blast furnace temperature with time for an off standard coal/oxygen-ratio during the beginning of operation.

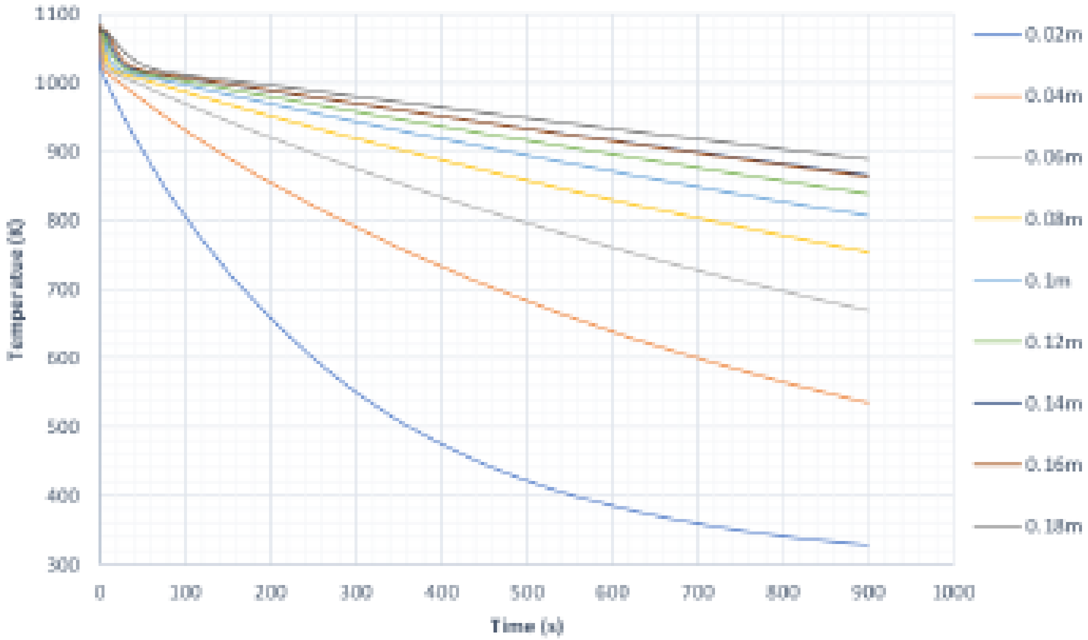
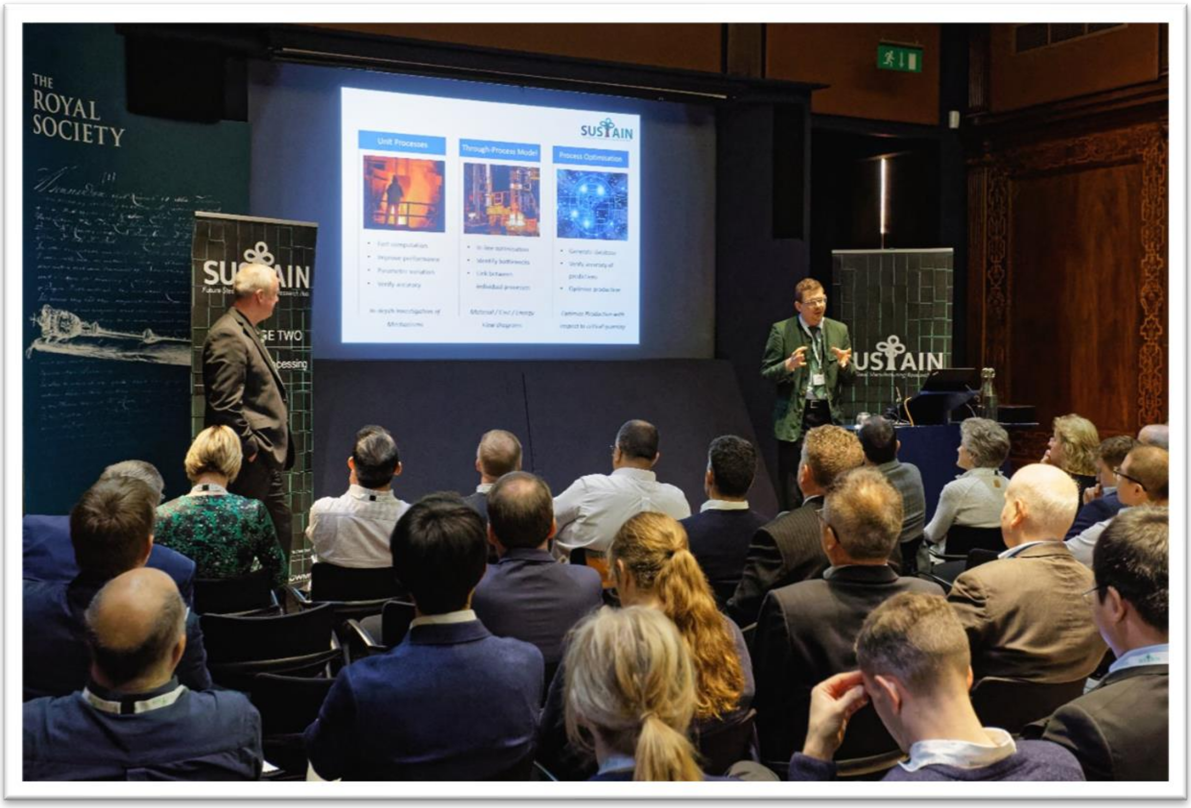


