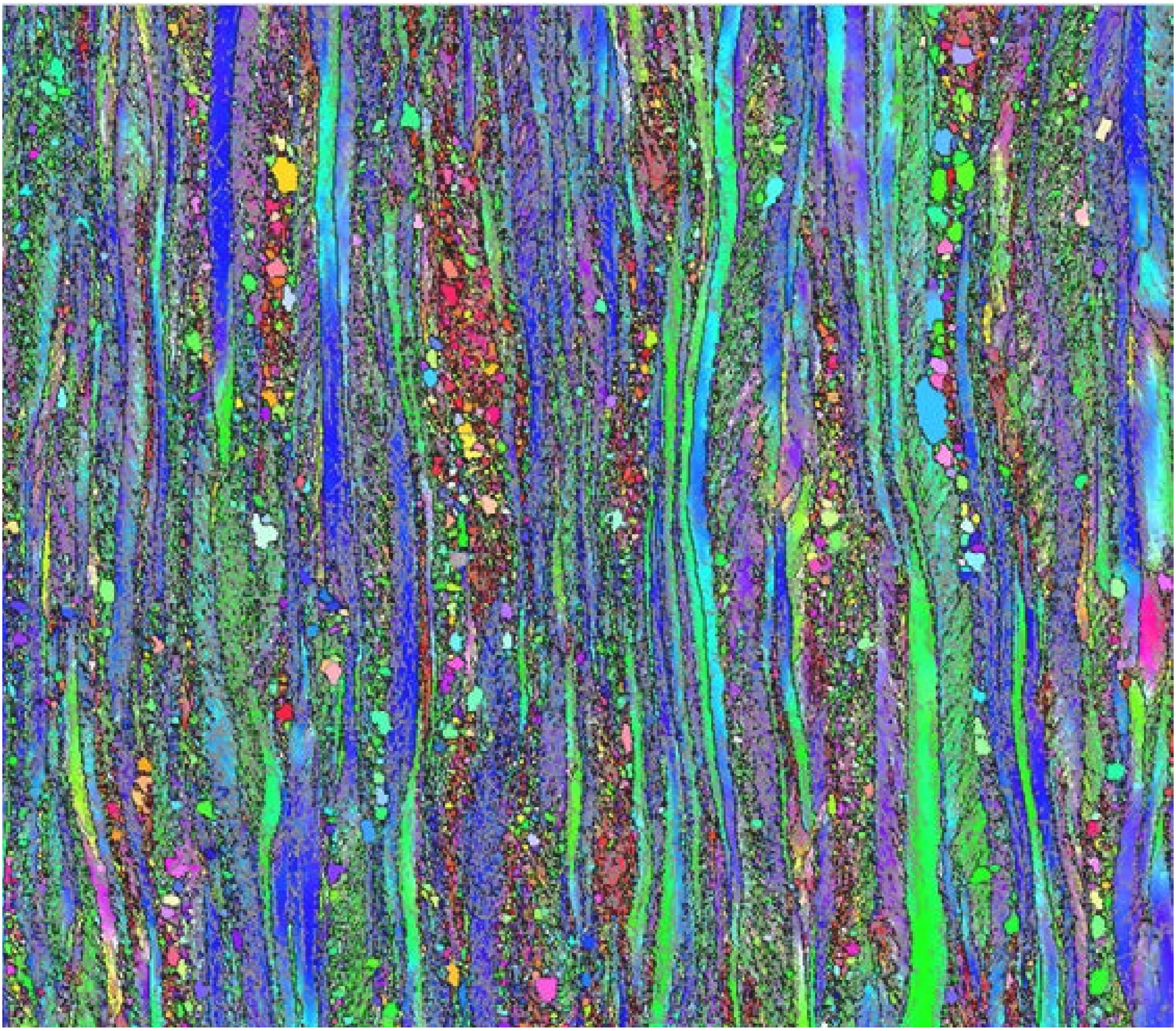
sustain
future steel manufacturing research hub

Annual Review 2021/2022



Engineering and Physical Sciences Research Council

Swansea University Prifysgol Abertawe

The University Of Sheffield.

WMG THE UNIVERSITY OF WARWICK

sustain
future steel manufacturing research hub

sustainsteel.ac.uk

@SustainSteel

Sustain Steel

info@sustainsteel.ac.uk

SUSTAIN Future Manufacturing Research Hub
Swansea University Bay Campus
Fabian Way
Crymlyn Burrows
Swansea
SA1 8EN

"The steel industry is the backbone of an industrialised nation and is often an indicator of a nations growth and progress in terms of infrastructure and quality-of-life improvements. The UK finds itself vulnerable in the scale, capability and competitiveness of its own steel industry, and it is urgent and crucial to support new developments, improve efficiency and demonstrate leadership in the climate change challenge to secure the future of this vital UK industry sector."

Dr Louis Brimacombe
Strategic Advisory Board Chair

Cover image: Task 8, EBSD imaging showing partial recrystallisation in IF steel, captured by Dr Fanfu Wu

Contents

04 Introduction to the Hub

Welcome	04
Hub Overview	05
SUSTAIN in Numbers	06
Partner Engagement	07
2021/2022 in Pictures	08
Steel's Role in a Decarbonised Society	10

12 Core Research

Programme Structure	12
Grand Challenges & Themes	13
Task Updates	15

30 Hub Funded Research

Feasibility Studies	31
Early Career Researcher Platform	34

39 Hub Activity

Facilities	39
Events & Outreach	42
Awards & Recognition	44

44 Publications

Publications, Articles & Media	44

46 Meet the Team

Management Team	46
Strategic Advisory Board	47
Operational Committee	48
Investigators	49
Researchers	50
Aligned PhD/EngD students	50
Operations Team	51

Welcome

Dear Partners, Members and Future Collaborators

We would like to give you all a very warm welcome to third SUSTAIN Annual Report. Since its launch in April 2019, the SUSTAIN Future Manufacturing Hub has made significant strides in the race to decarbonise the UK steel industry by 2050, with key projects already delivering practical solutions that are almost ready for pilot scale deployment. The first round of projects, launched in 2019/20 have already led to a number of additional projects funded by EPSRC, Innovate and WEFO (Welsh European Funding Office), with an additional post-project pipeline expected once these projects have concluded. The high level of engagement and support from industry, especially during the COVID-19 lockdown period, has ensured that the programme remains on point and that our project leads and researchers have full access to industrial knowledge, experience and equipment to complement the Hub's academic resources. The SUSTAIN brand and its mission has also attracted a series of world leading academics and consultants, who have already made significant contributions, particularly in the areas of recycling and digitisation.

Although COVID-19 brought significant challenges to industry and the practical implementation of the projects themselves, the overall outcome for SUSTAIN has been positive. Additional EPSRC funding for industrial secondments allowed SUSTAIN to develop an inward-looking short project, Task 0. This project scrutinised the interaction and industrial impact of the whole programme, raised the overall level of industry-academic interaction and identified opportunities for improvement and areas of best practice. This was performed by seconded technical experts from the businesses. The exercise has also produced a streamlined process for new project development, which will be used for SUSTAIN's second round of projects that will identify and fill any remaining gaps in the industrial transition to net zero.

> "The high level of engagement and support from industry, especially during COVID-19... has ensured that the programme remains on point"
>
> Dr Richard Curry
> SUSTAIN Programme Manager

The SUSTAIN Operations & Management Team

During the pandemic the SUSTAIN Hub, including industrial partners and UK Steel have given a consistent, aligned message to Welsh and UK Governments. This, together with the current national focus upon sovereign capability and resource management will provide a heightened realisation of the importance of steel production and the benefits of national price, availability and quality control for every sector of the UK economy. Looking across the channel to Europe, it is clear that other competitive countries already see this benefit, demonstrated by the multi-billion pound government investments to transform the industry. With similar investment, the UK steel industry, standing shoulder to shoulder with SUSTAIN and the wider UK academic network, will be able to accelerate the green transition into a practical reality.

Although there are still many challenges lying ahead, it is clear that the SUSTAIN concept is making positive gains in aligning the industry, its resources and challenges to work closely with academia to deliver a carbon free, sustainable future. We would like to thank all of our partners and collaborators for their continuous support to the SUSTAIN Hub and look forward to new members joining us in the future.

The SUSTAIN Team

Hub Overview

Steel is a key stakeholder in global decarbonisation. The industry's global output has risen to 1.8 billion tonnes of raw product per annum with an associated 3.6 billion tonnes of CO_2 being emitted into the environment. In the UK alone, its production currently accounts for 15% of total annual industrial CO_2 emissions due to the constant need for this ubiquitous material that underpins the modern world. The UK contributes approximately 7 million tonnes of steel and 15 million tonnes of CO_2 from five intensive facilities which will enable a focussed and manageable decarbonisation approach.

The SUSTAIN (Strategic University Steel Technology and Innovation Network) Future Manufacturing Research Hub is a £35M project funded over 7 years with £10M from UKRI (EPSRC) as well as contributions from Universities, Trade Bodies, Research and Technology Organisations (RTO's) and Businesses aiming to support the development of new, smarter and more environmentally friendly options to ensure the future of steel manufacturing in the UK.

The Hub is based at Swansea University, with spokes at the University of Sheffield and WMG, University of Warwick. Our headline industrial sponsors are British Steel, Celsa Steel UK, Liberty Steel, Sheffield Forgemasters and Tata Steel. The Hub currently has academic partnerships with Cardiff University, Durham University and University College London.

SUSTAIN 2021/2022 in Numbers

Our Team

53 staff working with SUSTAIN at 3 universities

20 Co-Investigators 16 PG Researchers
12 PD Researchers 5 Supporting Staff

Research Outputs

>30 webinar & conference presentations

20 journal papers

3 patents submitted

Sustainability in Steel | SUSTAIN Bi-Annual Conference 2021

190 attendees over two live days

18 technical talks
2 panel sessions
1 workshop

>500 recording views
18 virtual booths from projects, partners and related programmes

Project Partners & Collaborators

24 project partners & collaborators

>25 engagement & workshop events

Outreach & Engagement

>13,500 website views from >4,900 unique visitors

>350 young people reached through outreach activities

Additional Projects & Funding

3 new projects funded by the hub in 21/22

8 aligned projects secured in 20/21 totalling

£6.7m in additional funding

Partner Engagement

"Steel has a vital role in all our futures. Although decarbonisation is a massive challenge for the steel sector, the role steel plays in all aspects of life means that intelligent use of new high value steels with smart applications is also a key factor in addressing the global climate challenge.

SUSTAIN brings together innovative ideas from leading Universities who know the sector well matched with industrial experience to push forward on both the internal R&D challenges of the steel producers and the developments needed to address those wider societal challenges.

My own Institute benefits from being part of that SUSTAIN dialogue helping to bridge the gap between promising research and industrial implementation in areas such as improving processes, energy efficiency, alternative fuels and reductants, sustainable use of materials, recycling of wastes, smart manufacturing and producing the right new products for the future – a near perfect alignment with SUSTAIN's goals."

Alan Scholes
Materials Processing Institute

"Steel is the most important material, given that within a developed economy, everything is either made from steel, or using steel.

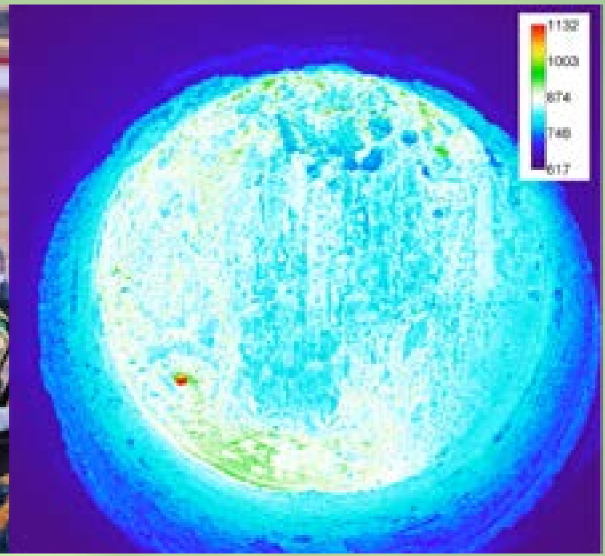
In order for the UK to reach Net Zero, we should be producing more steel, not less. Global steel demand is forecast to increase substantially over the coming decades and therefore, the UK cannot divest its Net Zero responsibility to foreign countries, but must take ownership of those emissions within our economy."

Gareth Stace
Director General, UK Steel

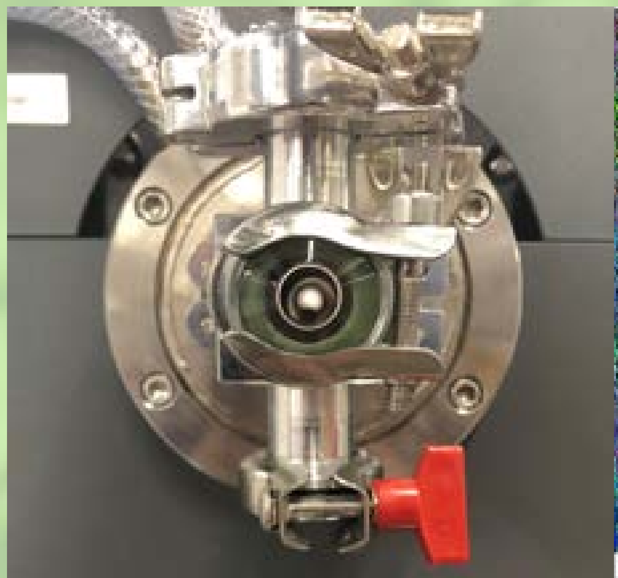
"Our journey to net zero requires that we decarbonise all sectors. Steel is a key industrial sector in the UK, supporting also a variety of industries, such as automotive and construction, as well as renewables. The decarbonisation of the steel sector requires a partnership approach from industry, government and academia to ensure the sustainable manufacturing of steel in the UK. The SUSTAIN Future Manufacturing Research Hub plays a key role in the sustainable transition of the UK steel sector to net zero."

Professor Mercedes Maroto-Valer
Director of IDRIC, Heriot-Watt University

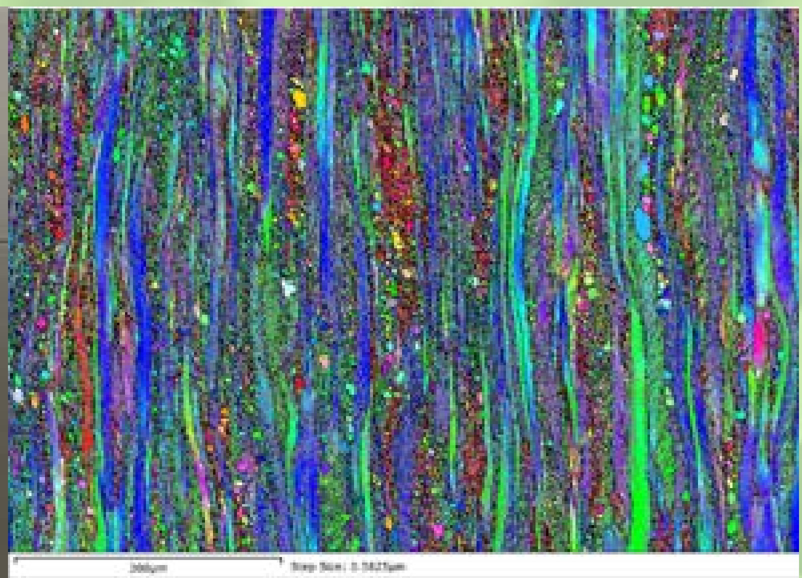
Awards: Swansea University's Vice Chancellor Prof. Paul Boyle and Head of Materials Science and Engineering Prof. Dave Worsley collecting a 2021 Queen's Anniversary Prize



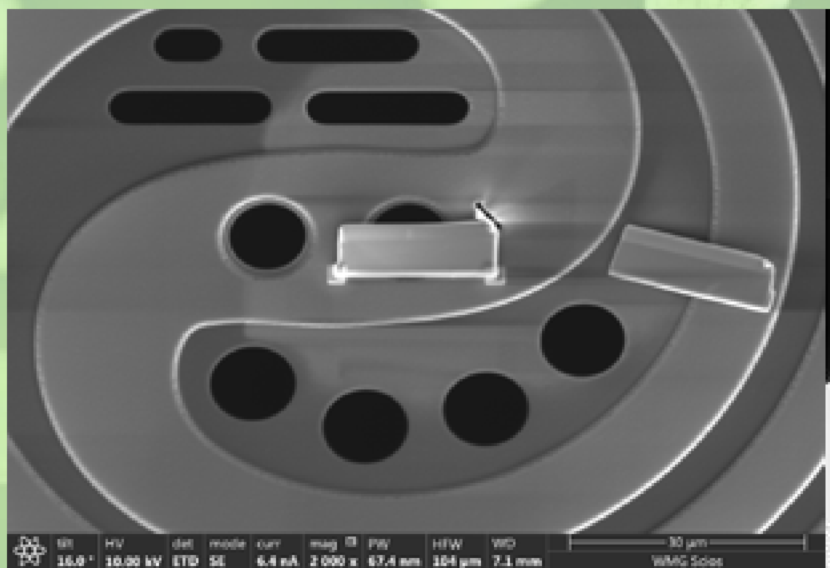
Task 6: Thermal image of refractory insulation



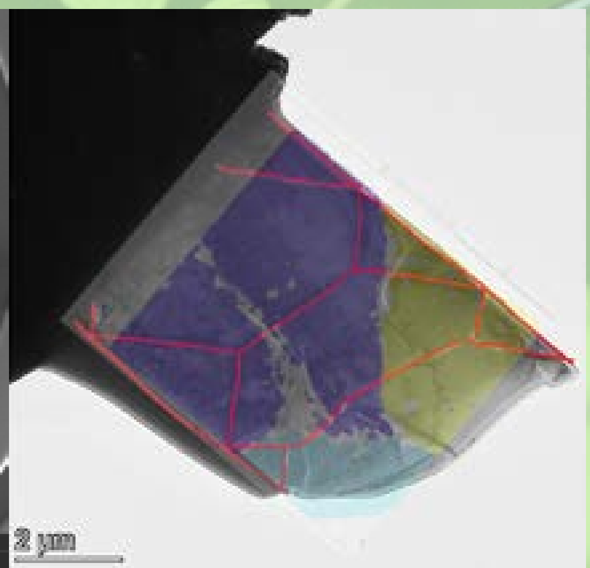
Facilities - SaMI: Furnace viewing ports allow visualisation and recording of simulated industrial processes using advanced camera systems



Task 8: In-situ EM sensor measurements showing change in signal during heat treatment to 700ºC. EBSD micrographs for 700ºC interrupted in-situ tests



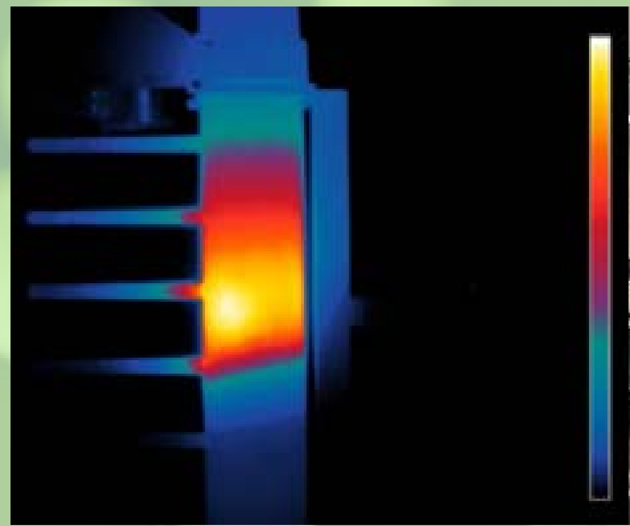
ECR - Lei Zhou: Samples on in-situ TEM heating stage to look at the effect of temperature on magnetic domain structure



ECR - Lei Zhou: Magnetic domain wall movement was observed during the change in temperature and applied magnetic field

Task 12: The studied chamber furnace located at Swerim AB

Task 9: Microstructure of Super13Cr steel containing 28% austenite, Euler contrast showing orientation



Task 2: Thermal image of a sinter pot

Events: SUSTAIN Workshop "The Steel plant of the future: How to achieve Net Zero" at the European Electric Steelmaking Conference 2021

Events: Sustainability in Steel | SUSTAIN Bi-Annual Conference 2021 virtual lobby

Task 1: Pressure unit under construction

The Role of Steel in a Decarbonised Society

By Professor Cameron Pleydell-Pearce

The UK stands on the verge of a green industrial revolution in which the steel supply chain will play a vital role. This much is certain. Every major economy is investing in the future of its steel industry and placing it at the centre of its net zero strategy (e.g. the €700M EU investment in its clean steel partnership[1]). This is essential in the UK as it is facing three simultaneous crises: consumption-based emissions, waste and energy. These necessitate a re-think of our approach to support our society via a transition towards a circular economy without waste, but with energy efficient processes manufacturing a new future. Beyond the UK, every major economy is racing to re-engineer the way to deliver prosperity for its citizens in the context of energy and goods supply chains destabilised by conflict and the pandemic. Hence, even if the climate crisis imperative were to be ignored (which it cannot) the sheer competition for materials and independent energy sources will continue to drive change. So, if this is inevitable and has already started, what is the role of steel in this new normal and why should responsibility for it sit in the UK?

The UK is disproportionately rich in valuable resources

Electric Arc Furnaces (EAF) fed by scrap and powered by green electricity provide the easiest route to decarbonise steelmaking though with significant challenges surrounding residual elements for some products (Task 3). Nevertheless, all steel decarbonisation roadmaps (e.g. EUROFER[2]) predict continued production from iron ore, predominantly via the blast furnace with CCUS. This is driven by a ~1Bn tonne shortfall that will exist between the global utilisation of steel (2.5Bn tonnes) and global scrap availability (1.3Bn tonnes) by 2050. All of the current global scrap resource is actually in use (and always will be), though inefficiently downcycled. This, combined with comparative immaturity/higher cost of decarbonised iron production will cause the price of steel to continue to rise until the UK Steel Industry net zero target of 2050, driven by energy, raw material and an uncertain balance in supply and demand. Estimates suggest a ~$500/T uplift based on conversion to H_2 reduction alone[3]. In response, the forecast developed economies of 2050 with the most scrap have already responded with export controls[4,5] marking it as a critical raw material. In contrast, the UK currently exports 8Mt of its 10Mt arising scrap every year against a utilisation of 10Mt of raw steel and 16Mt in total (including steel embodied in imported goods). This is an unusually large medium-term risk and long-term opportunity for the future UK economy compared to many other countries. These megatonnes will also provide economies of scale for the other precious materials that exist in them at (currently) uneconomically low concentrations, despite them being critical for the UK's energy and technology security.

Steel intensive products will improve your quality of life

Whether it be an electric motor dependent on high quality electrical steel cores, a wind turbine, the next generation of rail infrastructure or a home that generates, stores and releases its own energy, steel intensive and dependent products are already transforming our way of life and will continue to do so. However, net zero technologies require increased steel intensity in many cases. Consider steel intensive modular construction as just one example. Our partner project, SPECIFIC® IKC is already producing demonstrator buildings[6] utilising steel intensive off-site construction that integrates green technologies with the material. These are complemented by a number of social housing projects which aim to provide greatly reduced energy costs and a lower carbon footprint to their inhabitants. Current UK Government figures estimate that 3.18 million households are in fuel poverty (pre-Ukrainian war)[7], so the potential for steel to improve the UK quality of life is irrefutable.

Steel as a service

Beyond providing a decarbonisation vector for their customers via steel's net zero CO_2 footprint and the product functions illustrated above, steelmakers will play a key role in the future circular economy. Steel is already the most recycled human-made material on earth. Recycling is the widest, most energy intensive vector of the circular economy with significant opportunities to reduce the carbon footprint of materials through remanufacture, re-use and maintenance. Delivering the transformation requires specialist materials knowledge as it travels through these routes which is held primarily by the steelmakers (material custodians in the circular economy). The key enablers of this transformation are digital technologies. Smart sensors and computer models in steelmaking will soon provide far more detailed information on steel products. This can be digitally attached to the materials through supply chains using blockchain technology (incorruptible digital ledgers/materials passports) providing user confidence in its re-use or remanufacture and enabling steel servitization. Hence the implementation of decarbonised circular supply chains depends on the maturity of these digital technologies. Such digitally driven approaches are being trialled within SUSTAIN in the DSIH (Digital Steel Innovation Hub) enabled by sensor technologies developed in Task 8[8]. Our industrial partners are already investigating several exemplars at large-scale including rail infrastructure and construction products.

Spotlight on Carbon

Steel is by definition an alloy of iron and carbon, thus some form of carbon will always be required; plus carbon has a key role in steel processing as a reductant or reagent (including EAF and use of H_2 DRI). There is potential for "rapid" (5-10 year) commercialisation of alternative carbon sources that include polymer, paper and biomass substitutions derived from agricultural and societal waste streams producing net energy benefits of 46 GJ/t over polymer recycling[9]. These transitions have been achieved before with Government subsidies[10]. The speed of adoption will be driven by political and economic factors (carbon price, waste classification policies etc). However, at present there is not a clear reward for investment in the utilisation of alternative carbon sources in the UK. By contrast, Japan has invested billions in the utilisation of alternatives from societal waste streams for steelmaking providing significant advantage in commercial readiness. SUSTAIN's Task 2 activities are directly addressing this by assessing the suitability of using alternative carbon sources to solve a key challenge for society as a whole, not just the steel industry.

What if steel doesn't decarbonise in the UK?

The consequences for the steel sector would be existential, this is broadly recognised and most producers are prepared to invest if suitable certainty can be gained on the future policy landscape. Perhaps the question could and should be re-directed to ask, what would be the consequences for the UK manufacturing sector, or in fact the UK population and wider society if it were to no longer have a domestic supply of steel? Given the inevitable inflationary pressures on materials supply chain prices through decarbonisation and reduced geopolitical security, failure to secure domestic supply of key materials in general, and steel in particular, will be viewed in the future as equivalent to existing issues with domestic gas storage and production.

References

1. Memorandum of Understanding for the Co-programmed European Partnership for Clean Steel - Low Carbon Steelmaking, *EN Annex 3* (available online: https://ec.europa.eu/info/sites/default/files/research_and_innovation/funding/documents/c_2021_4113_f1_annex_en_v4_p1_1213800.pdf)
2. EUROFER Low Carbon Roadmap *Pathways to a CO_2 Neutral European Steel Industry* (available online: https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutral-European-Steel-Industry.pdf)
3. Aist.org *PR-382-024.21003.pdf*
4. Metal Movers: EU scrap restrictions – The deep dive, *Argus Media* (available online: https://www.argusmedia.com/en/blog/2022/january/31/podcast-metal-movers-eu-scrap-restrictions-the-deep-dive)
5. Commodities 2022: Steel, scrap markets regionalize, led by China, as decarbonization gains pace, *S&P Global Commodity Insights* (available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/122121-commodities-2022-steel-scrap-markets-regionalize-led-by-china-as-decarbonization-gains-pace)
6. Active Building Demonstrators, *SPECIFIC* (available online: https://www.specific.eu.com/demonstrators)
7. Annual fuel poverty statistics report: 2021, *UK Government* (available online: https://www.gov.uk/government/statistics/annual-fuel-poverty-statistics-report-2021?msclkid=bfec4065d02411ec9871b8d411ea2ead)
8. Data Driven Innovation, SUSTAIN Steel (available online: https://www.sustainsteel.ac.uk/data-driven-innovation)
9. Buergler T, Brunnbauer G, Pillmair G, Ferstl A (2007) Waste plastics as reducing agent in the blast furnace process - synergies between industrial production and waste management processes. In: METEC InSteelCon 2007, proceedings, 3rd international steel conference on new developments in metallurgical process technologies, Düsseldorf, Germany, 11-15 Jun 2007. Düsseldorf, Germany, Stahlinstitut VDEh, pp 1037-1043 (2007)
10. How to switch a power station off coal, *Drax Global* (Available online: https://www.drax.com/sustainable-bioenergy/switch-power-station-off-coal)

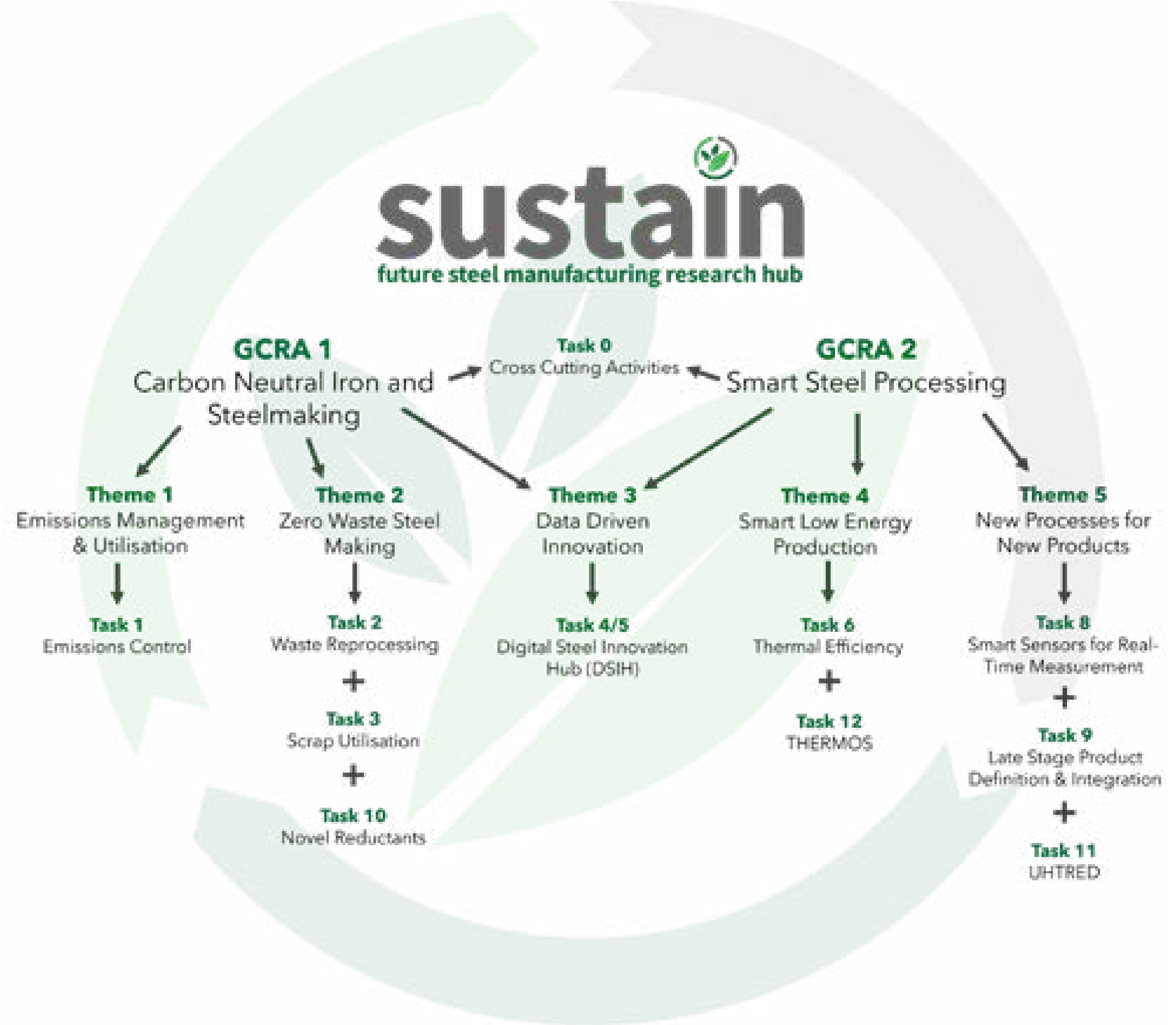
Research Programme Structure

Research Format

With the aim of identifying and developing solutions for a greener, cleaner, smarter future, the work within the SUSTAIN Hub focuses on two Grand Challenge areas: Carbon Neutral Iron and Steelmaking and Smart Steel Processing. Within these Challenges sit five Themes, containing the Hub's current projects, comprising eight Core Tasks, three Feasibility Studies, six Early Career Researcher projects and the cross cutting activities facilitated by Task 0.

Progress reports by Task

All the Core Tasks are now underway and making good progress, despite the challenges faced over the last two years. Detailed updates on the ongoing work of these tasks can be found in the following section of this report. Due to the similarity and crossover in the scope of Tasks 4 and 5, it has been decided to merge this activity and these Tasks are in the process of being combined.



> "Research towards sustainable steel: re-tuning of the workhorse of society"
>
> Professor Sybrand Van Der Zwaag
> TU Delft

SUSTAIN Grand Challenges & Themes

The SUSTAIN project aims to address two Grand Challenges:

Carbon Neutral Iron and 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 us noticing. 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 to eliminate the carbon footprint of the steelmaking processes and provide a sustainable method of production for a carbon neutral industry which supports global needs.

Smart Steel Processing

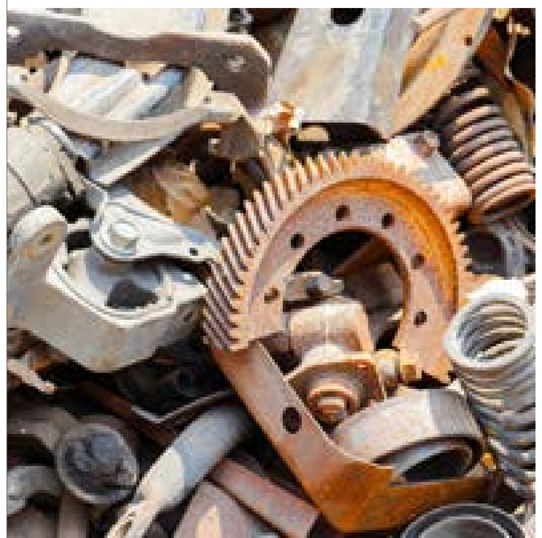
This Grand Challenge aims to revolutionise the steel industry through the development of steels with enhanced mechanical and physical properties, develop increased functionality and utilise the recent developments in sensor technology and digital systems. Focussing on production and supply chains, the Smart Steel Processing 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 giving the end customer and government bodies full confidence in the product's performance, ethical raw material sourcing, production and carbon footprint.

These Grand Challenges are split into five Themes:

Theme 1: Emissions Management and Utilisation

This theme focusses on carbon capture and usage of large sources of CO_2 and management of other harmful gaseous and particulate emissions.

The first challenge is demonstrating a robust recovery and separation process to extract CO_2 from a range of output gas streams. Then, the re-use of the captured CO_2 will be investigated at laboratory scale, before upscaling to industry.



Theme 2: Zero Waste Steelmaking

This theme concentrates on the reuse of domestic and industrial waste products within the steelmaking process. The projects here focus on the substitution of fossil fuels with applicable landfill waste and the reuse of end of life ferrous materials.

The UK currently exports approximately 10M tonnes of scrap steel per year which could be recycled locally. The main challenge in its reuse is the management of unknown elements inherited from a range of steel types, and well as non-ferrous and non-metallic contamination, introducing impurities.

Theme 3:
Data Driven Innovation

To be transformative, the industry will have to be disruptive. The goal of this task is to ultimately generate disruptive enabling technologies for 21st Century supply chains and business models.

New approaches to process modelling and optimised fast-algorithm techniques will be used to allow real-time simulation and prediction of complex thermodynamic, kinetic and mechanical processes.

Theme 4:
Smart Low Energy Production

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.

Theme 5:
New Processes for New Products

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.

One area of focus is microstructural monitoring during processing, whilst the other looks at the development of ultra-high-performance steel 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.

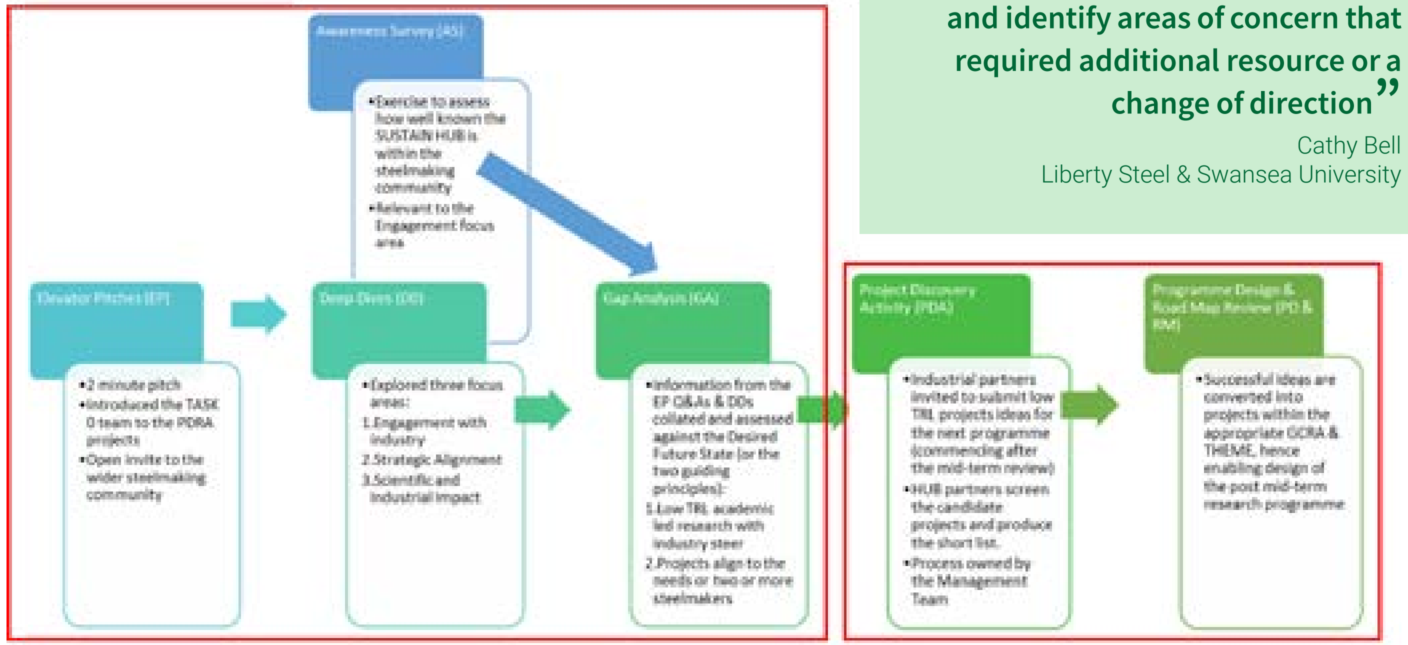
Task 0: Cross Cutting Themes

Start date: May 2021 End date: November 2021
Project leads: Cathy Bell, John Madill, Peter Warren
Project partners: Liberty Steel, Tata Steel, British Steel

In response to the COVID-19 pandemic, additional funding was granted by EPSRC to support expert secondment from the industrial partners to work with the SUSTAIN academic team. This was designed to accelerate sector-specific, practical, sustainable, net-zero steel production philosophies and identify technical barriers. Identified opportunities, barriers and solutions would then be used to feed SUSTAIN's medium term scope and cement an effective long-term UK transition plan.

The industrial secondments permitted key technologists from the industrial partners to work closely alongside SUSTAIN project leaders, researchers and technologists from other businesses. This provided a unique opportunity for industrial partners to review the level of engagement, strategic alignment and impact of the research conducted to date.

Through a series of elevator pitches, deep dives and a general SUSTAIN awareness survey, the projects and company engagement was assessed to produce a gap analysis exercise. This then led to valuable feedback and suggestions for the SUSTAIN Operational Committee to consider and outcomes and analysis were fed back in full to the project leads and researchers.



Above: Structure of Task 0 processes, exercises and outputs

A second activity also used the technical developments and company focus to design a project 'discovery document' to maximise the capture of high impact projects for the second phase of SUSTAIN. These new projects will aim to fill any scientific and technical gaps that are important for the progression of the UK steel industry into a carbon free future. A brief summary of the process is presented in the diagram below.

Overall, the Task 0 project performed exceedingly well with a high level of engagement from both the industry and academia. The findings were reported to the Operational Committee and Strategic Advisory Board and improvement opportunities were agreed and embedded in SUSTAIN. Supplementary benefits, such as greater awareness of SUSTAIN amongst the lower levels of the businesses and much greater familiarity and engagement between academia and industry have also been observed.

> **"This detailed one-off review was a great opportunity for both the Researchers and Industrial Partners to identify and acknowledge what was going well and identify areas of concern that required additional resource or a change of direction"**
>
> Cathy Bell
> Liberty Steel & Swansea University

Task 1: Emissions Control

Start date: October 2020 Expected end date: October 2023

Project leads: Professor Andrew Barron, Professor Peter Styring, Dr Enrico Andreoli

Researchers: Dr George Dowson, Dr Craig Armstrong

Project partners: Swansea University, University of Sheffield

Project Abstract

SUSTAIN Task 1 is focused on the capture and use of carbon dioxide emissions, specifically those from steelmaking manufacturing operations. We develop and apply equipment, processes, and materials for CO_2 capture placing particular emphasis on flexibility and efficiency of separation, to provide decarbonisation solutions tailored to different manufacturing process gas streams and emissions. We combine capture with utilisation where CO_2 is chemically converted to value-added products using thermochemical and electrochemical approaches. Our aim is to provide the UK steel industry with designed scalable options for carbon dioxide valorisation.

Key findings:

Large carbon capture apparatus moved to an industrial collaborator to build a larger-scale trailer-based demonstrator for real-world testing

Procurement of bespoke components for carbon capture pressure swing adsorption unit completed, including SCADA system

Novel carbon capture materials tested in industrially relevant breakthrough dynamic conditions in collaboration with an academic partner

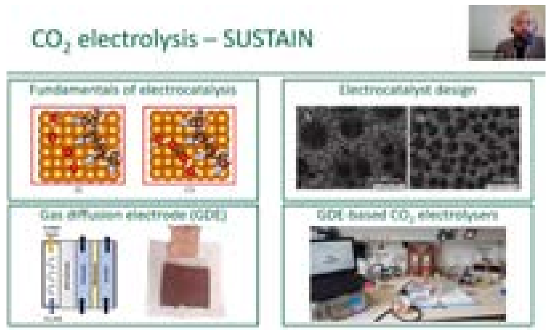
Protocol for self-supported CO_2 conversion gas diffusion electrodes completed, now testing long term stability

Background research into dimethyl ether (DME) production has resulted in a paper which will form the basis of the second-stage reactor

Progress to Date

The development of both equipment and materials for carbon capture has progressed at a pace. The large-scale apparatus developed at Sheffield can now reach 100% of design pressure with CO_2 tank concentrations from 0-50%. The apparatus is now located at an industrial collaborator for scale-up into a modular unit to be transported to manufacturing sites for testing. The procurement of parts for the pressure swing adsorption unit developed at Swansea is completed, this is a major achievement given the many challenges it has brought upon the team. We are currently contacting engineering companies for unit assembly; programming of the control system is ongoing. Novel materials for carbon capture have been fully tested, including dynamic breakthrough measurement with an academic collaborator. We now have a better understanding of the typology and applicability of materials to our processes. CO_2 electrolysis work has progressed steadily, however slower than planned due to the time required for the appointment of a new postdoctoral researcher. In the meantime, we have completed operando experimental work at the Diamond Light Source. Task 1 has published a total of ten scientific peer-reviewed manuscripts, submitted three patent applications, and participated in four conferences. This October, a visiting research scholar from Henan University, China will join our postdoctoral researcher in Swansea to work on the development of CO_2 electrolysis.

The 0.25 t/day demonstrator is almost complete, including a bespoke PLC control system, and is due for delivery in May 2022.



Left: Enrico presenting at the SUSTAIN Conference December 2021

Core Research: Task 1

Pathways to Industrial Impact

Work on CO_2 electrolysis to value-added products is currently at TRL2-3 and industrial impact in the form of demonstrators is foreseen within the next 5-10 years. SUSTAIN Task 1 is addressing timely technical issues that the research community has identified, essential to overcome in order for the technology to become viable. These include the development of stable gas diffusion electrodes and bespoke electrolyser design, in particular, we are working to translate already establish processes such as the chlor-alkali electrolysis to the needs of CO_2 electrochemical conversion.