Figure 10. Change of pellet temperature in a sinter cooler as a function of pellet diameter.

Outputs

None as yet – a workshop bringing the key industry partners together to discuss plans for this task in detail had to be postponed and plans for a virtual workshop are now under discussion.



Task 6 – Thermal Efficiency

Professor Cameron Pleydell-Pearce (Swansea), Dr Karen Perkins (Swansea), Dr Matthew Carnie (Swansea), Dr Ria Mitchell (Swansea), Dr Matthew Burton (Swansea), Dr Mike Dowd (Swansea) and Geraint Howells (Swansea)

Introduction

Refractories are the fourth most critical material group to the steel industry (behind iron ore, coal and scrap) and affect the steel's embodied energy and quality. By way of example the average annual steel plant budget for refractories is around £25m without considering prior (extractive metallurgy), or post processing (re-heating for thermomechanical processing). Magnesia Carbon materials make up the vast majority of total supply to both BF/BOF and EAF steelmakers in ladles. We are using advanced characterisation and testing techniques to improve understanding of structure-property relations in this family. The team is also exploring new bulk structured thermoelectric systems via a PhD project that could be integrated into the lining for self-powered energy generation or sensor applications.






Key Aims

- Develop as multiscale ex-situ structural characterisation approach for refractories
- Improve understanding of structure-property relations in magnesia carbon refractories
- Develop robust, cost effective thermoelectric materials/devices for integration into refractory linings
- Build UK academic skill base in the field of refractories

Planned Impact

This activity has the potential to significantly improve value in use of refractories and introduce greater online diagnostic capability with the potential to deliver multi £m annual savings for any one steel making company.

Progress to Date

To date the project has been assessing the characterisation approach and its feasibility for refractory materials. To understand through volume behaviour a selection of samples have been scanned via X-Ray computed tomography (XCT) in both the virgin and post processed conditions. The early signs are promising with excellent structural detail revealed and good contrast between the different constituents of the refractory, which may be generally considered a composite of different mineral aggregates secured by an intergranular carbon-based binder. Some samples have also been analysed in the oxidised condition to determine whether the decarburisation of the materials can be assessed by XCT alone.

This provides confidence that a correlative microscopy approach developed at Swansea to XCT structures before and after processing, using digital volume correlation to track the evolution of specific microstructural features before and after treatment, will be successful. This will be the target of study in the next phase of the project. The discernible differences in density between the intergranular binder and refractories make these structures ideally suited to this. Specific features of interest from the broader 3D volume can then be tracked through to SEM, FIB-SEM and even TEM analysis whilst recording their role in the wider context of the system (a "google maps" approach).

The PhD program covering thermoelectrics is currently at an early stage and is investigating initial options for the adoption of printed type SnSe thermoelectric generators in the high temperature processes. Key scientific challenges to overcome, are the significantly higher temperature regimes than those generally targeted for these technologies and the long-term stability of the devices (chemical/structural decomposition over time). The SnSe system is of particular interest because: 1. it is a new system and 2. there are interesting efficiency trends as a function of temperature highlighted in preliminary work, however this relationship and device stability requires significant research activity to determine its success. Based on the preliminary research it is anticipated that the thermal stability of the material will need to be enhanced to make the systems suitable for this application. As both strands of the work program mature, the ambition is to investigate the potential integration of the technologies into refractory linings.