The pressure swing adsorption unit developed at Swansea will be deployed at Rockwool Ltd. in Bridgend, Wales, during the second half of the year and will be operational in 2023. The unit can perform carbon capture on simulated gas; CO_2 separations relevant to steelmaking will be evaluated. This work is part of the partner operation RICE (Reducing Industrial Carbon Emissions).

Industrial site testing of the Sheffield PSA system is due to begin in May/June 2022. This will then be integrated with a DME pressure reactor to produce synthetic-diesel for use by site ground transportation.

Above: The pressure unit under construction

Key Outputs:

AESSEAL have built the prototype carbon dioxide refining system at Sheffield on a pro bono basis. George Dowson has received training from the engineering company, including mentoring

AESSEAL in-kind funding for development of the FluRefin Carbon Dioxide Refining System

Ten-day access to the synchrotron Diamond Light Source. The project consisted of in-operando in-situ EXASF measurements of CO_2 conversion electrocatalysts

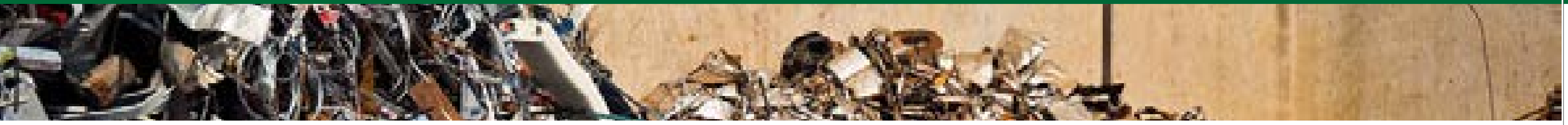
Invited contribution to Nature Catalysis: Andreoli E. CO_2-to-ethylene electroreduction gets a boost

What is the current state of the art in this field?

Carbon dioxide utilisation takes numerous forms and includes many different approaches. One approach of great interest is electrolysis where CO_2, water, and renewable electricity are combined to make carbon-based bulk chemicals such as carbon monoxide, methanol, and ethylene. Within the field of CO_2 electrolysis, alkaline electrolysers are the focus of much interest since they share technical solutions already employed in the large-scale production of other chemicals, including water electrolysis for green hydrogen generation. The current state of the art of alkaline CO_2 electrolysis is the use of selective electrocatalysts [1] and gas diffusion electrodes [2], but both are not stable enough for industrial application. Other issues are electrolyser designs do not achieve stable performance and CO_2 carbonation is a major efficiency issue [3]. SUSTAIN Task 1 is addressing all these issues to deliver industrially relevant performance at the lab scale.

State of the art for carbon capture is in aqueous amines, although these suffer a number of stability issues and high energy use that are making them difficult to commercialise. The Sheffield PSA unit reduces cost and footprint and includes an energy recovery system. It has been submitted as part of a Carbon Reduction XPRIZE bid. A patent application for the unit has now been filed.

[1] Zhang W., et al. Progress and Perspective of Electrocatalytic CO2 Reduction for Renewable Carbonaceous Fuels and Chemicals. Advanced Science, 2018, 1700275.
[2] Hernandez-Aldave S. and Andreoli E. Fundamentals of Gas Diffusion Electrodes and Electrolysers for Carbon Dioxide Utilisation: Challenges and Opportunities. Catalysts, 2020, 10, 713.
[3] Rabinowitz J. A., et al. The future of low-temperature carbon dioxide electrolysis depends on solving one basic problem. Nature Communications, 2020, 10, 5231.



Task 2: Waste Reprocessing

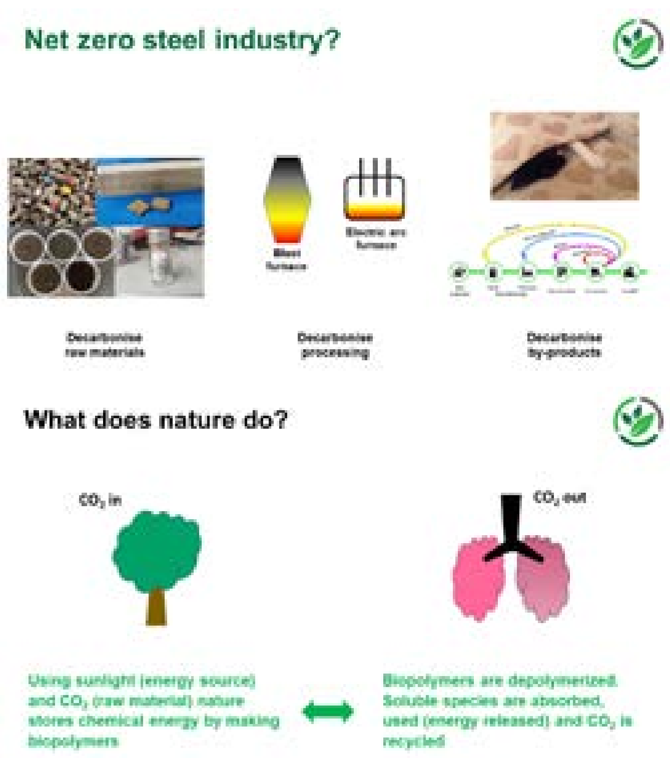
Start date: June 2020 Expected end date: June 2023
Project leads: Professor Peter Holliman, Dr Richard Thackray
Researchers: Dr Eurig Wyn Jones
PhD students: Fawas Ojobowale, Lisa Ahmad, Zachary Lowther, Sam Reis, Matthew Wilcox
Project partners: Swansea University, University of Sheffield, Tata Steel, N&P Recycling

Project Abstract

Blast furnace ironmaking uses fossil fuel carbon (e.g. coke and coal) to provide energy and to reduce iron oxide to liquid iron. In this Task, life cycle analysis is combined with experimental testing to investigate using non-fossil fuel carbonaceous waste to displace fossil fuel carbon within the ironmaking process. By using non-fossil fuel sources of carbon, we aim to reduce net carbon dioxide emissions and so help to decarbonise the overall process.

Progress to Date

We have used ultra-fast 20,000°C/s pyrolysis to study the volatiles released from different non-fossil fuel carbon sources. These data have been baselined against currently used coals and correlated with chemical analysis and calorific values.



Above: Slides from Peter Holliman's presentation at the SUSTAIN Conference December 2021

We have commissioned a new bomb calorimeter (purchased from a successful Welsh Government capital grant) and used this to measure calorific values (CVs) of different carbon feedstocks (fossil fuel versus non-fossil fuel). We have set up torrefication and hydrothermal carbonisation experiments to upgrade carbon feedstocks, to re-measure their CVs etc. and to compare this with the processing energy to measure energy balance.

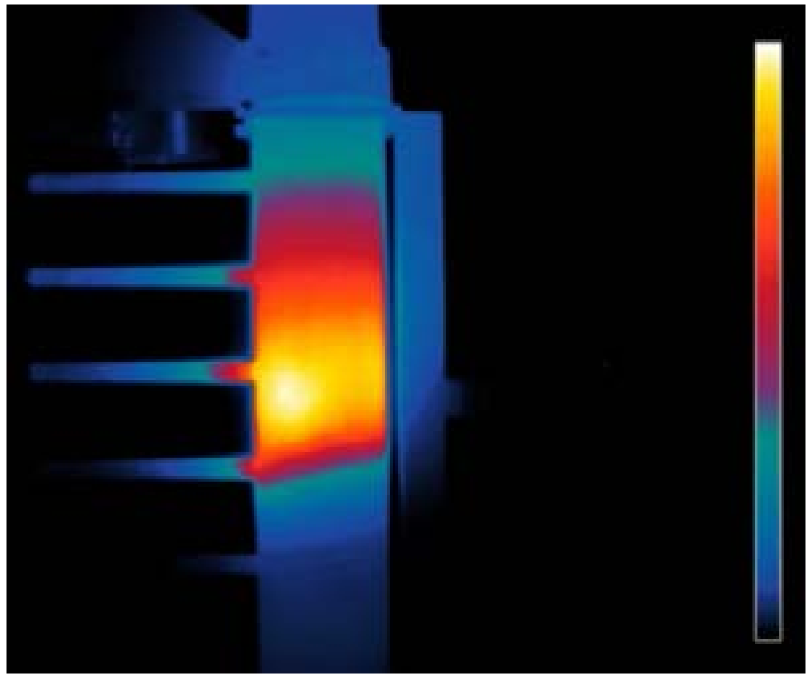
We have collaborated with Cardiff University to study rapid heat treatments (using their drop tube furnace) in combination with our ultra-fast pyrolysis to understand changes happening to carbon feedstocks over very short (i.e., 0-300 ms) timescales.

We have been developing ultra-fast thermal imaging and have applied this to different ironmaking scenarios (e.g., the sinter plant) to produce some interesting operando-style data. We have thermally imaged samples within the visualisation furnace showing interesting thermal lag data. Additionally, we are commissioning a new thermal processing reactor to explore thermal transfer using a new ultra-fast thermal camera which we have purchased following a successful bid to the recent IMPACT capital fund.

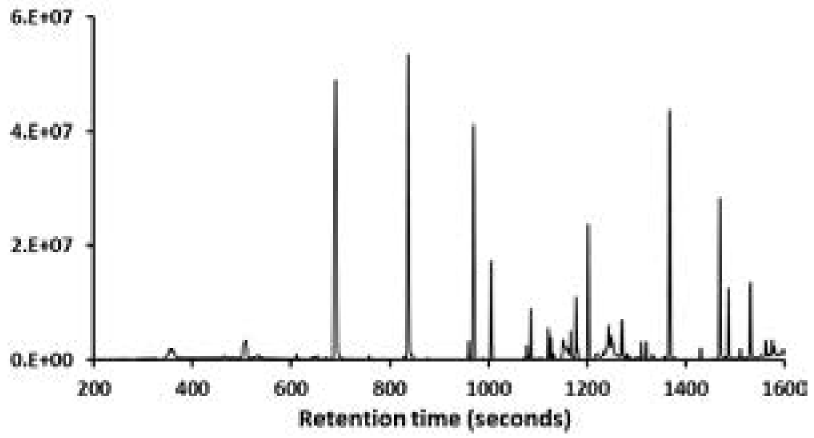
The Sheffield EngD project (Lisa Ahmad) looking at life cycle analysis of alternative ironmaking materials started in Oct 2021. Zachary Lowther started a PhD at Swansea in Oct 2021 looking at fireproof insulation using waste slags and Sam Reis started an iCASE PhD at Swansea in Oct 2021 looking at environmental sustainability of ferrous sintering for the blast furnace.

Key Output:

Ongoing work with British Steel looking at non-fossil fuel materials to displace coal or coke



Above: Thermal image of sinter pot



Above: Chromatogram from ultra-fast pyrolysed coal

Key findings:

Thermal imaging provides useful insights in both slow motion and timelapse scenarios

Kinetics of thermal processes in blends is important to fuel switching

Ultra-fast pyrolysis GCMS can be used to study fuel switching by studying blends

Temperature lag varies considerably between materials which is important for energy transfer

Carbon feedstocks can be upgraded to improve their BF performance

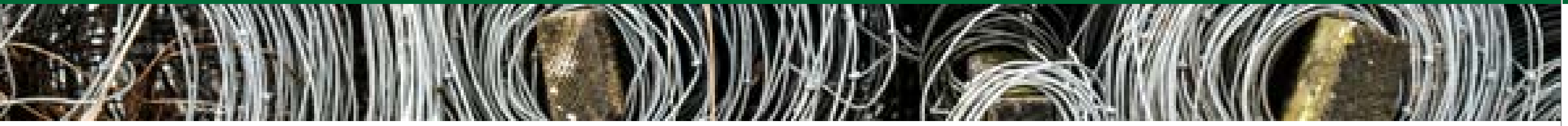
Pathways to Industrial Impact

We have been working with British Steel to look at biomass-derived coke and plastic waste as alternative carbon feedstocks for blast furnace. British Steel have already carried out some small-scale trials of different materials in their blast furnaces. A key part of the SUSTAIN research is to understand how different carbon sources behave in the blast furnace, and also to understand how changing raw material composition can effect operational conditions. Another issue is how blending different carbon sources affects their behaviour. Ultimately, the pathway to impact will be driven by de-risking the technology change so that blast furnace operators can feel more comfortable with increasing the scale of fossil fuel displacement so that suppliers can then ramp up production and develop the supply chain.

What is the current state of the art in this field?

Coal and coke remain the state of the art for ironmaking. Electric arc furnaces are the main commercial option but these rely on electricity and recent fluctuations in energy prices have seen production suspended. EAFs also struggle to deal with tramp elements in the scrap feedstock.

For non-EAF ironmaking, carbon capture and storage have been studied but retrofit is expensive and has little commercial benefit. Direct reduction of iron is also being studied as is molten oxide electrolysis. Hydrogen reduction is also a big research area but this is expensive, more energy intensive and is still a linear economy. Alternative carbon feedstocks are being studied and have shown some success (e.g. in Japan where plastic waste is used in blast furnaces ironmaking and Voest Alpine trials of refuse-derived feedstock).



Task 3: Scrap Utilisation

Start date: December 2019 Expected end date: August 2023

Project leads: Dr Zushu Li, Professor Claire Davis, Dr Richard Thackray

Researchers: Dr Mo Ji

PhD students: William Robertson

Project partners: University of Warwick, University of Sheffield, British Steel, Celsa Steel UK, Liberty Steel, Sheffield Forgemasters, Tata Steel

Project Abstract

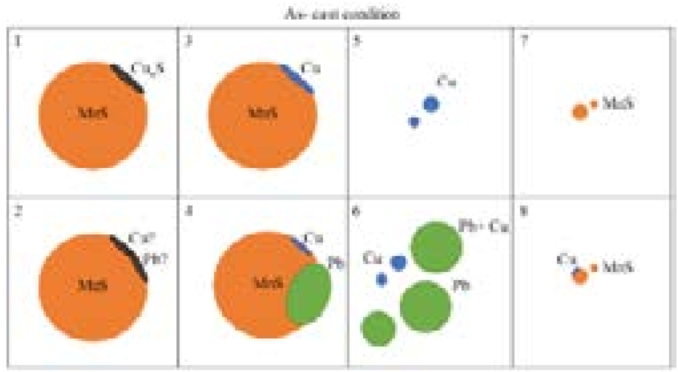
Significantly increasing use of UK generated steel scrap in steel production has become a strategic direction for the UK steel industry. This project provides fundamental understanding and technological development to maximise the scrap usage in manufacturing high quality steel products more economically, by investigating the influence of residual elements inherited from steel scrap on the processability and properties of typical steel products. It focuses on downstream processes of steel manufacturing i.e. casting, re-heating, hot-rolling, cold-rolling, annealing and resultant mechanical properties. This will help achieve net-zero emissions, and maintain the sustainability and profitability of the UK steel industry.

Progress to Date

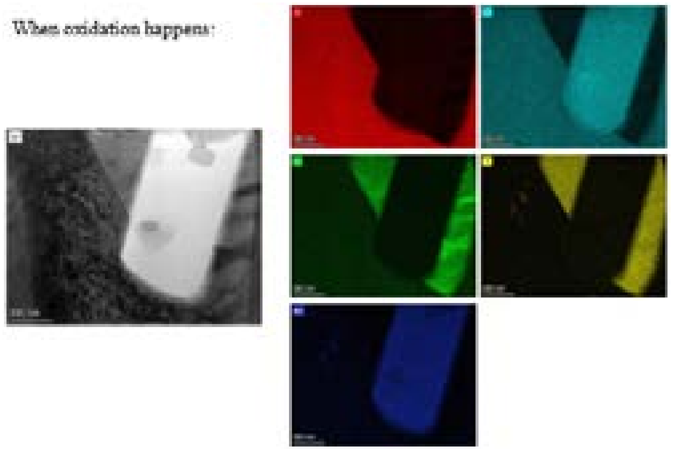
To benchmark the effects of residual elements on microstructural development and property changes of steels, industry through process samples of free cutting steel (high residual levels) and pearlitic rail steel (low residual levels) have been characterised. The evolution of inclusions, pearlite colony size, surface ferrite fraction, interlamellar spacing, and microstructural changes throughout the process have all been evaluated.

Engagement with industrial partners enabled the identification of the key obstacles in increasing steel scrap usage in terms of the steel processability and properties, i.e. hot shortness, hot ductility, and machinability for the free cutting steel, and phase transformation kinetics and hardenability for the pearlitic rail steel.

For the free cutting steel, the residual element Cu was found to co-exist with inclusions in steel and with FeS at austenite grain boundaries during reheating/oxidation. The latter may effect the hot shortness and mechanical properties of the steel, which will be investigated by hot bending tests. The behaviours of residual elements and inclusions were found to vary through the as-cast slab thickness, caused by changes in cooling rate during solidification.



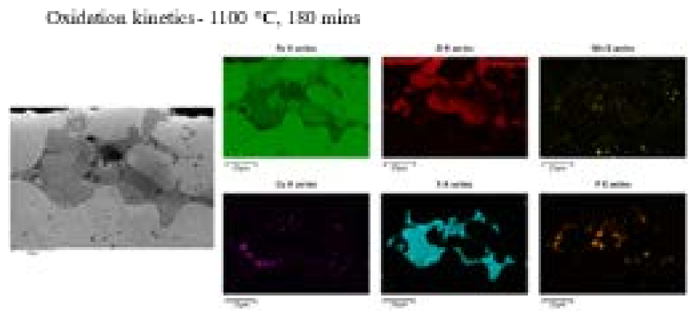
Above: 8 categories of inclusions in free cutting steels



Above: STEM image showing the formation of CuS at austenite grain boundaries during oxidation.

This may effect their behaviours during later processing (rolling, drawing) and therefore final properties. Further studies will be performed.

Measuring the pearlitic transformation kinetics (e.g. pearlite colony growth) using High Temperature Confocal Laser Scanning Microscopy (HT-CLSM) was preliminarily proved to be an effective approach. Tests at different cooling rates for steels with high and low residual elements will be carried out to examine the transformation kinetics and hence pearlite interlamellar spacing and resultant final strength.



Above: Oxidation test at 1100 °C for 180 mins showing the Cu co- existed with FeS along the austenite grain boundaries

Above: Example of STEM image of MnS with presence of Cu (category 3 inclusion)

Key findings:

The cooling rate during solidification through the as-cast slab thickness affects the inclusion behaviours and residual elements distribution

Eight categories of inclusions have been identified in the as-cast samples of low carbon free cutting steels with presence of Pb and Cu

Cu co-exists with FeS at austenite grain boundaries during oxidation at 1100°C, which may effect hot shortness and steel mechanical properties

HT-CLSM was successfully trialled to in-situ measure the pearlite transformation rate

What is the current state of the art in this field?

Increasing scrap utilisation in BOF steelmaking and full scrap-based EAF steelmaking can help the steel industry achieve net zero. This is particularly promising for the UK steel industry considering the abundant domestic scrap supply. One of the limitations for increasing scrap utilisation in steel production is the residual elements in scrap adversely affecting production, processability and product properties of steel. Effects of residual elements have been widely studied focusing on the final product properties, such as mechanical properties (pearlitic steels), hardenability (carbon steel) and machinability (free cutting steel). However, effects of residual elements (individual and combined) on through-process microstructure evolution, phase transformation, recrystallisation and subsequent product properties are still not well understood.

For free cutting steels, there is a lack of the relationship among the residual elements concentration, cooling rate during solidification, inclusion characteristics (composition, morphology, size, distribution) and the segregation of residual elements, which would affect the hot ductility and machinability in return. Although extensive research has been carried out on hot shortness of various residual elements, interaction between MnS inclusions and residual elements and its impact on hot shortness remains unclear.

The synergistic effect of residual elements on pearlite transformation kinetics is far less understood. The extent of partitioning of residual/alloying elements (Cu, Mn, Cr) in ferrite/cementite and pearlite front is dependent on the concentration of each residual/alloying element, transformation temperature and cooling rate. The quantitative relationship among residual elements concentration and pearlite transformation kinetics at various cooling rates and transformation temperatures are desirable for pearlitic steel grades to precisely control the final microstructure.

Key Outputs:

Research into the economic, environmental and social opportunities around scrap metal, particularly steel (position paper)

"Green Steel: The Role of Scrap" webinar

Pathways to Industrial Impact

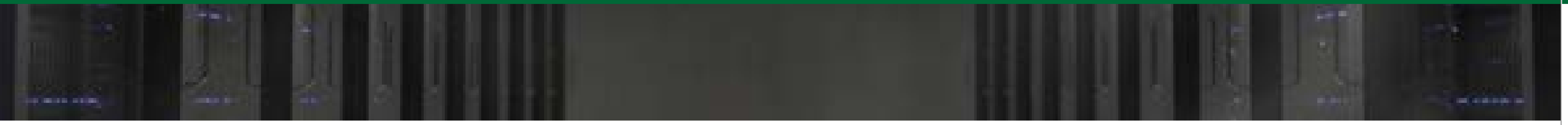
Industrial partners: We have been closely engaging with industrial partners to:

1. obtain through process samples for the selected typical steel grades
2. identify the key challenges for increasing scrap utilisation in the production of the selected steel grades
3. review the project research progress
4. potentially implement research findings to industrial practices

Partners in SUSTAIN: (monthly, half year & annual) progress report, annual review, biannual conference to disseminate the research outcomes and shape the research programme.

Wider community: specifically designed workshops/webinars such as the "Green Steel – the Role of Scrap" webinar; national and international conferences such as EEC21; papers published/to publish in selected journals.

Policymaking: research report, technology roadmap and policy recommendations to policy makers, for example, the completed scrap report to DEFRA/BEIS.