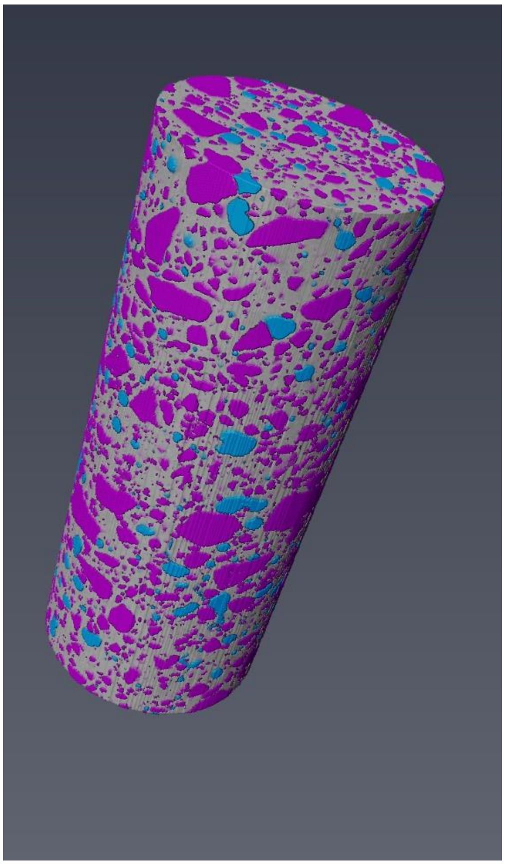


Figure 11. 3D Structural analysis of refractory core sample by XCT.

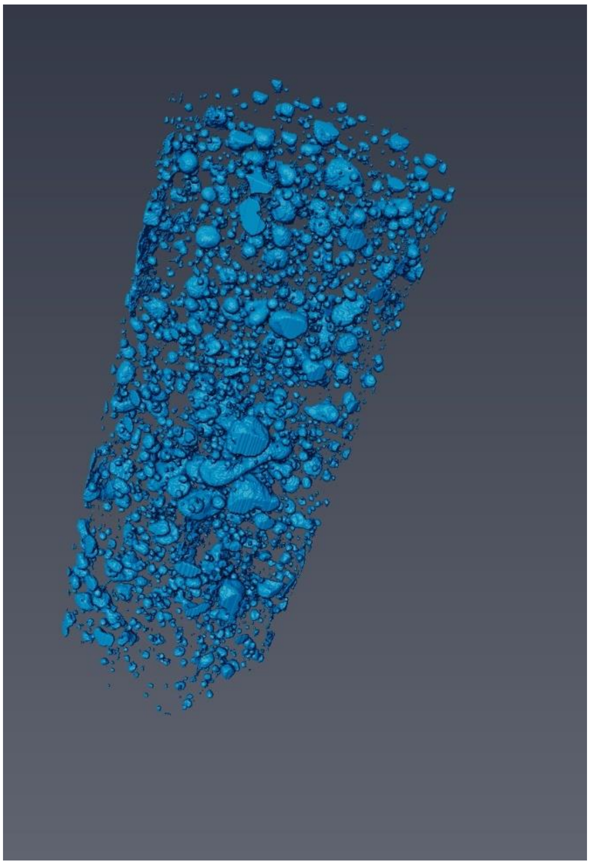


Figure 12. Segmentation of the same volume to reveal porosity.

Outputs

Fellowship proposal in preparation on thermoelectric devices.

Task 7 – Production of Direct Reduced Iron (DRI) by Using Renewable Energy Generated Hydrogen

Dr Zushu Li (Warwick)

Introduction

Hydrogen is an environmentally cleaner resource of energy to end users without the release of pollutants, such as particulate matter or carbon dioxide at the point of end use. Significant development of renewable energy enables the production of pure hydrogen by water electrolysis (instead of reforming natural gas) without environmental impact, although substantial work (e.g. cost, storage, distribution infrastructure) needs to be done to overcome the challenges for H_2 to be a major economy factor. The production of direct reduced iron (DRI) by using renewable energy (electricity)-generated hydrogen will be an ultra-low or even zero CO_2 emissions alternative ironmaking technology. Globally a few major initiatives are underway however, substantial fundamental understanding is required for realisation of this concept and its integration with steelmaking.

Decarburisation is one of the globally recognised technology trends having far-reaching implications for the steel industry and its supply chain such as automotive, construction and packaging. Carbon Capture and Storage (CCS) is considered as one of the key technologies enabling a deep decarburisation of the economy by mid-century. However, it is still lacking funding for any practical work. The rapid deployment of renewable energy technologies and issues of social acceptance of the CCS technology itself also compound the implementation of the CCS technologies. On the other hand, the renewable energy-based steel manufacturing technologies have been attracting great attention globally, such as H_2-based DRI production and electrolysis. Direct reduced iron (DRI) produced using renewable energy (electricity) generated hydrogen will be an ultra-low or even zero CO_2 emission ironmaking process, which can be used alongside and/or replace existing ironmaking practices. This research will help ensure the viability of future UK steel manufacturing.

Key Aims

- To create fundamental knowledge for an ultimately low carbon ironmaking process by using renewable energy (electricity) generated hydrogen
- Use DRI as a dilution additive for the use of high residual scraps, in the production of high-quality steel products
- Use DRI as scrap replacement/dilution additive for dirty scraps in BOF steelmaking for the production of high-quality steel
- H_2-based DRI technology can be a long-term technology for achieving the compulsory target of CO_2 emissions reduction in steel industry

Planned Impact

The DRI produced by this technology can be used for scrap replacement in BOF steelmaking, and will be an ideal dilution additive for (high residual) steel scrap in the EAF route (DRI + scrap-based EAF) to produce high quality steels at low cost.

Progress to Date

Planned start date Oct 2020 (this may be put back due to Covid-19).

Task 7 – Disruptive Processes – Near Net Shape Casting and Reduced Rolling Technology

Professor Claire Davis (Warwick)

Introduction

Near net shape casting produces material that needs minimal hot deformation to achieve the required product thickness and uses significantly less energy compared to traditional continuous casting to large sections with subsequent hot rolling / forging; for example energy use could be reduced by >3 GJ/T for strip steel produced by belt casting. However, the removal/reduction of reheating and thermo-mechanical deformation, whilst saving energy, mean that desirable microstructural modifications of recrystallisation and multiple phase transformations may be excluded.

In addition, the higher cooling rates associated with thinner product casting mean the solidification structure is altered. Thus, it is important that quantitative composition - process parameter - microstructure relationships are established for new processing routes, which requires fundamental knowledge on the effect of near net shape casting and reduced thermo-mechanical processing on the development of microstructure and properties.

One of the advantages of near net shape processing is the high cooling rates through the thickness. By reducing the dendritic spacing then segregation is less severe offering opportunities for:

1. Product uniformity
2. Alloy modifications

Key Aims

- Establish quantitative Composition -Process parameter - Microstructure relationships
- Development of low energy steelmaking principles
- Understanding effects of accelerated cooling upon bulk material properties

Planned Impact

Introduction of this and other similar near-net shaped casting processes will greatly reduce the thermal energy required for the steelmaking process and may enable new products with lower alloy composition to be used over existing products, reducing the cost of manufacture and widening the recycling applications of the material.

Progress to Date

Planned start date Oct 2020 (this may be put back due to Covid-19).

Task 8 – Smart Sensors for Real-Time Measurement: Electromagnetic Sensors

Professor Claire Davis (Warwick) and Dr Frank Zhou (Warwick)

Introduction

Improved monitoring of steel production allows for greater digitalisation and control, leading to more efficient, less energy intensive manufacturing. Improved monitoring of processes is a key factor to the sustainability, growth and modernisation of the steel industry. Great improvements have been made for real-time monitoring and feedback control, but several areas have been highlighted where insufficient information is currently available which require new and improved sensing approaches. One area is microstructural monitoring during processing and electromagnetic (EM) sensors are ideal candidates. The task is focusing on development of new EM sensors and signal-microstructure relationships for use in steel processing.