Tasks 4 & 5: Digital Steel Innovation Hub (DSIH)

Start date: September 2019 Expected end date: May 2024

Project leads: Professor Janet Godsell, Professor Giovanni Montanna, Professor Arnold Beckmann (T4), Dr Richard Thackray, Dr Michael Auinger (T5)

Researchers: Dr Aurash Karimi, Dr Uchenna Kesieme (T5)

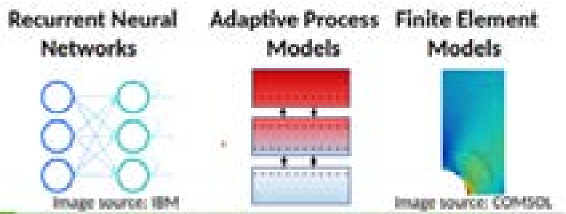
PhD students: David Ireland (T4)

Project partners: Swansea University, University of Sheffield, University of Warwick, Loughborough University, British Steel, Celsa Steel UK, Sheffield Forgemasters, Liberty Steel, Tata Steel, CarbonChain

Project Abstract

Task 4: This work aims to create a data-driven step-change improvement in the competitiveness of UK end-to-end steel supply chains (SCs). It will utilise the recent developments in the technology to both harness and analyse data that can bring to improve the value-add and productivity of products, processes, and SC in the UK steel industry. The project explores how the adoption of industrial digital technologies (IDTs) could improve steel SC productivity and sustainability. Deep reinforcement learning algorithms are developed to train multiple robotic agents to collaboratively solve tasks such as object manipulation using direct input from mounted cameras. In addition, the project assesses the use of a demonstrator tool in enabling real-time predictive maintenance and facilitating product-related knowledge and data sharing among different stakeholders.

Task 5: 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 over the entire process chain. This will be achieved by 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.



	Recurrent Neural Networks	Adaptive Process Models	Finite Element Models
Conceptualise model parameters		✔	✔
Physical simulation		✔	✔
Fast predictions from input	✔	✔	
Model imperfect manufacturing conditions	✔	✔	
Easy to select model parameters	✔	✔	

Above: Table of benefits and drawbacks between machine learning models (left) and physics-based models (right). The reaction zone model under development is in the middle.

Key findings:

Task 4 Supply Chain

Results from the SC Digital Readiness (SCDR) assessment show that steelmakers have a lower digital maturity level

Initial case study results indicate six sources of misalignment gaps within and between organisations

Task 5

Process models which learn directly from process data can outperform parameter-based models

Initial results from analysis of the Liberty Steel data shows that LCI/LCA and energy flows are a suitable way to measure and quantify material and process efficiency

Progress to Date

Task 4 Supply Chain:

- Conducted SC Digital Readiness survey to industrial partners
- Conducted a workshop with the industrial partners to share SC Digital Readiness results
- Developed an Industrial Digital Technologies (IDTs) guide
- Conducted a semi-structured interview with an industrial partner to verify the IDTs guide
- Conducted a case study with Tata Steel and Moveero to optimise SC productivity, sustainability and carbon emission

Task 5

- Produced initial LCA results from the analysis of Liberty Steel data
- Received results from questionnaire sent to our partners about modelling capabilities/strategies. Basically, our approach is the right one but we will need to consider cross-compatibility between existing simulation routines in industries
- Developed a novel Python software routine which combines a reaction zone model and machine learning techniques. It will allow investigation of the blast furnace stoves at Port Talbot

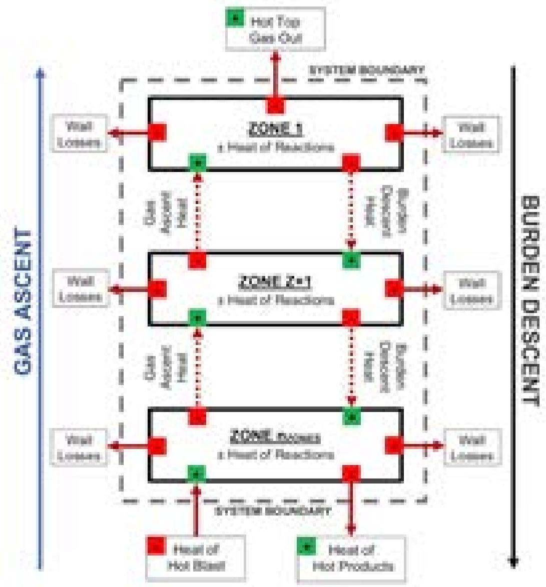
Pathways to Industrial Impact

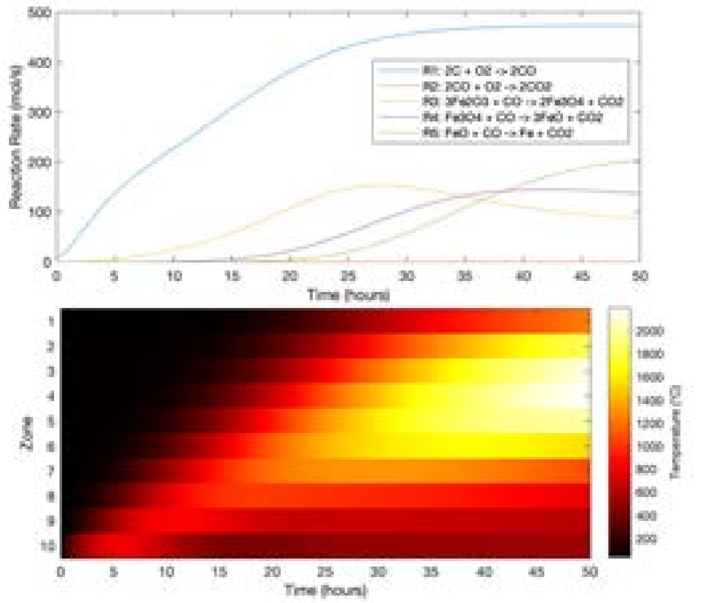
Task 4 Supply Chain: To conduct an SCDR international survey to compare with the UK steel industry.

Task 5: Working closely with Tata Steel UK in order to model blast furnace stoves to allow us to create models that perform well in imperfect conditions. Well performing models will allow for process optimisation, thereby reducing costs, and increasing energy efficiency. We are aiming to prototype this by October 2022. We are also aiming to have completed the LCA/material efficiency work by October 2022 which will allow Liberty Steel to identify areas of current inefficiencies, and provide quantifiable primary and secondary business benefits.

What is the current state of the art in this field?

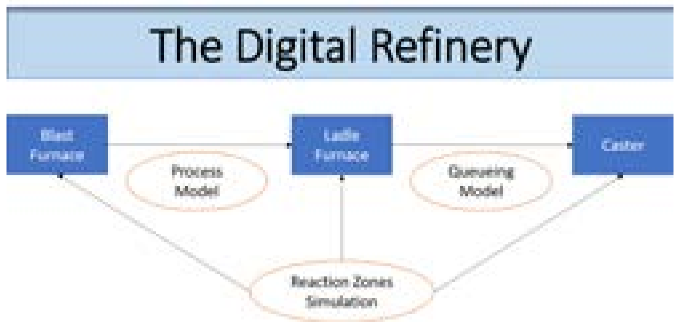
Task 5: The current state of the art is proprietary software which usually uses databases of empirically-gathered parameters to model similar situations, such as ThermoCalc for thermodynamic calculations, COMSOL for physical simulations or in-house programmes, written for only one specific purpose.





Above: Example of a reaction zone model for blast furnace simulations. This work has been carried out during the MSc project of Gabriel Eyre under the supervision of the SUSTAIN T5 team at Warwick.

Below: Schematic view of the digital process model, based on the Reaction Zone approach



Key Output:

Task 5: Developed a novel Python software routine which combines a reaction zone model and machine learning techniques, to create simulations on-the-fly from process data, currently tested against existing finite-difference models. It will allow investigation of the blast furnace stoves at Port Talbot.

Task 6: Thermal Efficiency

Start date: January 2020 Expected end date: April 2024

Heating: Dr Hollie Cockings, Caydn Robinson, Professor Jonathan Willmott

Thermochemical: Dr Jonathan Elvins, Dr Sahand Hosouli, Nigel Koungampillil

Thermoelectrics: Dr Matt Burton, Dr Matt Carnie, Geraint Howells

Refractories: Professor Cameron Pleydell-Pearce, Nicola Thomas, Ebrima Sallah

Project partners: Swansea University, British Steel, Celsa Steel UK, Liberty Steel, Sheffield Forgemasters, Tata Steel, Vesuvius PLC

Project Abstract

According to the International Energy Agency (IEA), heating accounts for 66% of industrial energy demand, which itself makes up 20% of total energy demand. Steel production represents a significant proportion of that demand and as there are some fundamental thermodynamic limitations to consider, such as iron's melting point (1538°C) and its key solid state phase transformation temperatures (e.g. g > a at 920°C). Currently, a typical UK integrated plant loses 20PJ/yr through the largest heat vector. Task 6 of SUSTAIN looks to minimise loss through improved insulation, more efficient heat transfer and two key thermal energy harvesting technologies (see Fig. 1).

Progress to Date

Since the last review two new sub-tasks have now started:

Heating: The first new sub-task is led by Dr Hollie Cockings and deals with the efficiency of re-heating. More specifically it looks to closely correlate the surface oxidation of steel during heating with changes in emissivity. These emissivity changes determine the radiative heat transfer efficiency that dominates re-heating efficiency at the temperatures required (~1200°C). The work is using representative re-heating atmospheres in the lab to replicate oxide formation which is complemented by in-situ /ex-situ emissivity measurements. This is linked directly with the optimization of industrial process models to improve predictive capability of thermophysical behaviour.

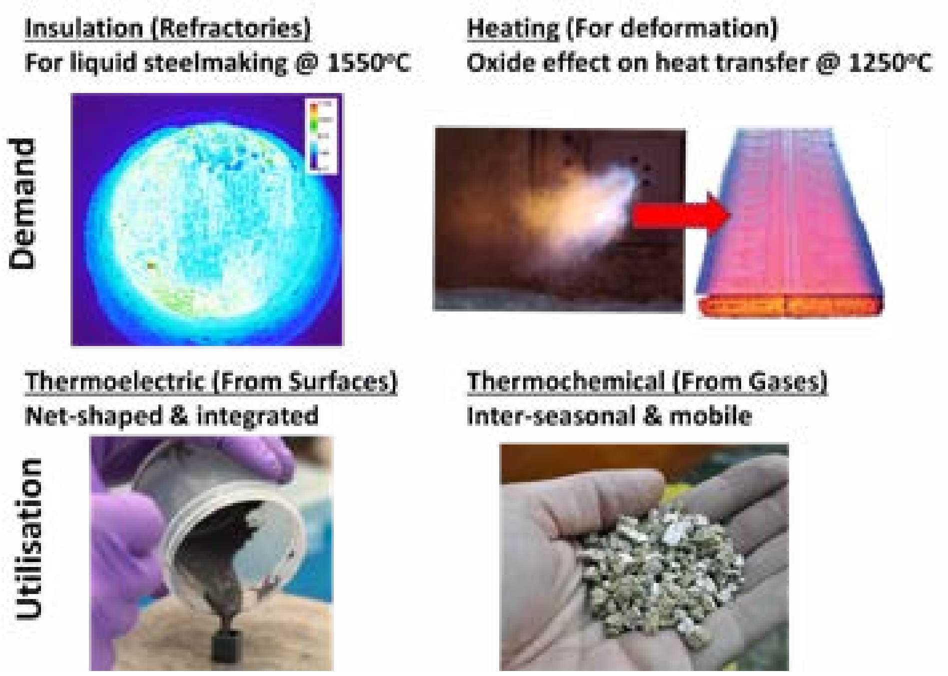


Figure 1: The approach to targeting thermal efficiency in steelmaking within Task 6 of SUSTAIN, addressing both demand reduction and utilization of waste heat (top left to bottom right: thermal image of refractory ladle (courtesy of J. Wilmott Sheffield University), gas fired burner and reheated steel slab, casting a novel thermo-electric generator, non-toxic earth abundant thermochemical storage medium).

Thermochemical storage: The second new sub-task is being led by Dr Jonathan Elvins and is co-sponsored by the ERDF funded FLEXISApp research programme and the EPSRC funded IDRIC programme with support from SUSTAIN core partners. It is looking at the charging behaviour of salt-in-matrix based thermochemical storage materials for heat storage under industrially relevant conditions. Further, a TEA is being conducted to determine the economic viability of not only the charging / discharging of the material, but also the associated logistics of transporting the heat to customers. The work has strong potential for synergy with the work in the task around refractory insulation.

Insulation: The steelmaking refractories are generally carbon-bonded to prevent thermal shock and enable not only process thermal efficiency, stability and safety but are also a key determining factor in the quality of the steel produced. Building on previously reported developments in the microstructural characterization of these refractories in SUSTAIN, we have in the last year validated a method to characterize the thermal stability and structural integrity of the carbon component using a combination of Raman spectroscopy and model free kinetics derived from rapid non-isothermal thermogravimetric analysis (Fig. 2). The results should permit more rapid FMEA and material quality assurance of these materials. Next, we will deploy the techniques developed to date to asses novel low conductivity material prototypes produced at our industrial partner Vesuvius ahead of industrial trials.

Thermoelectric: Both N & P type Sn-Se thermoelectric materials have been produced and a novel screen printing based method has been developed to supplement the previous casting technique. This has led to improved efficiencies and we are now looking to develop earth abundant, lower cost alternatives from economic scalability via Matt Burton's recently won SUSTAIN ECR proposal (well done Matt!).

Key findings:

First near near-net shaped 3D printed Sn-Se thermoelectric legs (P and N-type) have been produced with peak Zt (efficiency) values close to target steelmaking surfaces

Novel and rapid refractory characterization methods have been found to be effective in measuring degradation in the materials over time with implications for improved FMEA and quality assurance approaches

New work has been initiated in the areas of thermochemical storage and high temperature heat transfer behaviour in re-heating furnaces

Over the next year we will look for opportunities to integrate these workstreams more closely to accelerate adoption and amplify our research impact

Pathways to Industrial Impact

The potential for impact of this activity is large. If say, 25% of that heat was recoverable the aforementioned ~ 20 PJ/yr were to be harvested, even at 5% efficiency, savings could be £10Million/year (based on an electricity price of £0.15/kWh). If the remainder was to be thermochemically stored it would provide enough heat for 500,000 homes that currently have a heating carbon footprint of 1.5MTCO_2/yr. From a demand perspective, for just one process step alone, every 1°C saved through improved insulation would reduce costs by £400k/yr. Hence, there is commercial as well as environmental impetus for both reducing heat loss and recovering industrial waste heat.

Each sub-task has its own pathway to impact. Close cooperation between SUSTAIN, steelmakers and their refractory supply chain is being levered to characterize and pilot novel low conductivity materials at industrial scale (1-2 years per prototype). Data from the improved heat transfer efficiency studies will be fed straight into industrial process control models to realise immediate impact (3-4 years). Thermoelectric materials developed at lab-scale will first be implemented as self-powered sensor applications (3 years) in advance of large-scale harvesting at higher complexity (5-7 years). Finally, thermochemical charging demonstrators have already been commissioned in large buildings in partnership with the SPECIFIC® programme permitting rapid trialing of new materials at scale (2-3 years).

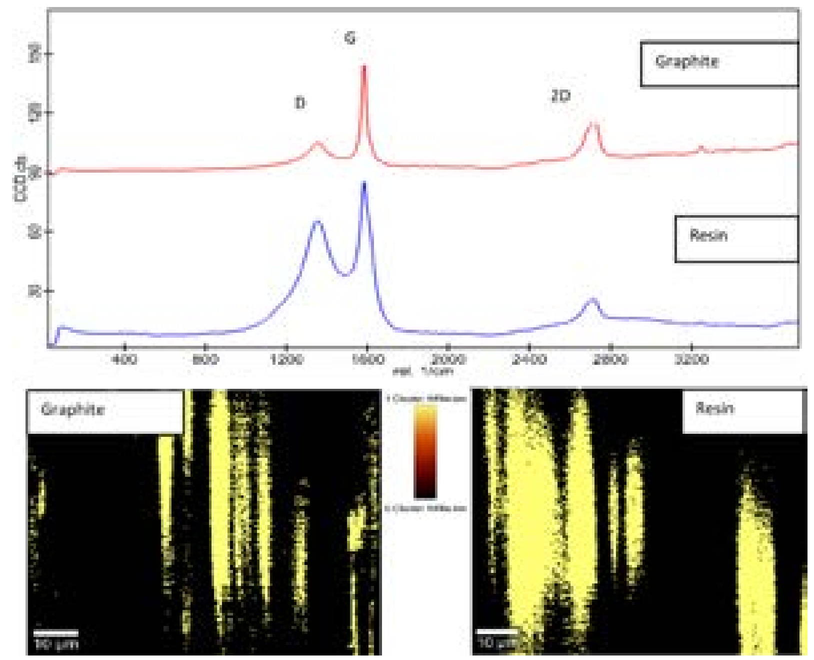
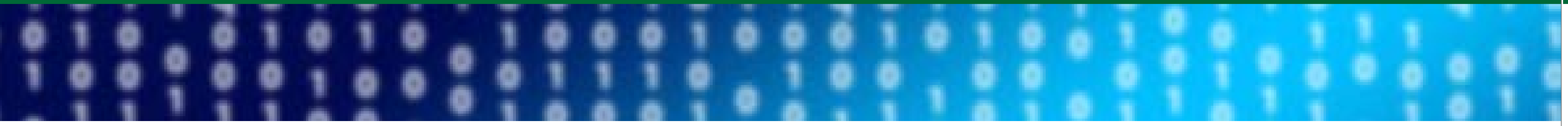


Figure 2: Raman Spectra showing characteristic peaks for the graphite and resin constituents of the carbon binder for steelmaking refractory bricks, the ratio between the peaks was used to measure degradation through oxidation. This was complimented by spatially resolved data (below) which could be correlated to previous microstructural observations of damage. Data produce in collaboration with Henry Royce funded facilities at the UKAEA



Task 8: Smart Sensors for Real-Time Measurement

Start date: August 2019 Expected end date: August 2023

Project lead: Professor Claire Davis

Researchers: Dr Lei (Frank) Zhou

Project partners: University of Warwick, University of Manchester, Primetals Technology Limited, British Steel, Liberty Steel, Tata Steel

Project Abstract

Improved monitoring of steel production allows for greater digitilisation and control, leading to more efficient, less energy intensive manufacturing. Improved monitoring of processes key 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 is microstructural monitoring during processing and electromagnetic (EM) sensors are ideal candidates. The project is focusing on development of new EM sensors and signal-microstructure relationships for use in steel processing.

Progress to Date

Dr Zhou was successful in obtaining a SUSTAIN ECR grant in February 2021 for 12 months at 0.5 FTE. The ECR project focuses on fundamental understanding of the effect of temperature and magnetic field on domain wall movement and magnetic properties in low carbon steels. Lorentz microscopy in the TEM has been carried out to observe the movement of domain walls under the influence of changing magnetic field and, separately, changing temperature using the heated sample holder. The results show that domain structures are affected by the sample geometry but that domain wall movement is observed and that pinning by microstructural features, such as grain boundaries/carbides occurs. Initial observations show that both increasing magnetic field and increasing temperature allow domain walls to overcome pinning sites. High temperature magnetic measurements using a cylindrical EM sensor and an Epstein Frame (with Manchester University) for quantitative relationships between magnetic permeability at high temperatures and ferrite grain size has been made.

Dr Zhou has also worked on an industrial contract with Primetals Technology Limited (PTL) for 12 months at approx. 0.5 FTE. This focusses on modelling the commercial EMspec sensor system, supporting PTL in commercial installation and signal interpretation.

In addition, the new EM sensor array concept has progressed from the design phase into sensor construction fitted into the furnace-roller rig at WMG. The sensor array FE model has been validated using samples with known magnetic behaviour. The next stage is to use the upgraded furnace-roller table controlled water cooling system for hot measurements.

Pathways to Industrial Impact

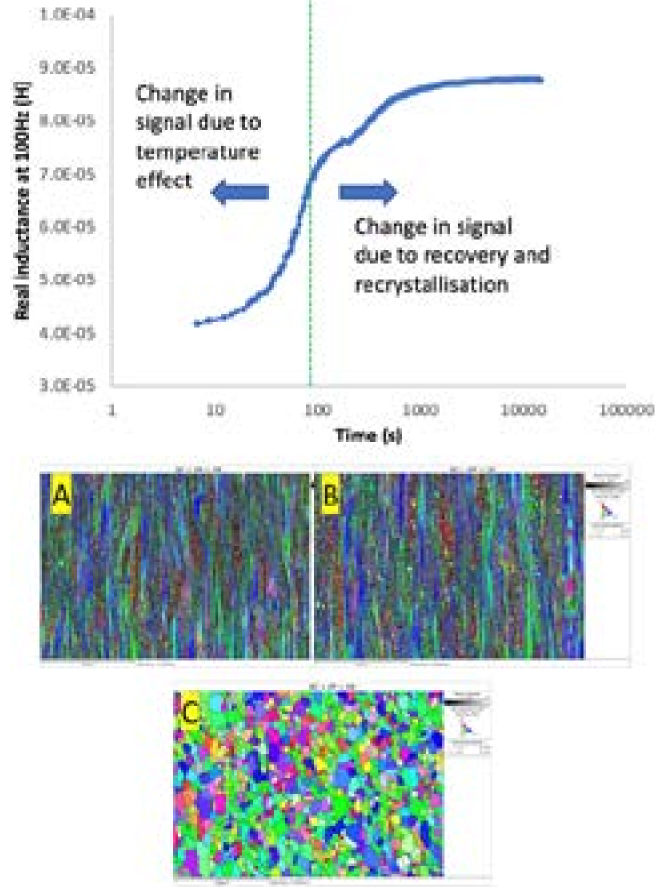
Commercial sensor systems are available for cold strip steel monitoring, with signals correlated to mechanical properties. Currently the only commercial system for hot strip steel microstructural monitoring is the EMspec system, produced by Primetals Technology Limited. There is a need to extend knowledge and application to non-strip steel geometries and grades. Potential impacts, therefore, are the development of new sensor systems that can be installed in steel plants, such as arrays for complex geometries or high temperature in-situ sensors for monitoring thermal induced microstructural changes. The sensor array prototype system has been built and room temperature validation completed, the next stage is lab tests for high temperature phase transformation monitoring. The underpinning knowledge is now proven therefore the route to impact is for industrial trials and signal interpretation, which requires funding for the industrial array system and engineering / scientific support for installation and signal analysis. Collaborative projects with industry partners through appropriate funding bodies will be sought for these activities. In-situ high temperature furnace measurements requires further research for signal sensitivity to target microstructural changes.