Key Aims

- To design, build and install a sensor array into a furnace-run out table
- Run experimental trials for EM sensor array inspection
- Develop sensor-sample models for complex geometries
- To extend the permeability–microstructure model for complex microstructures
- The development of full magnetic behaviour-microstructure model

Planned Impact

Developing EM sensor arrays for real-time in-situ monitoring, characterisation and control of steel microstructures during processing for a range of grades and applications.

Progress to Date

Good progress has been made on designing and modelling of the EM sensor array for the furnace-run out table at WMG. The size of the sensor head, casing, number of sensor heads and spacing between them has been decided to optimise the sensitivity to microstructure changes. This has been carried out in collaboration with long term partners at the University of Manchester (feedback and discussions with Professor Tony Peyton). The next stage is to source the materials required for building the sensors (ferrite cores) and to design the sensor casing to fit the run out table (collaboration with Dr Russ Hall and linking with High Value Manufacturing Catapult funded project to upgrade the furnace-roller table). In addition, further modelling is required for the phase excitation design of the sensor, to optimise signals and signal interpretation, and to generate the sensor-sample models for the complex geometries of the target applications (rod waps and narrow strips).

Alongside the sensor array work, a feasibility study for EM inspection of the microstructure of annealed rod samples (a 100Cr6 bearing grade and a 23MnB4 cold heading grade) has been carried out. The results show that the sensor output can clearly separate the samples in the different annealing states at room temperature. This suggests that in-situ testing at annealing temperatures may be able to monitor microstructural development, so annealing heat treatments using the newly made laboratory in-situ EM sensor are planned.

The approach for a full magnetic field behaviour (BH) -microstructure model is being developed. Recent progress has allowed the assignment of an initial magnetisation curve to the individual microstructural phases and predict the BH relationship for a two phase balance mixture. Further modelling will be carried out and literature data will be used to validate the models in the first instance.

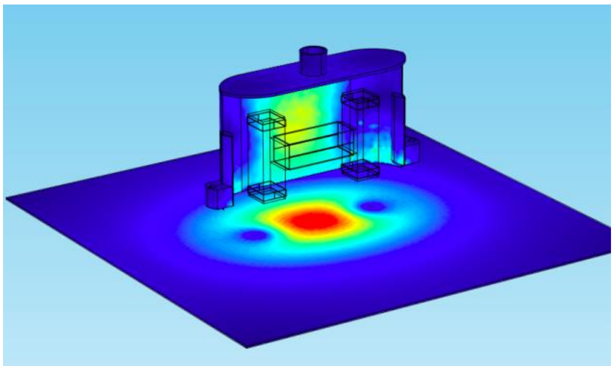


Figure 13. Comsol multi-physics FE model for the EMspecTM sensor and steel plate showing magnetic flux density concentration in the steel.

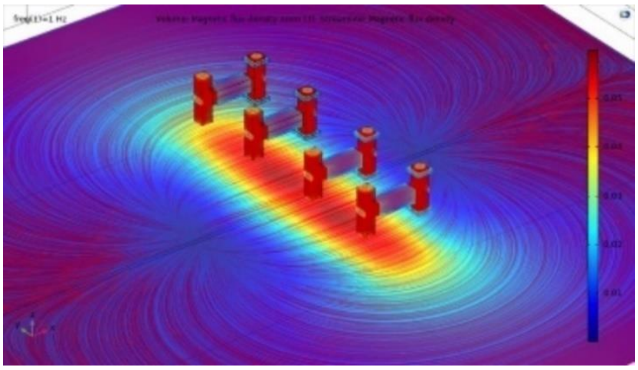


Figure 14. Comsol multi-physics FE model for new sensor array design with four sensor heads and steel plate showing magnetic flux density concentration in the steel.