Key Outputs:

Paper: Steel microstructure – Magnetic permeability modelling: The effect of ferrite grain size and phase fraction (DOI: 10.1016/j.jmmm.2020.167439)

Paper: Electromagnetic sensors for in-situ dynamic microstructure monitoring of recovery and recrystallisation in interstitial free steels (DOI: 10.1016/j.jmmm.2022.169187)

Core Research: Task 8



Above: In-situ EM sensor measurements showing change in signal during heat treatment to 700°C. EBSD micrographs for 700°C interrupted in-situ tests. A: 3 minutes, B: 30 minutes and C: 210 minutes showing recrystallisation progress

Key findings:

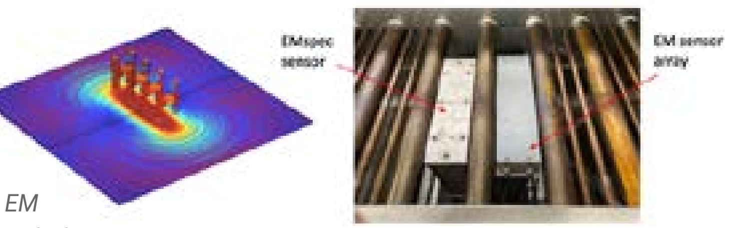
A four EM sensor head array system has been designed, built and installed in furnace-roller table

Sensor array FE model has been validated against samples with known magnetic properties

In-situ magnetic domain observation using Lorentz microscopy, in the TEM with a high temperature sample holder has been completed

Both increasing magnetic field and temperature allows magnetic domain walls to overcome pinning features

Quantitative magnetic measurements at high temperature for structural steels shows the effect of microstructure on magnetic properties



Right: (left) New four EM sensor head array FE model and (right) New EM sensor array installed in the WMG laboratory furnace-roller table demonstrator

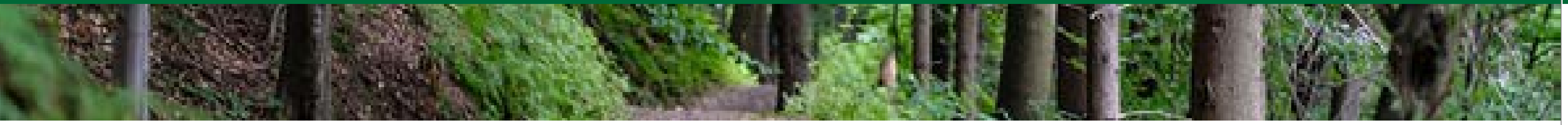
What is the current state of the art in this field?

Several non-destructive techniques such as X-ray, ultrasonic and electromagnetic sensors have been studied to correlate to microstructure parameters in steels [1–3]. EM sensors are widely used for assessing microstructures and properties in steels, including on-line in strip mills [4–6]. EM sensors are also being used for high temperature microstructure monitoring in the lab with the sensor and sample at high temperature [7] [8].

There has been significant work done on relationships between magnetic parameters and microstructures in steel, for example the coercive field is usually considered to be inversely proportional to the grain diameter, d [9,10] or to the inverse of the square root of d [11,12]. In dual or multi-phase steel, the relative permeability values are strongly influenced by phase-type and balance [13,14]. The multiple microstructure parameter impacts on the magnetic properties mean that EM sensors can potentially provide sensitivities to all these microstructure features. On the other hand, it proves to be challenging when unpicking the individual microstructure parameters from each other using the EM signals. In order to understand and predict the significance of each and combined microstructure parameter change on the magnetic permeability, the effect of ferrite fraction and ferrite grain size on the relative permeability was modelled using a 2D finite element (FE) microstructure – electromagnetic model using COMSOL Multiphysics [13,15].

The magnetic properties also change significantly with temperature and there is limited data available for high temperature magnetic behaviours. The low field relative permeability and BH curve changes with temperature for pure iron, and a limited number of structural steels have been studied up to the Curie point using ring samples or high-temperature cylindrical EM sensors [16].

[1] H.-J. Kopineck, R. Löffel, H.-B. Otten, Industrial on-line texture determination in rolled steel strips, J. Nondestruct. Eval. 12 (1993) 13–19. https://doi.org/10.1007/BF00565904.
[2] B. Hutchinson, B. Moss, A. Smith, A. Astill, C. Scruby, G. Engberg, J. Bjorklund, Online characterisation of steel structures in hot stripmill using laser ultrasonic measurements, Ironmak. Steelmak. 29 (2002) 77.
[3] M.P. PAPAELIAS, M. Strangwood, A.J. PEYTON, C.L. Davis, Measurement and modeling of the electromagnetic response to phase transformation in steels, Metall. Mater. Trans. A. 35 (2004) 965–972. https://doi.org/10.1007/s11661-004-1000-0.
[4] A. Skarlatos, C. Reboud, T. Kebe, F. Van Den Berg, R. Schmidt, Simulation of IMPOC system for online monitoring of steel mechanical properties Modelling approach, in: 12th Eur. Conf. Non-Destructive Test. (ECNDT 2018), Gothenburg, 2018. https://www.ndt.net/search/docs.php3?id=22809 (accessed November 29, 2021).
[5] A.J. Peyton, W. Yin, S. Dickinson, C.L. Davis, M. Strangwood, X. Hao, A.J. Douglas, P.F. Morris, On-line microstructure analysis of rod by using induction spectroscopy, J. Ironmak. Steelmak. 37 (2010) 135–139.
[6] H. Yang, F.D. van den Berg, C. Bos, A. Luinenburg, J. Mosk, P. Hunt, M. Dolby, J. Hinton, A.J. Peyton, C.L. Davis, EM sensor array system and performance evaluation for in-line measurement of phase transformation in steel, Insight Non-Destructive Test. Cond. Monit. 61 (2019) 153–161. https://doi.org/10.1784/insi.2019.61.3.153.
[7] R. Hall, M. Strangwood, L. Zhou, C. Davis, Dynamic measurement of recovery and recrystallisation in interstitial free steel using a high temperature electromagnetic sensor, LA Metall. Ital. 2 (2016) 35–42.
[8] L. Zhou, F. Wu, R. Hall, C. Davis, Electromagnetic sensors for in-situ dynamic microstructure monitoring of recovery and recrystallisation in interstitial free steels, J. Magn. Magn. Mater. (2022).
[9] F.J.G. Landgraf, J.R.F. da Silveira, D. Rodrigues-Jr, Determining the effect of grain size and maximum induction upon coercive field of electrical steels, J. Magn. Magn. Mater. 323 (2011) 2335–2339. https://doi.org/http://dx.doi.org/10.1016/j.jmmm.2011.03.034.
[10] M.J. Sablik, F.J.G. Landgraf, Modeling microstructural effects on hysteresis loops with the same maximum flux density, IEEE Trans. Magn. 39 (2003) 2528–2530. https://doi.org/10.1109/TMAG.2003.816466.
[11] J. Degauque, B. Astie, J.L. Porteseil, R. Vergne, Influence of the grain size on the magnetic and magnetomechanical properties of high-purity iron, J. Magn. Magn. Mater. 26 (1982) 261–263. https://doi.org/http://dx.doi.org/10.1016/0304-8853(82)90166-4.
[12] G. Bertotti, F. Fiorillo, M. Pasquale, Reversible and irreversible magnetization in soft iron-based polycrystalline materials, J. Appl. Phys. 69 (1991) 5930–5932. https://doi.org/doi:http://dx.doi.org/10.1063/1.347819.
[13] L. Zhou, J. Liu, X.J. Hao, M. Strangwood, A.J. Peyton, C.L. Davis, Quantification of the phase fraction in steel using an electromagnetic sensor, NDT E Int. 67 (2014) 31–35. https://doi.org/http://dx.doi.org/10.1016/j.ndteint.2014.06.007.
[14] X.J. Hao, W. Yin, M. Strangwood, A.J. Peyton, P.F. Morris, C.L. Davis, Modelling the electromagnetic response of two-phase steel microstructures, NDT E Int. 43 (2010) 305–315. https://doi.org/10.1016/j.ndteint.2010.01.006.
[15] L. Zhou, C. Davis, P. Kok, Steel microstructure – Magnetic permeability modelling: The effect of ferrite grain size and phase fraction, J. Magn. Magn. Mater. 519 (2021) 167439. https://doi.org/10.1016/j.jmmm.2020.167439.
[16] L. Zhou, R. Hall, C.L. Davis, Measured and modelled low field relative permeability for dual phase steels at high temperature, J. Magn. Magn. Mater. 475 (2019) 38–43. https://doi.org/10.1016/j.jmmm.2018.11.096



Task 9: Late Stage Product Definition and Integration

Start date: October 2020 Expected end date: October 2023

Project leads: Professor Mark Rainforth, Professor Eric Palmiere, Dr Martin Strangwood

Researchers: Dr Peng Gong

PhD students: Sam Morgan

Project partners: University of Sheffield, University of Warwick, British Steel, Liberty Steel, Tata Steel

Project Abstract

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 various transformation products is probably the single most important factor in determining the final properties of most steels. The role of local segregation is also critical in the transformation and subsequent heat treatment. 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.

Progress to Date

1. A systematic range of compositions have been produced, within the specified composition for Super 13% Cr steels, but with systematic changes in the Ni, Mn and Mo contents. This will allow the effect of these elements on the amount and stability of the reverted austenite to be assessed.
2. Heat treatment trials of these new steels are under way. This will explain the effect of composition and it is hoped that it will pave the way for a steel with less sensitivity to tempering temperature.
3. A detailed analysis of the austenite stability (transformation on cooling, transformation on deformation) is being undertaken using the steels listed above.
4. Detailed analysis of commercial steels that have a range of tensile properties has been undertaken. This includes steels that had significant variations in reverted austenite content that resulted in significant variations in the yield strength, including those in and out of specification.
5. Local or meso scale changes in composition have been shown to not be responsible for the variations in the yield strength. The only likely explanation is small changes in tempering temperature.

Pathways to Industrial Impact

The research will have a direct pathway to Liberty Steel, as it will recommend changes in steel composition and process conditions to optimise the mechanical properties. The understanding of retained/reverted austenite stability will have wider applicability to all industrial partners.

Key findings:

The amount and composition of reverted austenite formed during the heat treatment of a Super 13Cr steel is a strong function of time and temperature, with even small (~5°C) changes in temperature resulting in large changes in austenite content

The carbon content in reverted austenite is a linear function of the tempering temperature for the first temper but does not change on the second temper

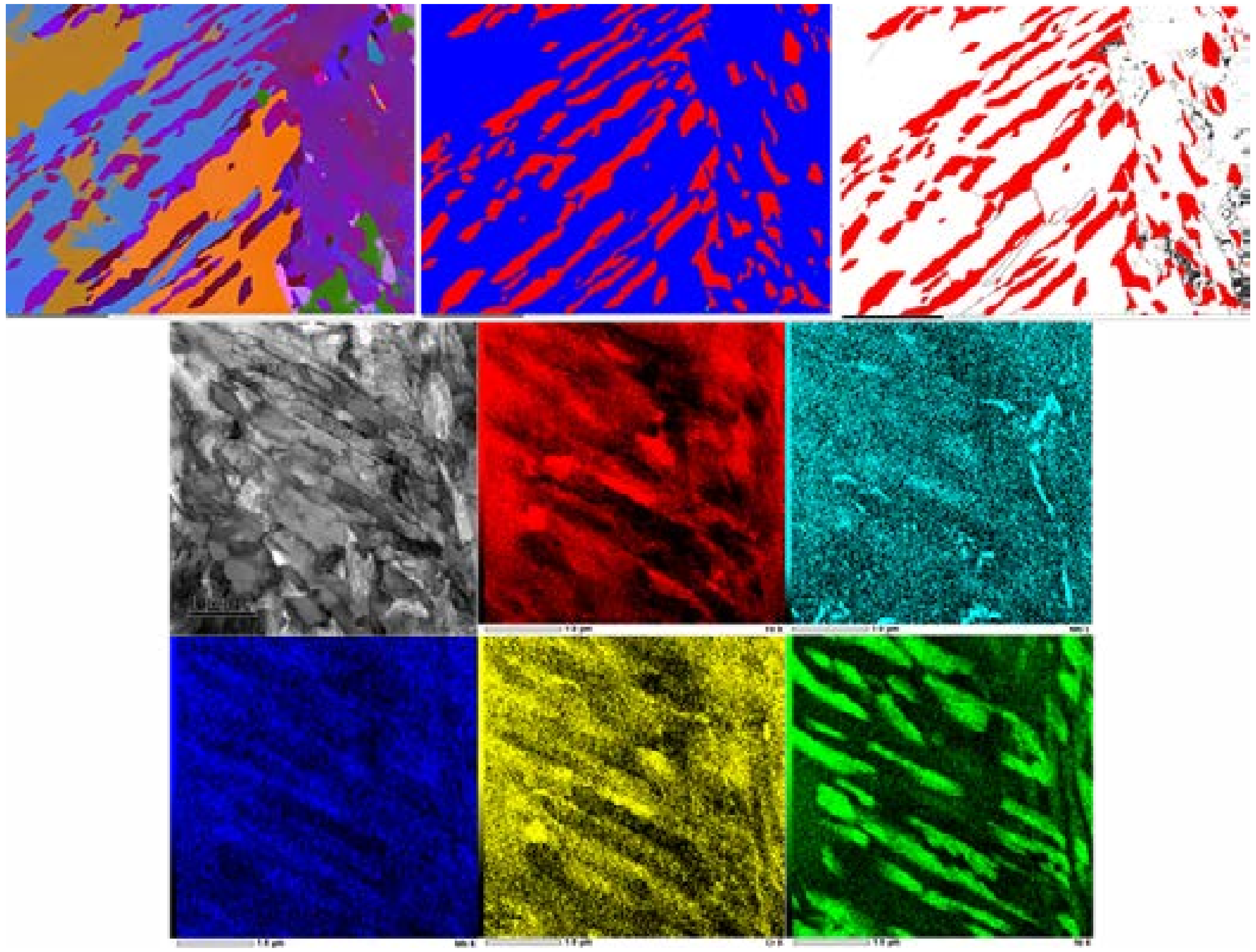
The nickel content decreases in the austenite with tempering temperature on the first temper but increases slightly on the second temper. The chromium and molybdenum do not partition strongly during tempering

The second temper results in austenite that is much more resistant to strain induced transformation, as a result of solute redistribution

Variations in reverted austenite content result in significant variations in the yield strength, making the difference as to whether they are in or out of specification

Large variations in reverted austenite content in the commercial product are not a result of compositional variations in the product; no local segregation can explain the differences

Accordingly, the variations in reverted austenite have to be a result of small differences in heat treatment temperature



Above: Figures showing the microstructure of Super13Cr steel containing 28% austenite. Top three images, left to right: Euler contrast showing orientation, phase distribution (austenite red, martensite blue) and the austenite distribution (red) relative to the martensite orientation (black). Bottom six images showing compositional maps, clockwise from top left: TEM bright field image, Fe, Mo, Mn, Cr and Ni.

Key Output:

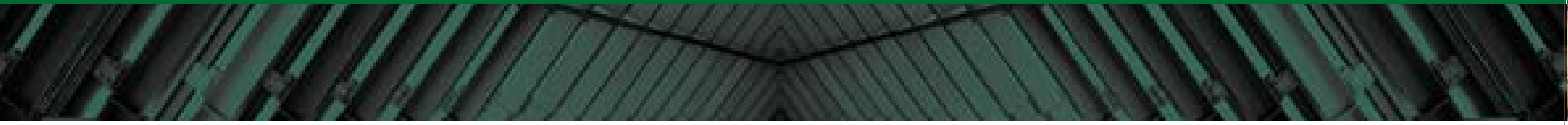
Compositional differences are not the principal determinant of yield strength in these steels. The principal issue is the precise heat treatment temperature.

What is the current state of the art in this field?

The austenite transformation to various transformation products (ferrite, pearlite, martensite, bainite) is remarkably complex and is controlled by a large number of factors. Although it is well established that the austenite grain size and prior deformation are strong influencing factors, there are conflicting reports on the precise mechanisms. For example, it is not clear whether a larger or a smaller austenite grain size accelerates transformation to ferrite/pearlite. While the Ms and Mf temperatures are normally considered to be related to composition, in heavily alloyed grades, such as Super 13Cr, the austenite grain size also controls the Ms and Mf temperatures.

Carbon segregation is often observed at the lath boundaries in the as-quenched martensite, but nickel is usually uniformly distributed. However, during tempering, the distribution of Ni changes, and it can play a strong role on the formation of austenite at lath boundaries. At lath boundaries there is a competition between carbide formation and the formation of austenite. The situation is complicated by the presence of Ni and Mn, but the exact effects are not known.

It is well known that the mechanical properties (ductility and toughness) of super martensitic stainless steel, particularly the yield stress, are strongly dependent on the volume fraction of reverted austenite, which is very sensitive to the heat treatment. The stability of retained austenite is still not fully understood, but depends on many factors, such as the size, the shape (e.g. acicular or globular) and the composition. There is much work left to do to understand the dominant factors.



SUSTAIN Hub Funded Research

Feasibility Studies

The SUSTAIN Feasibility Study Calls are designed to attract new partners to the project. Collaborations developed through these Feasibility Calls may have potential to lead to further partnerships and future funding bids. Such Calls are the Hub's primary mechanism for introducing new academic collaborators and developing additional research spokes.

In Summer 2020, the Hub launched its First Call for Feasibility Studies, offering funding for three feasibility studies to conduct novel research which was aligned to and complementary to the current research programme. This first call was open to UK academics eligible to receive EPSRC funding, for a maximum duration of six months, and a maximum value of £50,000 (80% FEC). Three new Tasks (10 - 12) were funded in this round, which are all now complete or nearing completion. Progress on these projects is documented in the following pages.

SUSTAIN's Feasibility Studies Call will be opening for a second round in Summer 2022. Application and scope information will be available on SUSTAIN's website (www.sustainsteel.ac.uk) and our social media soon.

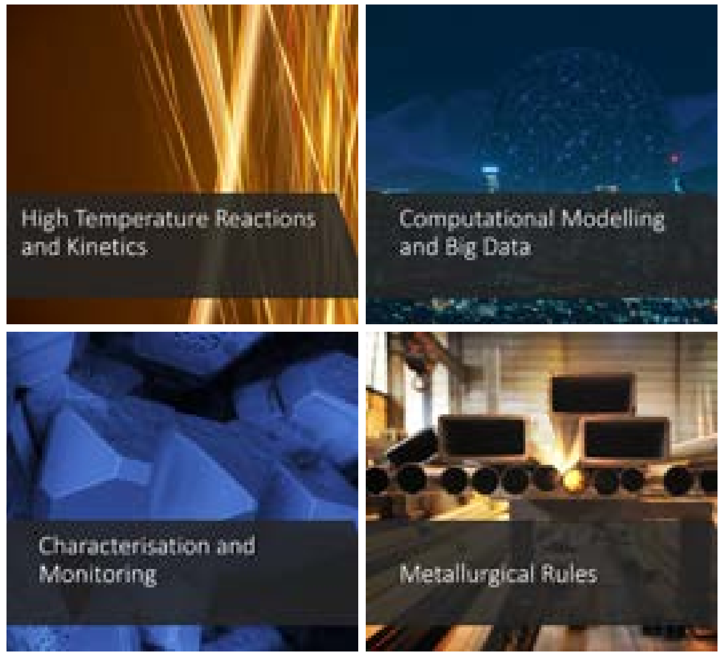
Technology Translation Fund (Available soon)

The SUSTAIN programme has funds of up to £20,000 per application available for individuals who would like to apply for funding that broadly supports the Hub's two Grand Challenges.

This call will be open to those within SUSTAIN, academics within the wider Hub network and from non-associated academics. More information surrounding eligibility and criteria will be avaialble on our website (www.sustainsteel.ac.uk) soon.

Early Career Researcher Platform

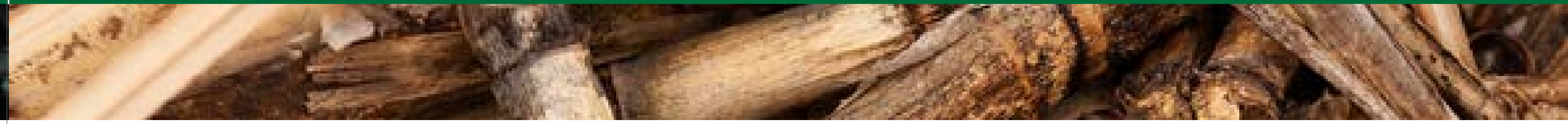
The SUSTAIN Early Career Researcher (ECR) Platform Calls are open to ECRs based in existing SUSTAIN Hub and Spoke institutions (Swansea University, University of Sheffield and University of Warwick), designed to provide ECRs with an opportunity to apply for EPSRC funding as part of this Hub. Research proposals aligned to and complementing the current research programme have been encouraged, especially (but not limited to) the following areas:



These funds aim to provide researchers with funding for six months (or equivalent FTE) to work on their own original research project.

In Autumn/Winter 2020 the Hub launched its first ECR Platform Call and awarded funding to three researchers. One of these is now complete, with the other two on course to finish in the next couple of months. Further details of their progress can be found following the Feasibility Study updates.

Over Autumn/Winter 2021 the Hub ran a second ECR Platform Call and awarded funding to a further four researchers. These projects are all due to start imminently and an overview of the their project aims is presented later in this review.



Task 10: Drop-tube Furnace to Investigate Novel Reductants

Start date:	December 2020	End date:	May 2021
Project lead:	Dr Julian Steer		
PhD students:	Ahmed Mohammed Al Moftah		
Project partners:	Cardiff University, Swansea University, Tata Steel, N&P Recycling		

Project Abstract

This proposal looked at the technical feasibility of re-purposing a non-recycled paper and plastics product known as Subcoal™ as a non-fossil fuel reductant suitable for injection in a blast furnace.

This research aimed to determine if paper and plastics could be used in the iron making process, as a means to reduce the amount of coal, and provide an alternative to land filling non-recyclable paper and plastics in a way that recovers value from these products.

Key findings:

Subcoal non-recyclable wastes have good burnout compared to conventional injectants

A range of renewable bio-based reductants were identified as alternatives to coals and suitable for improving blend burnouts

Biochar is a very promising blast furnace injectant

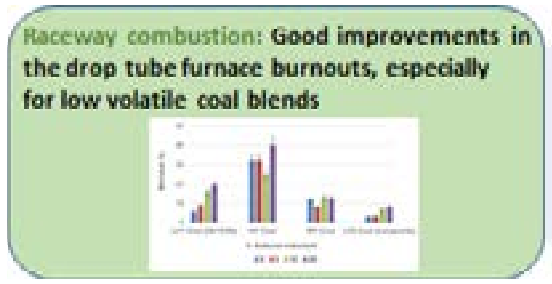
Project Outcomes

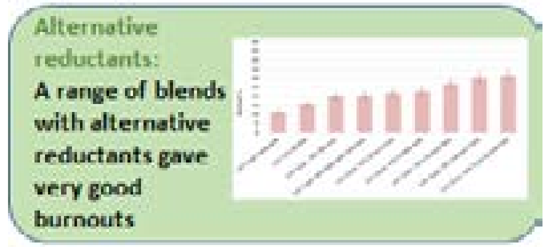
The project demonstrated a range of potential alternative reductants which could be considered in injectant coal blends for the blast furnace ironmaking process. This would reduce the reliance on imported coal in the process; reduce the CO_2 emissions per tonne of hot metal; contribute to sustainability goals by reducing the land filling of non-recyclable waste; and potentially improve the economics of the process. This was achieved through the evaluation of the technical feasibility through the following objectives:

- Identified and measured the burnout and gasification of alternative reductants using a drop tube furnace.
- Developed a method for fluidised bed gasification as an alternative method for utilisation instead of co-milling with coal.
- Quantified the presence of problematic volatile components.
- Determined the variability of Subcoal as a potential carbon feedstock for the blast furnace.
- Wrote two papers in Chemengineering:
  - "Thermal Decomposition Kinetic Study of Non-Recyclable Paper and Plastic Waste by Biochar Thermogravimetric Analysis";
  - "Thermogravimetric kinetic analysis of Non-Recyclable waste CO_2 gasification with catalysts using Coats-Redfern method"

What has this feasibility study allowed you to do?

It has provided the opportunity to have a broader look at alternative reductants to reduce CO_2 emissions; the potential repurposing of non-recyclable products; and an alternative use/benefit for the blast furnace.





Task 11: Ultra-High Temperature Reliable Electronics Development (UHTRED)

Start date: September 2020 Expected end date: February 2021
Project leads: Dr Alton Horsfall, Dr Andrew Gallant
PhD students: Jonathan Hammler
Project partners: Durham University

Project Abstract

The aim of the project was to identify the feasibility of vacuum channel transistors for the realisation of analogue and digital functions in ambient conditions where the temperature exceeds 1000°C. The initial phase of the work used particle tracing simulations to identify the ballistic transport of electrons in a stylised transistor structure to validate the concept. The outcomes from this were used to develop compact models for the transistors that could be used to simulate the behaviour of circuits, leading to the design of a world leading capability in subsequent funded activity.

Project Outcomes

In line with the primary aims of the original proposal, we have:

- Identified suitable metals and dielectrics for long term operation at 1000°C
- Developed and simulated a range of device structures based on vacuum channels that can operate at 1000°C
- Investigated the use of compact models for the design of analogue and digital primitive circuits

These outcomes represent the preliminary steps required to demonstrate proof-of-concept for ultrahigh temperature compatible electronic devices and circuits. The long-term aim is to provide a pathway for the operation of electronics at temperatures that are comparable to those found in blast furnaces and teeming ladles. By improving the close monitoring of high temperature production processes, this aligns with the SUSTAIN KPI to improve energy efficiency and production yields during steel manufacture.

Key findings:

Basic logic building blocks may be fabricated using the selected technology at ultra-high temperatures

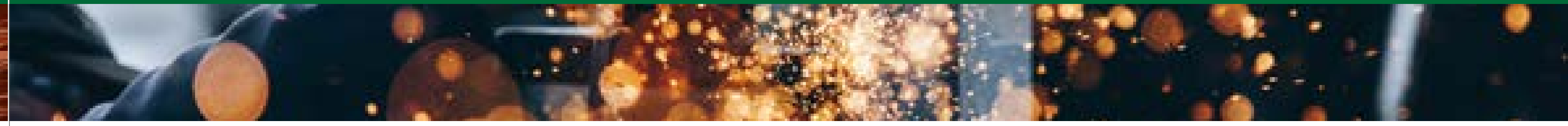
Vacuum tube technology can be used to overcome electronic limitations of high temperature devices when exceeding 700°C

A fabrication technique for such devices may be possible using conventional cleanroom methods

What has this feasibility study allowed you to do?

The SUSTAIN project has allowed us to take the high temperature sensor technology we currently research to a much more challenging level where the impact will benefit the keystone of British manufacturing: Steel. Many of the process measurement and control opportunities that benefit other industries, such as the chemical industries have so far been impossible in steel. This has forced the industry to rely upon modelling and inferred measurement which reduces the effectiveness and results in energy, production and yield losses that have been eliminated in other process industries. It is hoped that this developing technology will benefit the UK steel industry by aligning it to the slick process methodologies of the chemical and pharmaceutical industries and make steel ready for the full benefits of Industry 4.0 and AI.

The project has allowed us to push the boundaries of high temperature electronics to their limit and consider novel methods for achieving this. It has also allowed us to fund a talented PDRA for a further 6 months and provide opportunity for continuation of their work.



Task 12: Techno-economic Feasibility of Net-Zero Emission Solutions for Metal Heating (THERMOS)

Start date: November 2020 End date: October 2021
Project lead: Dr Yukun Hu
RA's: Xiaoyuan Cheng and Xiyao Sun
Project partners: University College London, University of Warwick, Air Products and SWERIM

Project Abstract

The transition to a low-carbon/net-zero metal heating process will require the transformation of existing reheating furnaces and the development of new ones. Major investment will be required that will take many years to be delivered. However, the transition pathway remains uncertain and, for much of the reheating furnace, the related technology deployments are still under debate. The proposed research focused on the techno-economic feasibility of net-zero emission solutions for metal heating, including Air-H_2 combustion, oxy-H_2 combustion, and H_2/NH_3 co-combustion.

Project Outcomes

By simulating the combustion behaviour of H_2 and NH_3/H_2 mixture in a combustion chamber in different environments, O_2 supply and combination ratios, it has been found that oxy-H_2 combustion exhibits the advantages of nearly zero NOx emissions. Apart from that, the flame temperature of the oxy-H_2 combustion is evidently higher than that of the air-H_2 combustion, but the average chamber temperature is less than that of the air-H_2 combustion and the NOx emissions are higher than that of the conventional combustion solution in the reference case because of the higher flame temperature.

The simulation results of feasible NH_3/H_2 mixture schemes are obtained and analysed. The primary considerations are the satisfaction of flame temperature, combustion efficiency and sustainability. The obtained results can act as a guide for industrial fuel engineers to design the NH_3/H_2 mixture fuel based on the specific requirements of the equipment and projects. Out of concern about the high-water vapour ratio environment may cause serious steel oxidation, in this study two machine learning algorithms of artificial neural network and random forest were used to predict the scale formation in the steel heating process of oxy-H_2 combustion and determine the features importance of steel oxidation.

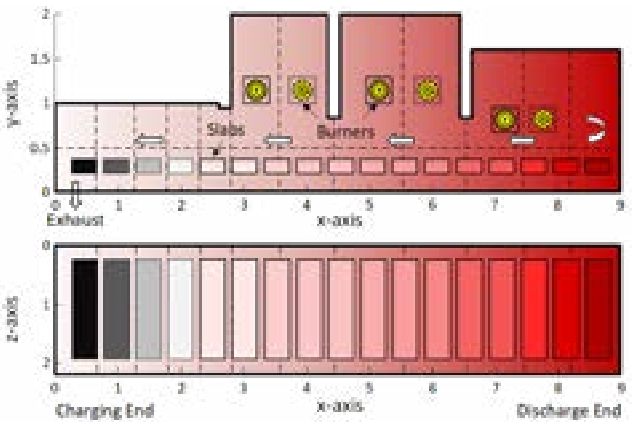
In comparing the competitiveness of hydrogen and natural gas in steel heating processes, the cost advantage of natural gas is likely to continue in the short term. The only possibility for hydrogen to exceed the competitiveness of natural gas is to unlock the potentials of renewable energy.

Key findings:

Much less mass input in oxy-hydrogen combustion, under the same fuel injection velocity, is not conducive to convection heat transfer

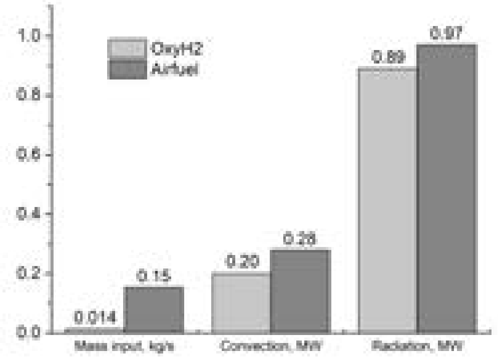
The quantified sensitivity indexes of water vapour, residual oxygen and temperature to oxide scale formation are 0.02, 0.45, and 0.8

The economic competitiveness of green hydrogen is expected to surpass that of natural gas by the 2040s



Above: Zonal modelling of a pilot scale walking-beam reheating furnace

Below: Parameter comparison between the oxyH2 and airfuel combustions



Microstructure and magnetic properties relationship at high temperature

Start date: May 2021 Expected end date: April 2022

Project lead: Dr Lei (Frank) Zhou

Project partners: University of Warwick, University of Manchester, Primetals Technologies Limited, Tata Steel, British Steel

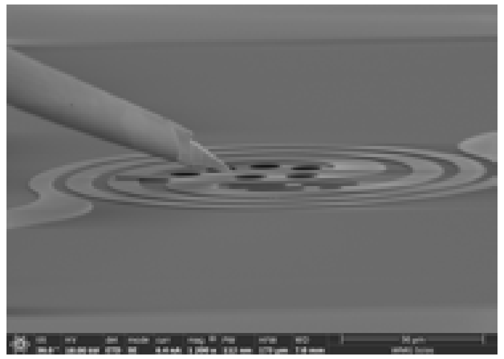
Project Abstract

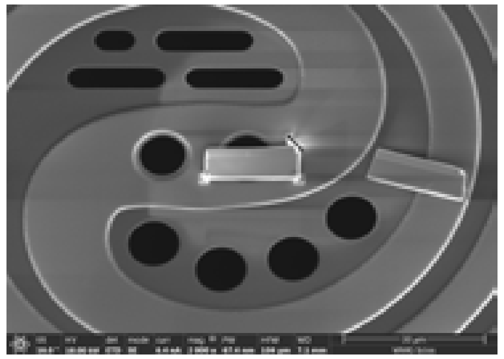
Electromagnetic (EM) sensors have shown enormous potential in the characterisation of microstructure both offline and on-line. The application of EM sensors for high-temperature on-line measurement drives the need for a better fundamental understanding of the interrelationship between temperature, microstructure parameters and magnetic properties in steels. This ECR project focuses on the fundamental understanding of the effect of temperature and magnetic field on domain wall movement and magnetic properties in low carbon steels.

Progress to Date

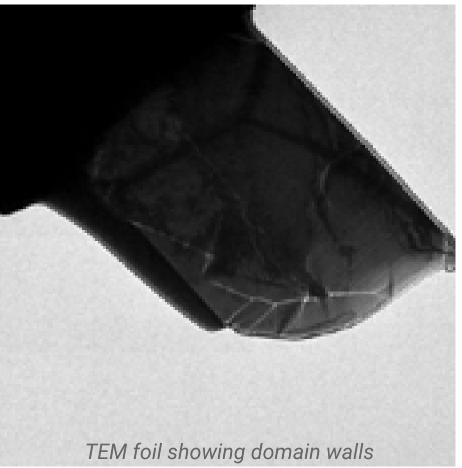
Lorentz microscopy in the TEM has been carried out to observe the movement of domain walls under the influence of changing magnetic field and, separately, changing temperature using the heated sample holder. The results show that domain structures are affected by the sample geometry but that domain wall movement is observed and that pinning by microstructural features, such as grain boundaries/carbides occurs. Initial observations show that both increasing magnetic field and increasing temperature allow domain walls to overcome pinning sites.

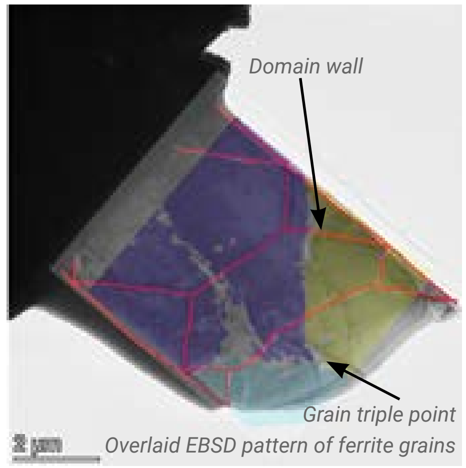
High-temperature magnetic measurements using a cylindrical EM sensor and an Epstein Frame (with Manchester University) for quantitative relationships between magnetic permeability at high temperatures and ferrite grain size has been made.





Above: Samples on in-situ TEM heating stage to look at the effect of temperature on magnetic domain structure





Above: Magnetic domain wall movement was observed during the change in temperature and applied magnetic field

Key findings:

In-situ magnetic domain observation using Lorentz microscopy, in the TEM with a high temperature sample holder has been completed

Both increasing magnetic field and temperature allow magnetic domain walls to overcome pinning features

Quantitative magnetic measurements at high temperature for structural steels shows the effect of microstructure on magnetic properties

Hub funded research: ECR platform

Sustainable Investment Assurance Model: SIAM

Start date: April 2021 End date: November 2021

Project lead: Dr Stephen Spooner

Project partners: Swansea University, Celsa Steel UK, GB Recycling, BEIS

Project Abstract

The project aimed to generate a view of sustainability and its measurement without influence from bias historical methodology for the manufacture and supply chain of steel within the UK. The initial case studies of assessing ongoing processes (Celsa Steel UK rebar production) and the pre-assessment of deploying new production methods (alternative steelmaking) were used to develop the framework of measurement while beginning to build precedence for its use simultaneously. The new framework would consider five distinct areas ("pillars") of sustainability including: Enviro/ecological, economic, social, synergy/functionality and moral/educational. Developing an understanding of current view of sustainability within each of these areas and deploying a way to measure both quality and performance of data within each pillar.

Project Outcomes

The initial SIAM framework development period was incredibly productive and found keen engagement from the public, private and education sectors. This resulted in the formation of SIAMs key principles of measure and generating a benchmarked measurement system for each of the pillars. Early exploration also included the analysis of established and developing digital technologies which may enable the delivery of SIAM in the future including existing LCA methodologies/open-source databases, blockchain solutions for data handling and a key change to the initial vision for SIAM was the change to generate "Vectors of Performance" rather than independent product and project measurements. This was due to the need to account for attempts being made to increase sustainability of a product at a given time rather than just its current rating - indicated as a key variable to present for encouraging efforts to improve ratings from the public experts focus group held in August 2021.

The specific case studies of UK rebar production, and alternative steelmaking were conducted at a high level (within SIAMs own system delivering values with only a 2* (out of 5) rating at data quality). This was because the available data was not of the full quality needed to conduct assessments at higher degrees of complexity/quality. This is a key learning outcome from SIAM – highlighting the need for improved data in specific areas for higher quality assessment. An additional output, which a significant amount of resource was diverted to, was a sustainability intervention priority roadmap. The road map was formed due to the complexity of sustainability assessments from LCA and supply chain elements within states of reduced control/legislative reporting. The roadmap itself can then be used as a benchmarking tool to rate the quality of data within a given assessment of the model.

Next steps

The TFI network+ have funded the next stage of SIAM development (along with support from CR+ and Louis Brimacombe BSI), where the framework will be assessed against additional foundation industries for its cross applicability and robustness of drivers

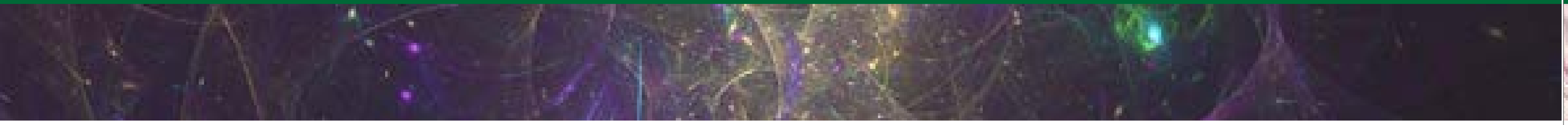
Key findings:

In many aspects the "sustainability" credentials of developed nations steelmaking are paralleled by developing nations

Current development commitments must be honoured and exceeded to be able to confidently claim world leading sustainability

After alternative production methods, industrial symbiosis presents the next largest opportunity for across-the-board sustainability improvements

Above: Examples of how SIAMs "pillars" align with the established global sustainable development goals



Process design of new reduced activation ferrite martensite (RAFM) steels for nuclear fusion reactors

Start date: May 2021 Expected end date: April 2022

Project lead: Dr Peng Gong

Project partners: University of Sheffield, University of Birmingham

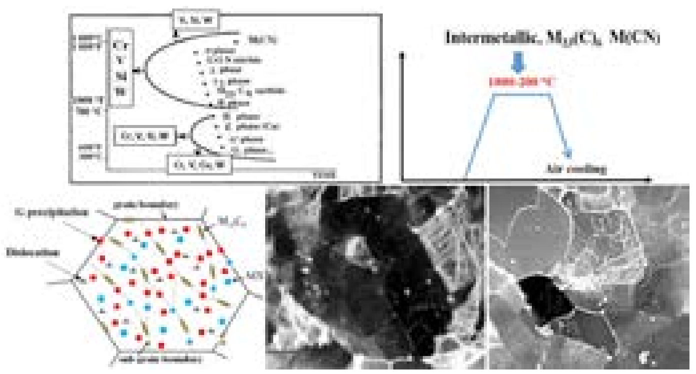
Project Abstract

To achieve the UK zero carbon emissions target by 2050, alternative low carbon energy generation sources such as wind, solar, nuclear and hydrogen must be developed to replace existing methods. Nuclear energy has the potential to help the UK reduce CO_2 to 68% by 2030 and to zero by 2050. Compared to a fission reactor, fusion could produce up to four times more energy with inexhaustible low-cost fuels (hydrogen and its isotope), no highly radioactive fission products, and no risk of large-scale nuclear chain reactions. However, the development of fusion reactors puts a high demand on materials, which must withstand high radiation levels (14.1 MeV), transmutation rates, temperatures, and thermomechanical stresses. This will require the design and development of superior materials and innovative, facile, manufacturing routes, especially for first wall structures and breeder blanket of fusion reactors. There is an urgent need to develop new RAFM steels for fusion reactor construction with service temperatures of 650°C, a lifespan of 30 years, and easy manufacturing routes. This project aims to design and produce new RAFM steels with superior high temperature creep resistance, toughness between 280-350°C with a minimum shift in DBTT under irradiation, and resistance to radiation. The new RAFM steels will combine the requirements of "water-cooling" and "helium-cooled" operation in one steel, to minimize production costs and joining issues.

Key findings:

Achieved dynamic recrystallization and deformation-induced ferrite through rolling development

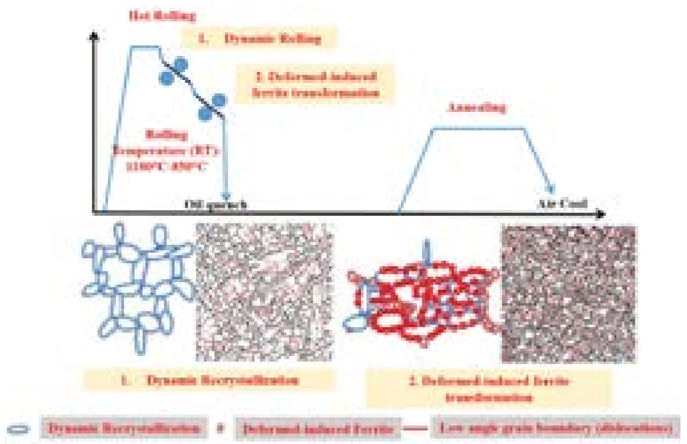
Refined the CrC precipitation and avoided Cr segregation on grain boundaries during heat treatment



Progress to Date

This project will design materials for the next generation of fusion reactors. Project progress includes:

1. Rolling process development
   - Use typical RAFM steel to develop rolling process
   - Lab Scale rolling: explore rolling parameters for dynamic recrystallization, deformation induced ferrite and extremely high dislocations on lab scale
   - Upscale rolling between lab and production scale: Vacuum induction melting ingot to 2.5kg, using the developed rolling process to roll the ingot with final thickness to the first wall and blanket thickness design on the fusion reactors
2. Alloy design for new RAFM steel
   - Select the best content of Si for intermetallic precipitation
   - Select the content of N for carbonitride
   - Use the developed rolling process on the new RAFM steels
3. Heat treatment development for precipitation & recrystallization
   - ThermoCalc modelling for ageing temperature for intermetallic precipitation
   - Experimental test for ageing time
   - Recovery and recrystallization
   - Precipitation
4. Mechanical property & microstructure analysis
   - Small punch for creep fatigue and DBTT
   - Microhardness and Tensile property
   - Microstructure analysis by EBSD and TEM



Above: Develop the manufacturing process for RAFM steels
Left: New annealing process design for intermetallic precipitation

All Printed Half-Heusler Abundant Thermoelectric Generators (ALPHA TEGs)

Start date: April 2022 Expected end date: September 2022

Project lead: Dr Matthew Burton

Project partners: Swansea University, SPECIFIC® IKC, Cardiff University, Queen Mary University, European Thermodynamics Ltd, Liberty Steel

This project aims to make thermoelectric generators economically viable for use in steel works. To achieve this they will be manufactured through printing (lower cost and embodied energy than zone melting or spark plasma sintering, easier processability), use Earth-abundant elements (Hf free half-Heuslers, reduces costs) and manufactured bespoke shaped generators (increases efficiency). These TEGs can capture low grade waste heat (>800 K), that is regarded as too low for other potential uses. Examples include outside VOD tanks, ladles, casters and vessels.

The capture of otherwise wasted heat with thermoelectric generators can be beneficial to the steel industry in two ways. Firstly, the harvested energy in electrical form could be used to reduce a steel works electricity demand on the grid, thus reducing their electricity costs and consequently net carbon emissions. Secondly, the generators could be used to power a variety wireless sensors. These sensors could, for example, monitor temperatures, which would reduce energy demand (no constant heating and cooling cycles) and increase production by potentially increasing the lifetimes of equipment. This would make steel works more efficient, cost effective and reduce carbon emissions.