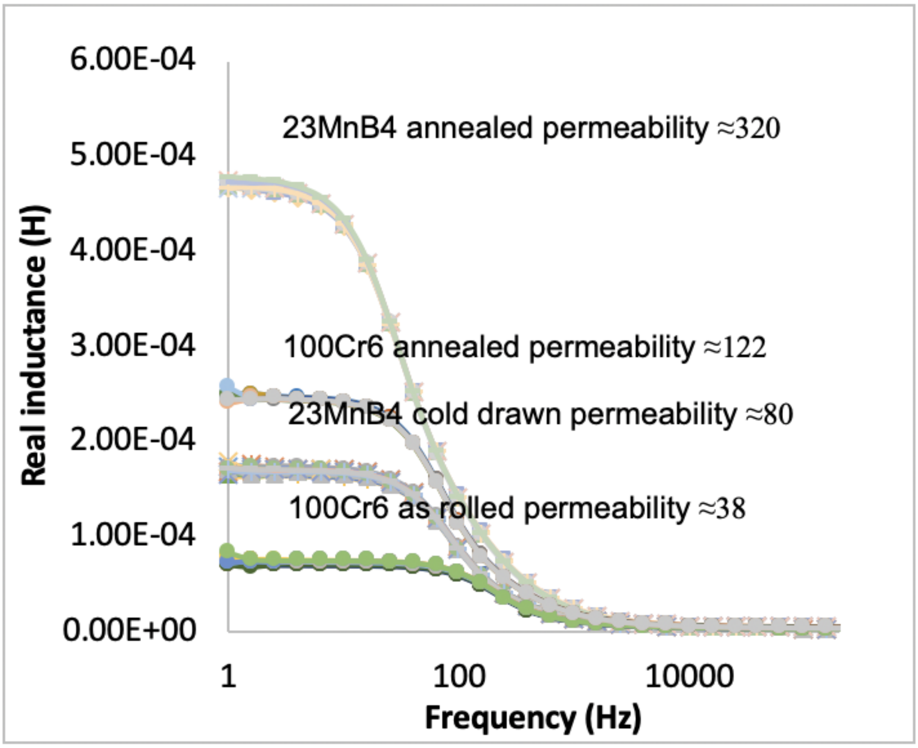


Figure 15. EM sensor output (real inductance) plotted with frequency for 100Cr6 bearing grade and a 23MnB4 cold heading grade showing that the EM sensor can clearly separate the different microstructure states. Relative permeability values were calculated from the inductance values.

Outputs

- Quarterly review meetings with industry partners (Tata Steel, Liberty Steel, British Steel, Primetals Technology Limited) as part of WMG-University of Manchester EM sensors review meetings
- Feasibility trials for microstructure monitoring during annealing of rod samples (samples provided by British Steel) – on-going
- Invited presentation "Advanced Sensors for Microstructure Control" at IoM3 50 Years of Alloy Development, Sheffield, 7-8 Nov 2019
- Planned conference presentation (postponed due to Covid-19): L Zhou, C Davis, "Measured and modelled low field relative permeability for dual phase steels at high temperature" 20th WCNDT 2020, Coex, Seoul, South Korea, 8-12th June 2020

Task 9 – Product Development, Late Stage Definition and Integration

Professor Mark Rainforth (Sheffield), Professor Eric Palmiere (Sheffield) and Dr Martin Strangwood (Warwick)

Introduction

Efficiency in steel production requires relatively minimal changes in the upstream procedures with product differentiation occurring during the latter stages of processing. The austenite transformation to ferrite/pearlite is probably the single most important factor in determining the final properties of most steels, which is why it has been studied since the mid 1940s. The ability to exert greater control over the transformation gives the ability to have greater control of the transformation product and subsequent final properties of the steel. This applies across all steel types, whether long products, strip or sections. This task will focus on understanding the transformation process and the influence of alloy composition and process parameters on it.

Key Aims

- Provide a new approach to understanding the relationship between steel composition and the phase transformation mechanisms and kinetics from austenite to ferrite/pearlite
- Provide precise mechanistic understanding of the role of individual elements in this transformation
- Develop a definitive statement on the effect of prior austenite grain size on transformation kinetics
- Determine factors controlling the stability of retained austenite
- Correlate the behaviour observed in model steels with commercial steels of interest to each steel producer

Planned Impact

To provide a new insight into the influence of key alloying elements and process parameters on the transformation of austenite to ferrite/pearlite.

Progress to Date

The project has only just been approved and is currently appointing staff.

Collaborators and Supporters

Funders

Academic Partners

Industrial Partners

UKRI

Engineering and
Physical Sciences
Research Council

Swansea University
Prifysgol Abertawe

The
University
Of
Sheffield.

WMG
THE UNIVERSITY OF WARWICK