Multi-field electromagnetic sensor detection for residual stress in steels

Start date: July 2022 Expected end date: June 2023

Project lead: Dr Fanfu Wu

Project partners: University of Warwick, British Steel, Liberty Steel, Tata Steel

Residual stresses can be developed in steel during processing in the absence of external loading or thermal gradients. Sometimes, residual stresses can be beneficial (for example compressive stresses from shot peening) or detrimental (for example spring back during forming). But in other cases, residual stresses at high levels can result in local plastic deformation, which causes component distortion and/or affects the fatigue life and fracture behaviours. For example, cracking and unexpected curvatures in hollow section steel products during and after cooling. It is therefore essential to be able to measure residual stresses and preferably in a non-destructive and rapid measurement manner.

The project aims to develop a fundamental understanding of the separate and combined effects of stress and microstructural features on full magnetic properties.

Objectives include:

- Measuring magnetic properties of steels with varying microstructure parameters (grain size and phase fraction) and applied stress at different applied magnetic field and frequency using a Brockhaus SST system
- Investigate magnetic anisotropy and hence the difference in demagnetisation field change due to stress
- Develop relationships for EM sensor signal – microstructure – stress in different steels (such as, NGO electrical steel, DP steel, low and high carbon steel)

Cu redistribution and precipitation in a low carbon steel

Start date: July 2022 Expected end date: June 2023
Project lead: Dr Jiaqi Duan
Project partners: University of Warwick, British Steel, Liberty Steel, Tata Steel

Recycling steel scrap for steel production using the Electric Arc Furnace (EAF) route can significantly reduce the CO_2 emissions. However, the steel scrap often contains impurities, and they will accumulate in the steel as the number of times the steel is recycled increases. Cu is an extremely important impurity element to understand its effects on the steel produced. Although considered as a 'tramp element', Cu sometimes is purposely added to steel for better physical properties. The Cu rich clusters and precipitates not only bring precipitation strengthening, but also enhance the thermal stability of the grain structure. Previous studies mainly focused on Cu precipitation in single phase steels (for example in ferritic steels, austenitic steels or martensitic steels) where deliberate additions are higher than most projected residual levels. These steels are often heat treated to give the Cu precipitation strengthening.

The proposed research will be a systematic and quantitative understanding of the impurity element Cu's redistribution and precipitation behaviours between various constituents and the corresponding effect on phase transformation kinetics and strengthening. The conclusions from this study can be applied to other dual- or multi-phase steels with high residuals due to high scrap use.

Effect Of Residual Elements on High Temperature Recovery and Recrystallisation of Niobium Based Microalloyed Steels

Start date: July 2022 Expected end date: June 2023
Project lead: Dr Mo Ji
Project partners: University of Warwick, British Steel, Liberty Steel, Tata Steel

Sn and Cu are residual elements picked up from scrap and it is known that they can segregate to interfaces, such as grain boundaries and dislocations, during steel processing and effect metallurgical transformations. Whilst purposeful alloying element additions are routinely used to control microstructural development during hot deformation, for example to affect recrystallisation or phase transformation, it is not known how the residual elements might affect these processes.

The scope of this proposal is to evaluate the impact of residual elements on the recrystallisation kinetics of TMCR steel products. Grain size control in hot rolling product is achieved via recrystallisation, in which the kinetics are strongly influenced by the steel composition, as well as the temperature, strain and grain size. The primary aim of the work is to investigate the solute drag effect of Cu and Sn during hot deformation, considering temperatures and strains relevant for hot rolling. The base steel composition and deformation conditions will be based on the pioneering work by Jonas et al. on solute drag [1], which was used to determine solute retardation parameters (SRP) for Nb, Mo, V, individually and in combination. The SRP are widely used in recrystallisation prediction equations in academic and industrial process models. This work will therefore develop comparable SRP for the key residual elements singularly and in combination. The second goal is to investigate the influence of Cu and Sn on the effectiveness of Nb on solute retardation.

[1] H. L. Andrade, M. G. Akben, and J. J. Jonas, 1983, "Effect of molybdenum, niobium, and vanadium on static recovery and recrystallization and on solute strengthening in microalloyed steels," Metall. Trans. A, vol. 14, no. 10, pp. 1967-1977.

Steels & Metals Institute SaMI at Swansea University

Swansea University Prifysgol Abertawe | Steel and Metals Institute Sefydliad Dur a Metelau

SaMI's unique SINTEC (Simulation & Integrity Testing in Extreme Conditions) facility enables process simulation, asset integrity testing and compositional analysis of materials at very high temperatures in reactive gas atmospheres including hydrogen, carbon monoxide, sulphur dioxide, ammonia, hydrogen sulphide & carbon dioxide.

By simulating industry processes such as steelmaking on the lab scale, SaMI is providing unique and essential facilities for research into breakthrough technologies to address industrial decarbonisation and net zero manufacturing and materials.

Industrial processes simulation in extreme environments

SINTEC is equipped with high temperature furnaces that can test various materials systems up to 1600ºC in controlled gas atmospheres. Integrated mass balance technology enables the study of materials in both oxidising and reducing environments. With online monitoring this provides an exclusive opportunity to take a virtual look inside industrial process.

Research study areas

- Optimising blast furnace performance through reduced reaction times for raw material feed
- Assessing alternative iron making technologies and fuel switching opportunities such as introducing hydrogen and non-fossil fuel carbonaceous alternatives into the process
- Evaluating refractory thermal efficiency and performance under different atmospheric conditions
- The surface interaction and wettability of molten metals by contact angle measurement
- Developing a visualisation furnace with viewing ports that creates the opportunity to use ultra-fast digital imaging and high-speed thermal camera systems
- High temperature oxidation kinetics of various material systems

Gas analysis & Metrology

SINTEC uses advanced analytical techniques including pyrolysis gas chromatograph mass spectrometry (GCMS) to study ultra-fast, high temperature processes in extreme environments. The equipment allows for in-situ measurements of the various gaseous and volatile organic species that evolve from simulated industrial processes.

Research study areas

- Displacement of fossil fuel carbon with non-fossil fuel carbonaceous waste within the ironmaking process
- Studying the volatile fraction of fossil fuel and non-fossil fuel (e.g. non-recyclable waste, plastics, biomass and modified biomass)
- Ultra-fast pyrolysis GCMS to study the ultra-fast thermal processes found in a blast furnace
- Capture waste gas samples from laboratory simulated industrial processes to exploit as a potential raw material for other processes

Left: Furnace viewing ports allow visualisation and recording of simulated industrial processes using advanced camera systems

Below: Swansea University PhD researcher Fawaz Ojobowale using the ultra-fast pyrolysis gas chromatography-mass spectrometer (GC-MS)

Product & asset integrity testing

SINTEC operates several corrosion chambers that simulate the conditions required to replicate the extreme environments experienced by components in service. The equipment enables lifetime assessment of materials in controlled atmospheres at temperatures up to 1800ºC.

Research study areas

- Wet sulphur dioxide evaluation for lifetime assessment of painted and other metallic products
- Sour service corrosion evaluation to investigate susceptibility of pipeline materials to hydrogen induced cracking in oil and gas industry applications
- Corrosion-Fatigue assessment of materials subject to high temperature corrosive environments and repeated cyclic loading
- Mechanical testing in environments containing hydrogen to study embrittlement behaviour

Practical solutions for companies

Working together closely with the steel industry and supply chain companies we are finding practical solutions to the biggest challenges the industry faces. SaMI's facility has enormous potential to help the steel industry transition to help achieve a net zero Wales.

We welcome enquiries from steel and supply chain companies looking for research solutions.

enquiries.sami@swansea.ac.uk
www.samiswansea.co.uk

Alloy Research and Design Capabilities Royce@Sheffield

The University of Sheffield and the Henry Royce Institute house world-class alloy research and development expertise and unique equipment. Their facilities offer development capabilities relevant for all metals, with alloy processing from grams to tens of kilograms, alongside a suite of advanced characterisation techniques allowing for a full-service approach to alloy design and research for academia and industry. Funding opportunities are available to support access for target groups.

Whether researching and designing alloys for traditional processing methods or for newer techniques such as additive manufacturing, Royce@Sheffield has a variety of equipment ideal for developing alloys, taking them through laboratory scale experimental simulations of industrial thermomechanical processing, and for characterising the new alloys developed.

Email royce@sheffield.ac.uk to discuss access.

Alloy Development

Cold Crucible Arc Melting Furnace and Casting Module

Used for research and prototype production, it offers the ability to melt, cast and rapidly solidify metal alloys of nominal 200g mass using a clean, ceramic free cold crucible process, at temperatures exceeding 3,000°C.

Vacuum Induction Melting Furnace

Used to meet the requirements of alloys which are often used in very demanding applications. There are two furnaces for small-scale development, up-scaling and research.

Strip Caster

This melt spinner casts a thin ribbon of rapidly quenched amorphous material in 100g batches. It uses induction melting in an inert atmosphere and a water-cooled, variable speed copper wheel to quench the metal and generate the ribbon.

Characterisation

X-Ray Diffractometer

This new in-situ multi-functional XRD system allows the study of advanced materials under in-service and extreme conditions.

Transmission Electron Microscope

The TEM provides high sensitivity materials analysis.

Hyperprobe Electron Probe Microanalyser

This EPMA uses an electron beam as the excitation source, is equipped with up to 5 channels of WDS, and is capable of elemental analysis of micro areas with a high energy resolution.

Field Emission Scanning Electron Microscope

This SEM is suitable for observing fine structures on the surface of a specimen. It is equipped with a Schottky electron gun and incorporates a wealth of the latest technologies for high-resolution image acquisition with bias voltage applied to the specimen.

Thermomechanical Processing

Reversing Hot Rolling Mill

Designed specifically for this facility to roll steels, titanium and nickel-based alloys from a maximum starting thickness of 80mm to a finished thickness of 3mm at up to 1300°C and includes a detachable run-out cooling table capable of accelerated cooling conditions.

Thermomechanical Compression

This machine was designed and built to simulate a wide range of industrial metalworking processes and is essential in the understanding of the influence of processing on both microstructure and properties.

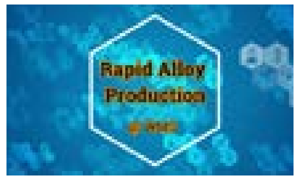
Advanced Materials Manufacturing Centre (AMMC), WMG, University of Warwick

Through Process Development:

The Centre supports full through process development of new and novel products, starting from trained computational simulation of both thermodynamic and process topologies of a given alloy design. The theoretical investigation can then be reinforced from our industrially benchmarked rapid through-put suite which includes **1g to 10kg vacuum alloy melting**, followed by casting, thermomechanical processing and finally surface treatments including PVD. Once test samples have been produced, we can interrogate a range of product performance attributes including environmental conditioning and mechanical testing in a range of environments and temperatures. Key equipment includes: **Arc and induction melting, hot and cold laboratory rolling mill, PVD coater and ETMT Themo-mechanical tester.**

High Temperature Reactions and Kinetics:

This programme makes use of bespoke high temperature furnaces, including the ability to replicate ironmaking/steelmaking gaseous environments while maintains addition and sampling of a system. Coupled with bulk laboratory experiments the team makes use of in-situ measurements techniques including our **High-temperature Confocal Scanning Laser Microscope (HT-CSLM)**, which allows micro visualisation of samples undergoing compression/tension and liquid interaction/ phenomena up to 1,800°C. To understand how material may behave at high temperatures further we also have **DSC/TGA** capable of up to 1550°C and high temperature viscometry. These facilities have been applied to investigations including raw material interrogation, simulation of novel ironmaking, direct reaction rate measurements and oxidation/carburisation.



Flagship Equipment

Gleeble HDS-V40

Confocal Scanning Laser Microscope

Vacuum Induction Melter

Hot and cold rolling

AMMC Website

Correlative Characterisation

The Centre houses a powerful suite of **electron microscopy** equipment. When combined with the co-location of the high power spoke of the national X-ray facility, which houses the first **micro focused 750kv X-ray computed tomography scanner** amongst other technologies, we can conduct highly specific correlative studies. An example would be capturing 3D internal of porosity and inclusion fraction of thin slab cross sections, which can be selectively located under **SEM** for composition and texture mapping, before moving on the further selected **TEM** to uncover aspects such as porosity ledging and complex inclusion structures.

Events & Outreach

Events Organised by the Hub

Sustainability in Steel | SUSTAIN Bi-Annual Conference 2021

On the 1st and 2nd of December 2021, the SUSTAIN Future Manufacturing Research Hub held its second Bi-Annual Conference, 'Sustainability in Steel'. Over the two live days, more than 190 attendees and booth representatives accessed the virtual conference platform.

This free to attend event was hosted online, due to the ongoing effects of COVID-19 and to make the event as accessible as possible to a wide audience. The conference aimed to raise awareness of the ongoing projects in the SUSTAIN Hub, demonstrating how this research is supporting the steel industry and its supply chains in the UK, as well as to share knowledge and best practice from a variety of external experts in the field. Conference attendees watched live presentations from a range of expert academic and industrial speakers, participated in the interactive workshop session and had opportunities to pose questions to our two expert panels.

The conference was run on a web-based virtual platform, which allowed attendees to interact with one another through the live text and video chat functions. The platform also hosted an online exhibition hall, which featured 18 booths from our projects, partners and related programmes, where attendees could browse a range of content including posters, videos and brochures.

The technical presentations were distributed over the two live conference days, with sessions covering a wide range of topical issues for the UK steel industry, including:

- Decarbonisation and de-fossilisation
- The role of scrap in the future of iron and steelmaking
- Supply chains and the Circular Economy
- The Hydrogen economy
- The use of Artificial Intelligence and digital processes
- High temperature microstructure monitoring and optimisation
- Skills and securing the talent pipeline

A range of speakers participated from the academic and industrial partners within the SUSTAIN network, and we were delighted to welcome those from outside the existing Hub structure, both from the UK and Internationally. It was fantastic to hear from those who could provide different perspectives on the issues facing the UK steel industry. The majority of the talks from the conference are available to watch on the Hub's YouTube Channel.

Green Steel | The Role of Scrap Webinar

This Webinar provided a great opportunity to hear about research findings and share views with the wider community for shaping future work to support a greener UK steel industry. Speakers included Dr Zushu Li, Dr Richard Thackray, Dr Frances Zhang, Dr Russ Hall, Prof. Claire Davis and Frank Schrama. The event was attended by 89 representatives from 38 organisations.

SUSTAIN Inreach Seminar series

In March 2021 the Hub launched an internal seminar series, to give PDRA's and PhD students the opportunity to present their work and develop a greater understanding of the scope of the Hub and identify where collaborations between existing tasks can be developed. These have been well attended over the last 12 months, and now the majority of PDRA's have presented, the format of this series is changing. Upcoming sessions aim to create a platform for discussion between researchers, academics and industrialists to share their views and ideas with others in the Hub, on topical areas including: Future Needs for Steel, Current State of the Art, Hydrogen Economy, Supply Chains and more!

SUSTAIN Leveraging Funds session

The aim of the session was for senior academics to showcase how they have previously been able to leverage funding within the programme and to use their own examples to encourage junior academics and PDRA's to follow suit. This event was well attended by SUSTAIN Hub members.

Community Outreach & Engagement

Over the last year, both online and in-person outreach and engagement events for schools and community groups has continued. Highlights include:

- Continued collaboration with the Discover Materials working group to introduce and inspire school children to find out more about Materials Science and Engineering, through webinars, teacher CPD and in-person stands at events
- Online and in-person events for Swansea Science Festival 2021
- Participation in engagement events, such as at the Royal Institution's "For Your Inspiration: Powering our sustainable future", to show young people the type of careers available which are helping to develop a sustainable future
- Featured in Welsh Government social media video for International Day of Women and Girls in Science 2022

Online Engagement

SUSTAIN's project website (www.sustainsteel.ac.uk) continues to be updated to feature up-to-date research, events and staff profiles. Over the last 12 months the website has received more than 13,500 page views from 4,900 unique visitors. The project newsletter, as well as the LinkedIn, Twitter and YouTube profiles have gained subscribers and followers throughout the year, and continue to provide a great platform for interactions with those both internal and external to the Hub.

Task Engagement Highlights

T0: Ran a series of elevator pitches, deep dives and a general SUSTAIN awareness survey.
T1: Participation in Carbon Dioxide Utilisation: Faraday Discussion online meeting in April 2021. Prof. Peter Syring chaired, Dr George Dowson and Dr Waqas Tanveer presented work from Task 1.
T2: Prof. Peter Holliman delivered a virtual public lecture "Driving the Circular Economy with Steel" to the South Wales Mining Association in March 2021.
T3: Dr Zushu Li presented on "Challenges and opportunities for steel scrap utilisation in the UK" at the virtual 3rd AIST Australia and New Zealand Steelmaking Symposium in November 2021.
T4: Prof. Jan Godsell presented at 'Steeling for a sustainable future: How could the UK steel industry compete through the supply chain?' Webinar in May 2021.
T5: Dr Richard Thackray presented "Steel research in the steel city" at the WMG Colloquium in October 2021
T6: Presentation to UKAEA (Nuclear project consortium)
T8: Prof. Claire Davis presented on " Metallurgical barriers for strip production through the EAF route (cast product to strip)" during a virtual scrap workshop in November 2021.
T9: Prof. Mark Rainforth delivered a Keynote presentation at the Thermec Conference in June 2021 titled " The effect of ageing on the microstructural evolution in a new design of maraging steel with carbon"
T10: Presented work at presented at the 1st FERIA conference
T12: Two papers were submitted to the 13th International Conference on Applied Energy in November 2021

Contributions by the Hub

European Electric Steelmaking Conference 2021

At the European Electric Steelmaking conference 2021, held in Sheffield, SUSTAIN hosted a booth in the exhibition hall and ran a hybrid conference workshop, supported by Hub academics. Members of the Hub were also involved in chairing sessions and presenting their work.

COP26

To showcase some of the decarbonisation work ongoing in the Hub, SUSTAIN have contributed to #COP26 Objects campaign run by the Materials Science and Engineering Department at Swansea University, to showcase how researchers and staff from different backgrounds can come together to make a difference. Catch up on the videos so far on YouTube.

Environmental Audit Committee

SUSTAIN has submitted evidence to the Technological Innovations and Climate Change: Green Steel inquiry. Professor Dave Worsley was a witness at the session investigating "How can steel production be decarbonised?".

Great Coastal Railway Journeys (S1 E23)

On-camera interview, filming and participation via a tour of facilities with Prof. Dave Worsley and Dr Hollie Cockings.

Metal Magazine

Dr Richard Curry contributed an article "The role of steel in creating a net-zero carbon, circular materials economy" to the Metal Magazine and Podcast.

Awards & Recognition

Queens Anniversary Prize

Swansea University has been awarded a Queen's Anniversary Prize in recognition of its Materials Science and Engineering research that is leading a revolution in renewable energy technologies, particularly solar electricity and heat generation and storage.

The Queen's Anniversary Prizes are awarded every two years and recognise the work carried out by UK universities and colleges which showcases quality and innovation and delivers real benefit to the wider world through education and training.

The Queen's Anniversary Prizes
For Higher and Further Education
2021

IOM3 Awards 2021:

Thornton Medal - Professor Dave Worsley, Swansea University
Presented to a speaker invited to present at either Institute conference or other specially convened meeting.

Gold Medal - Dr Richard Thackray, University of Sheffield
Gold Medal for services to the industrial application of metals.

Adrian Normanton Prize - Dr Stephen Spooner, Professor Claire Davis and Dr Zushu Li, University of Warwick
For the paper " Modelling the cumulative effect of scrap usage within a circular UK steel industry – residual element aggregation"

Dr Michael Auinger, University of Warwick
Appointed as a Turing Fellow by the Alan Turing Institute

Dr Enrico Andreoli, Swansea University
Appointed Editorial Board Member of Chemistry (MDPI)

Publications, Articles & Media

2020

Journal Paper: P. Gong, B.P. Wynne, A.J. Knowles, A. Turk, L. Ma, E.I.Galindo-Nava, W.M. Rainforth [2020]. Effect of ageing on the microstructural evolution in a new design of maraging steels with carbon. *Acta Materialia*. 196, 101-121 DOI: 10.1016/j.actamat.2020.06.029

Essay: R. Curry, G. Fletcher, [2020]. A steely solution. *Bright Blue Delivering Net Zero*. 144-150
Online: brightblue.org.uk/wp-content/uploads/2020/05/Final-Delivering-net-zero.pdf#page=145

Magazine Article: R. Waldram, [2020]. Supporting the development of Greener, Cleaner, Smarter Steel industry in the UK. *Swansea University Engineering, A Call for Engineers*. 16
Online: online.flippingbook.com/view/572041/16-17

2021

Journal Paper: Q. Guo, X. Li, P. Gong, J. Nutter, W. M. Rainforth, H. Luo, [2021]. Why Does Nitriding of Grain-Oriented Silicon Steel Become Slower at Higher Temperature?. *Steel Research International*, **92**, (2), 2000545 DOI: 10.1002/srin.202000545

News and Views: E. Andreoli [2021]. CO_2-to-ethylene electroreduction gets a boost. *Nature Catalysis*. **4**, 8–9 DOI: 10.1038/s41929-020-00568-9

Journal Paper: L. Zhou, P. Kok and C. L. Davis, [2021]. Steel microstructure - Magnetic permeability modelling: The effect of ferrite grain size and phase fraction. *Journal of Magnetism and Magnetic Materials*, **519** (167439). DOI: 10.1016/j.jmmm.2020.167439

Journal Paper: G.R.M. Dowson, P. Styring and J. Cooper, [2021]. Reactive Capture Using Metal Looping: The Effect of Oxygen. *Faraday Discussions*. DOI: 10.1039/D1FD00001B

Review Paper: I. Kapoor, C. Davis, Z. Li [2021]. Effects of residual elements during the casting process of steel production: a critical review. *Ironmaking & Steelmaking*. DOI: 10.1080/03019233.2021.1898869

Journal Paper: P. Styring and G.R.M. Dowson, [2021]. Oxygenated Transport Fuels from Carbon Dioxide. *Johnson Matthey Technology Review*, **65**, (2), 170-179. DOI: 10.1595/205651321X16063027322661

Journal Paper: D. J. C. Stewart, D. Thomson, and A. R. Barron, [2021]. The production of high value pig iron nuggets from steelmaking by-products - A thermodynamic evaluation. *Resources, Conservation and Recycling*, **170**, 105592. DOI: 10.1016/j.resconrec.2021.105592

Journal Paper: A. Koutsianos, L. B. Hamdy, C.-J. Yoo, J. J. Lee, M. Taddei, J. M. Urban-Klaehn, J. Dryzek, C. W. Jones, A. R. Barron and E. Andreoli [2021]. Drastic enhancement of carbon dioxide adsorption in fluoroalkyl-modified poly(allylamine). *Journal of Materials Chemistry A*, **9**, 10827. DOI: 10.1039/d1ta00879j

Review Article: M. Z. Khan, A. Iltaf, H. A. Ishfaq, F. N. Khan, W. H. Tanveer, R-H. Song, M. T. Mehran, M. Saleem, A. Hussain, Z. Masaud [2021].Flat-tubular solid oxide fuel cells and stacks: a review. *Journal of Asian Ceramic Societies*, **9**, (3), 745-770. DOI: 10.1080/21870764.2021.1920135

Journal Paper: S.Beden; Q.Cao; A.Beckmann [2021]. Semantic Asset Administration Shells in Industry 4.0: A Survey. *2021 4th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS)*. DOI: 10.1109/ICPS49255.2021.9468266

Journal Paper: A. SenGupta, B. Santillana, S. Seetharaman, & M. Auinger [2021]. A multiscale-based approach to understand dendrite deflection in continuously cast steel slab samples. ***Metallurgical and Materials** Transactions A - Physical Metallurgy and Materials Science*, **52**, 3413-3422. DOI: 10.1007/s11661-021-06313-6

Journal Paper: P. Styring, G. R. M. Dowson, I. O. Tozer [2021]. Synthetic Fuels Based on Dimethyl Ether as a Future Non-fossil Fuel for Road Transport from Sustainable Feedstocks. *Frontiers in Energy Research: Process and Energy Systems Engineering*, **9**, 663331. DOI: 10.3389/fenrg.2021.663331

Journal Paper: J. A. Rudd, S. Hernandez-Aldave, E. Kazimierska, L. B. Hamdy, O. J. E. Bain, A. R. Baron, E. Andreoli [2021]. Investigation into the Re-Arrangement of Copper Foams Pre- and Post-CO2 Electrocatalysis. *Chemistry*, **3**, 687-703. DOI: 10.3390/chemistry3030048

Journal Paper: S. Beden, Q. Cao, A. Beckmann [2021]. SCRO: A Domain Ontology for Describing Steel Cold Rolling Processes towards Industry 4.0. *Information*, **12**, 304. DOI: 10.3390/info12080304

Journal Paper: J. W. Wilson, L. Zhou, C. L. Davis, A. J. Peyton [2021]. High temperature magnetic characterisation of structural steels using Epstein frame. *Measurement Science and Technology*, **32**, 125601. DOI: 10.1088/1361-6501/ac17fa

Journal Paper: A.M.S.H.Al-Moftah, R.Marsh, J. Steer [2021]. Thermal Decomposition Kinetic Study of Non-Recyclable Paper and Plastic Waste by Thermogravimetric Analysis. *Chemical Engineering*, **5**, (3), 54. DOI: 10.3390/chemengineering5030054

Journal Paper: L. B. Hamdy, C. Goel, J. A. Rudd, A. R. Barron, E. Andreoli [2021]. The application of amine-based materials for carbon capture and utilisation: an overarching view. *Materials Advances*, **2**, 5843. DOI: 10.1039/d1ma00360g

Journal Paper: Q. Cao, C. Zanni-Merk, A. Samet, C. Reich, F. de Bertrand de Beuvron, A. Beckmann, C. Giannetti [2021]. KSPMI: A Knowledge-based System for Predictive Maintenance in Industry 4.0. *Robotics and Computer-Integrated Manufacturing*, **74**, 102281. DOI: 10.1016/j.rcim.2021.102281

Journal Paper: T. W. J. Kwok, P. Gong, X. Xu, J. Nutter, W. M. Rainforth, D. Dye [2021]. Microstructure Evolution and Tensile Behaviour of a Cold Rolled 8 Wt Pct Mn Medium Manganese Steel. *Metallurgical And Materials Transactions A*, **53A**, 597-609. DOI: 10.1007/s11661-021-06534-9

Journal Paper: Q. Cao, S. Beden, A. Beckmann [2021]. A core reference ontology for steelmaking process knowledge modelling and information management. *Computers in Industry*, **135**, 103574. DOI: 10.1016/j.compind.2021.103574

Online Article: W.M. Rainforth [2021]. New steel manufacturing method could lower emissions. *The Engineer.* Online: theengineer.co.uk/new-steel-manufacturing-method-could-lower-emissions

Online Article: [2021]. From concrete to steel, how construction makes up the 'last mile' of decarbonization. *Fortune.* Online: fortune.com/2021/02/16/concrete-steel-construction-design-climate

Online Article: S.Spooner [2021]. Automotive recycling - can we stop downcycling our materials? *ATF Professional.* Online: atfpro.co.uk/automotive-recycling-can-we-stop-downcycling-our-materials

Conference Keynote: Z. Li [2021]. Research and development for decarbonisation of the UK steel industry – current status. *China Symposium on Sustainable Iron- and Steelmaking Technology*

Conference Presentation: G. Dowson, W. T. Hassan [2021]. Reactive capture using metal looping: the effect of oxygen. *Carbon Dioxide Utilisation: Faraday Discussion*

Conference Presentation: G. Dowson [2021]. Reactive capture using metal looping: Decarbonising UK Steel Production: Pressure Swing CO_2 Capture and Fuel Synthesis Challenges. *ICCDU (International Conference on Carbon Dioxide Utilisation)*

Conference Presentation: P. Styring [2021]. Transport Fuels from CO2: Avoiding a Social Underclass in a Just Energy Transition. *ICCDU (International Conference on Carbon Dioxide Utilisation)*

Conference Presentation: Z. Li, W. Zhang, J. Duan, R. Hall, S. Spooner, T. Ibn-Mohammed, C. Davis, J. Godsell [2021]. Research and Development to enable the conversion of low quality scrap into high quality steel in the UK. *12th European Electric Steelmaking Conference*

Conference Presentation: Z. Li [2021]. Challenges and opportunities for steel scrap utilisation in the UK. *3rd AIST Australia and New Zealand Steelmaking Symposium*

Conference Workshop: R.Curry [2021]. The Steel Plant of the Future: How to Achieve Net Zero. *12th European Electric Steelmaking Conference*

Webinar: P. Holliman [2021]. It's not easy being green. *South Wales Materials Association (SWMA)*
Online: Zoom recording

Webinar: R. Waldram [2021]. Introduction to the Circular Economy. *Discover Materials for British Science week 2021*
Online: YouTube

Webinar: C. Pleydell-Pearce [2021]. SUSTAIN from nothing to now. *Sheffield Metallurgical & Engineering Association (SMEA)*
Online: YouTube

Webinar: J. Steer [2021]. Reduction of greenhouse emissions due to ironmaking. *Warwick Manufacturing Group Steel Group Colloquium*
Online: YouTube

Webinar: R. Curry [2021]. Carbon Neutrality in Steelmaking. *Northern Energy Transition Conference*
Online: YouTube

Webinar: Z. Li, R. Thackray, F. Zhang, R. Hall, C. Davis, F. Schrama [2021]. Green Steel: The Role of Scrap. *SUSTAIN*

Webinar: R. Waldram [2021]. Panel Session Host. *Discover Materials This Winter*
Online: YouTube

Webinar: Z. Suhaimi [2021]. Supply Chain Productivity: Moving from Theory to Practice. *Warwick Manufacturing Group*

Webinar: Q. Cao [2021]. From AI to Industry 4.0: a hybrid predictive maintenance approach based on knowledge graph and machine learning. *Shandong Normal University*

Online Video: W. H. Tanveer [2021]. Zero Carbon Tour Interview. *Planet Mark*
Online: YouTube

2022

Journal Paper: P. Gong, A. Turk, J. Nutter, F. Yu, B. Wynne, P. Rivera-Diaz-del-Castillo, W. M. Rainforth [2022]. Hydrogen embrittlement mechanisms in advanced high strength steel. *Acta Materialia*, **223**, 117488. DOI: 10.1016/j.actamat.2021.117488

Journal Paper: M. Legkovskis, P. J. Thomas, M. Auinger [2022]. Uncertainty quantification of time-dependent quantities in a system with adjustable level of smoothness. *Journal of Verification, Validation and Uncertainty Quantification*, **7**, 011005. DOI: 10.1115/1.4053161

TV Programme: D. Worsley, H. Cockings [2022]. Great Coastal Railway Journeys with Michael Portillo - Port Talbot to Pembrey Burry Port. *BBC2*, **1**, (23).
Online: BBC iPlayer

Social Media Interview: R. Waldram, S. J. Potts, A. Shorley [2022]. International Day of Women and Girls in Science. *Welsh Government.*
Online: Twitter

Webinar: R. Curry [2022]. Sustainable Steel Manufacture and a Possible Future for North East Steel. *The Mining Institute*
Online: YouTube

Meet the Team

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 Spoke institutions 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.

Professor Dave Worsley - Director, Swansea

Dave is a Tata Steel sponsored Professor and Head of Materials Science and Engineering in the Faculty of Science and Engineering, Swansea University focussing on applied industrial engineering and technology for sustainability. Dave champions de-carbonisation of the materials supply chain and renewable energy for buildings and transport. He has close ties with the UK metals and steel industries and has brought the UK's largest steel producers grouping together to tackle the environmental and sustainability issues head on with the SUSTAIN Hub.

Professor Cameron Pleydell-Pearce - Deputy Director, Swansea

Cam is a Tata Steel sponsored Professor in the Faculty of Science and Engineering at Swansea University. He has a long history of interfacing with industry and has significant experience of managing industry/academic research collaborations and relationships. A central focus of his career has been the establishment of a strong and vibrant research environment in Swansea University. Currently he is focused on consolidating and enhancing this environment locally and has a leading role nationally in steel research, development and innovation.

Professor Claire Davis - Spoke Director, Warwick

Claire holds a Royal Academy of Engineering / Tata Steel Chair in Low Energy Steel Processing at WMG, University of Warwick. She leads the Advanced Steel Research Centre based in the Advanced Materials and Manufacturing Centre at WMG, which comprises over forty researchers working on steel projects. Her personal research interests are in microstructure-processing-property relationships in steels. Current activities include work on electromagnetic sensors for microstructure characterisation, rapid alloy processing, new steel grade and processing developments and circularity for steel.

Professor Mark Rainforth - Spoke Director, Sheffield

Mark holds a POSCO Chair in Iron and Steel at the University of Sheffield. His research interests focus on processing and high resolution characterisation of microstructures, in particular in the development of new high strength steels.

Dr Richard Curry - Programme Manager, Swansea

Richard currently manages the SUSTAIN and iSPACE programmes at Swansea University. Following a brief academic career focussing on bioelectronic devices and non-planar device fabrication methods, Richard began working within steelmaking R&D, becoming Knowledge Group Leader for the Steelmaking and Casting groups within the UK Process R&D department. In 2013/2014 Richard was part of the trio that span out the Teesside Tata Steel R&D Laboratories to become MPI, leading the research, site and pilot plant as Operations Director. Richard left MPI in 2018 to join Professor Worsley's team and the SUSTAIN project.

Strategic Advisory Board

With representatives from academia, industry and government, the purpose of the Strategic Advisory Board is to evaluate industrial and academic impact, provide 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 Louis Brimacombe (Chair) - Consultant

Louis is a Fellow of IOM3 and a chartered Chemical Engineer. Currently working as a consultant and business advisor specialising in sustainable development and life cycle assessment (LCA). His leadership skills, innovative approach and vision has helped businesses to develop R&D programmes and embed life cycle thinking in their R&D and product marketing strategies.

Mike Greenall - NSG

Mike is the Chief Technology Officer of NSG, a Global Flat Glass manufacturer. He leads R&D and is based at the NSG Technical Centre in Lancashire. NSG is committed to a 21% reduction in CO2 emissions by 2030. NSG R&D is progressing several initiatives including Carbon capture, Low carbon fuels, electrification, and recycled materials. In a world first for any flat glass maker, in 2021 we successfully fired our UK Float Glass furnace with Hydrogen. The Glass and Steel industries face common challenges and technology roadmaps overlap. Mike joins the SUSTAIN team to share ideas across foundation industries.

Dr Robert Quarshie - KTN

Robert currently leads all materials activities at KTN. He holds a PhD in Materials Science/Electrochemistry (Development of High Energy Density Batteries) and a Postdoctoral Fellowship in Steel Metallurgy. Worked in various senior management roles in the steel industry, including R&D, Manufacturing, Customer Technical Services, Product & market development and strategy.

Professor Dierk Raabe - Max-Planck-Institut

Dierk Raabe studied music, metallurgy and metal physics. After his doctorate in 1992 at RWTH Aachen he worked at Carnegie Mellon University and joined Max Planck Society in 1999. His interests are in sustainable metallurgy, alloy design, computational materials science and atom probe tomography.

Naomi South - EPSRC

Naomi is a Research Portfolio Manager at EPSRC, working across the areas of materials engineering and circular economy. She has a background in mathematics and studied for an MMath before joining EPSRC in early 2020.

Gareth Stace - UK Steel

Gareth became Director-General of UK Steel in 2015. Acting as the sector's voice during the 2015-16 steel crisis and beyond. The role of UK Steel is to set out to the Government, MPs and the media that a vibrant steel sector in the UK is vital to the Government's ambition of 'Levelling Up' and achieving Net Zero Carbon. A globally competitive British steel sector will provide highly-skilled, well-paid jobs in areas of the UK that needs them most. All of the strongest global economies possess a strong steel sector.

Dr Walter Stahel - Product Life Institute

Stahel is an architect by training (ETH Zürich), researcher by experience, risk manager by necessity, Professor at University of Surrey by invitation, author and keynote speaker by conviction, member of the Club of Rome and Scientific Advisory Boards to pass on to others his circular economy experience of 45 years.

Professor Sybrand Van Der Zwaag - TU Delft

Sybrand van der Zwaag has been a full professor at the TU Delft for 29 years. His research deals with phase transformations in chemically simple steels as well as structure-property relationships in metals, polymers, ceramics and meta-materials. He pioneered the development of self healing materials.

Professor Mercedes Maroto-Valer - Heriot-Watt University

Professor Mercedes Maroto-Valer (FRSE, FIChemE, FRSC, FRSA, FEI) is Champion and Director of the UK Industrial Decarbonisation Research and Innovation Centre (IDRIC) focused on accelerating the transition to net zero of the UK industrial clusters and establishing the first world net-zero industrial cluster. Mercedes is Deputy Principal (Global Sustainability) and Director of the Research Centre for Carbon Solutions (RCCS) at Heriot-Wat University. Her internationally recognised track record covers energy systems, CCUS, integration of hydrogen technologies and low-carbon fuels. She has over 550 publications, holds leading positions in professional societies and editorial boards and has received numerous international prizes and awards.

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 SUSTAIN Management Team also sit on the Operational Committee, plus our EPSRC representative.

Chris Vaughan
Technical Director,
British Steel

Dr Gari Harris
R&D Manager,
British Steel

Chris Hagg
Head of External Affairs,
Celsa Steel UK

Eoin Bailey
UK Innovation Manager,
Celsa Steel UK

Peter Hogg
Chief Operating Officer,
Liberty Speciality Steels

Matt Green
Principal Researcher,
Liberty Speciality Steels

Prof. Jesus Talamantes-Silva
Research, Design and Technology
Director, Sheffield Forgemasters

Dr Laura Baker
Head, Product Management &
Development, Tata Steel UK

Byron Tucker
Head of R&D at Swansea
Technology Centre, Tata Steel UK

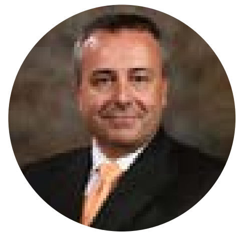
Alan Scholes
Chief Technology Officer,
Materials Processing Institute

Richard Warren
Head of Policy and
External Affairs, UK Steel

Investigators

Dr Enrico Andreoli
Swansea University
Theme 1, T1

Dr Michael Auinger
University of Warwick
Theme 3, T5



Prof. Andrew Barron
Swansea University
Theme 1, T1

Prof. Arnold Beckmann
Swansea University
Theme 3, T4

Prof. Matthew Carnie
Swansea University
Theme 4, T6

Dr Hollie Cockings
Swansea University
Theme 4, T6; ECR Champion

Prof. Claire Davis
University of Warwick
Theme 4, T7; Theme 5, T8

Dr Jonathon Elvins
Swansea University
Theme 4, T6

Prof. Janet Godsell
Loughborough University
Theme 3, T4

Prof. Peter Holliman
Swansea University
Theme 2, T2

Dr Zushu Li
University of Warwick
Theme 2, T3; Theme 4, T7

Prof. Giovanni Montana
University of Warwick
Theme 3, T4

Prof. Eric Palmiere
University of Sheffield
Theme 5, T9

Prof. Cam Pleydell-Pearce
Swansea University
Theme 4, T6

Prof. Mark Rainforth
University of Sheffield
Theme 5, T9

Dr Elizabeth Sackett
Swansea University
ECR Champion

Dr Martin Strangwood
University of Warwick
Theme 5, T9

Prof. Peter Styring
University of Sheffield
Theme 1, T1

Dr Richard Thackray
University of Sheffield
Theme 2, T2,3; Theme 3, T5

Prof. Jon Willmott
University of Sheffield
Theme 4, T6

Researchers

Dr Craig Armstrong
Swansea University, T1

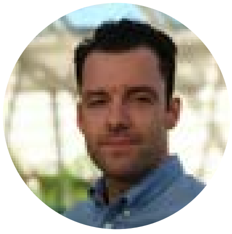
Dr Matthew Burton
Swansea University,
ECR project 2022

Dr George Dowson
University of Sheffield, T1

Dr Jiaqi Duan
University of Warwick,
ECR project 2022

Dr Peng Gong
University of Sheffield, T9
ECR project 2021

Dr Mo Ji
University of Warwick,
ECR project 2022



Dr Eurig Wyn Jones
Swansea University, T2

Dr Aurash Karimi
University of Warwick, T5

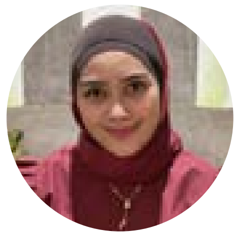
Dr Uchenna Kesieme
University of Sheffield, T5

Dr Stephen Spooner
Swansea University,
ECR project 2021

Dr Fanfu Wu
University of Warwick,
ECR project 2022

Dr Frank Zhou
University of Warwick, T8
ECR project 2021

PhD and EngD Students (Core & Aligned)



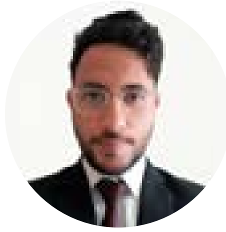
Lisa Ahmad
University of Sheffield, T2
LCA of Alternative Materials for Blast Furnace Ironmaking

Geraint Howells
Swansea University, T6
Use of thermoelectric coatings for heat recovery

Hannah Clarke
Swansea University
Development of formable automotive steel grades through alternative steel making technologies

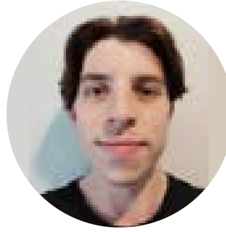
Freya Hamblin
Swansea University
Steps towards sustainability and decarbonisation – impact of high recycled content and advanced casting on high formability products

David Ireland
University of Warwick, T4
Deep Reinforcement Learning and Combinatorial Optimisation



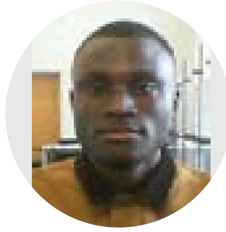
Mohammed Kamran
Swansea University, T8
Continuous Temperature Measurement of Liquid Metal

Nigel Kougampillil
Swansea University, T6
The Generation of Domestic Hot Water from SIM (Salt in Matrix) Technologies



Zachary Lowther
Swansea University, T2
Fireproof High Efficiency Inorganic Building Insulation from Waste Industrial Slag

Sam Morgan
University of Sheffield, T9
Predicting Optimised Steel Product Processing and Properties

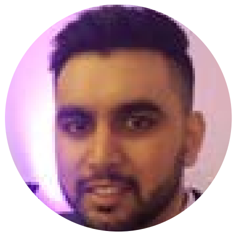


Fawaz Ojobowale
Swansea University, T2
Alternative reductants blast furnace

Sam Reis
Swansea University, T2
Environmental & commercial sustainability of Blast furnace sinter manufacturing

William Robertson
University of Sheffield, T3
Assessment of the Environmental Impact of Residual & Critical Elements in Steel Removal, Recovery and Substitution

Caydn Robinson
Swansea University, T6
Emissivity and oxidation evolution in reheating furnace environments



Ajitesh Sharma
University of Warwick, T7
Understanding effects of steel casting cooling rate ranges & thermo-mechanical processing on segregation spatial distributions & properties

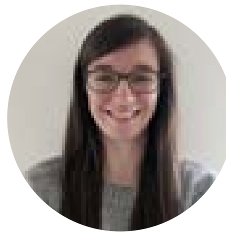
Rhys Thomas
University of Warwick, T7
Green hydrogen based direct reduced iron (DRI) for steel manufacturing

Matthew Wilcox
Swansea University, T2
Environmental optimization of sintering

Operations Team

Sarah Roberts
Project Officer

Paula Toft
EA to the Hub Director



Dr Becky Waldram
Outreach Officer

Lydia Webber
Administrative Coordinator

sustain
future steel manufacturing research hub

Funded by:

UKRI Engineering and Physical Sciences Research Council

Academic Partners:

Swansea University Prifysgol Abertawe

The University Of Sheffield.

WMG THE UNIVERSITY OF WARWICK

Industrial Partners:

BRITISH STEEL

CELSA GROUP CELSA STEEL UK

LIBERTY STEEL

SHEFFIELD FORGEMASTERS

TATA STEEL