The Strategic University Steel Technology and Innovation Network Presents

Research into the Decarbonisation of Integrated and EAF Steelmaking Plants

Dr Richard Curry, University of Swansea

sustain

future steel manufacturing research hub

UKRI Engineering and Physical Sciences Research Council

SUSTAINetwork Overview

Industry Challenges	Research Challenges	Innovation	Vision & Opportunity

SHEFFIELD FORGEMASTERS INTERNATIONAL

Climate change & sustainability → GCRA 1 → The University Of Sheffield.

LIBERTY STEEL

Capability → GCRA 2 → Swansea University Prifysgol Abertawe

BRITISH STEEL

TATA STEEL

Capacity & future skills ← Informed Investment ← WARWICK THE UNIVERSITY OF WARWICK

CELSA GROUP · CELSA STEEL UK

Innovation: UK Steel · HENRY ROYCE INSTITUTE · AMRC / The University Of Sheffield. · specific · MPI Materials Processing Institute · CATAPULT High Value Manufacturing · mtc · WMG THE UNIVERSITY OF WARWICK

Vision & Opportunity:

- Carbon neutral iron & steel making 2040
- £2.4bn GVA, 15% productivity boost & 35,000 jobs by 2030
- World leading intelligent infrastructure by 2030

Supply Chain Integration	Raw Materials	Technology Suppliers	Primary Producers	Metal Processors	OEMs & End Users

Durham University

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD X2

UCL

UNIVERSITY OF HULL

TFI NETWORK+

TRANSFORMING THE FOUNDATION INDUSTRIES

The Research

GCRA 1
Carbon Neutral Iron and Steelmaking

Task 0
Cross Cutting Activities

GCRA 2
Smart Steel Processing

Theme 1
Emissions Management & Utilisation

- **Task 1** Emissions Control
- +
- **Task 14** Flexible Operation in Net-Zero Steel Plant

Theme 2
Zero Waste Steel Making

- **Task 2** Waste Reprocessing
- +
- **Task 3** Scrap Utilisation
- +
- **Task 10** Novel Reductants
- +
- **Task 13** Photocatalysts for Upcycling of Plastic Waste

Theme 3
Data Driven Innovation

- **Task 4/5** Digital Steel Innovation Hub (DSIH)

materials made smarter Centre

Theme 4
Smart Low Energy Production

- **Task 6** Thermal Efficiency
- +
- **Task 12** Net-Zero Metal Heating (THERMOS)

Theme 5
New Processes for New Products

- **Task 8** Smart Sensors for Real-Time Measurement
- +
- **Task 9** Late Stage Product Definition & Integration
- +
- **Task 11** High Temperature Electronics (UHTRED)

Theme 1: Emissions Management and Utilisation
State of the Art

Carbon Capture

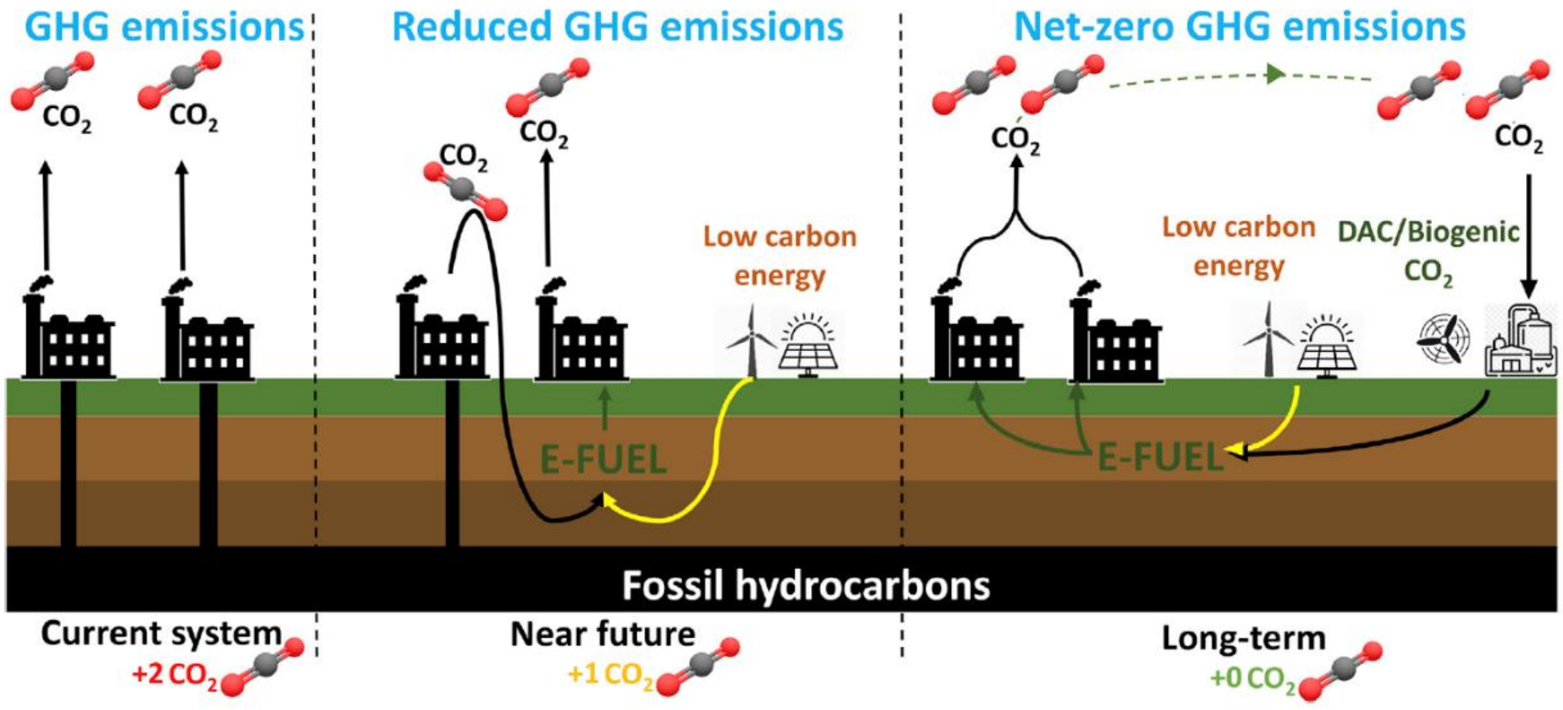


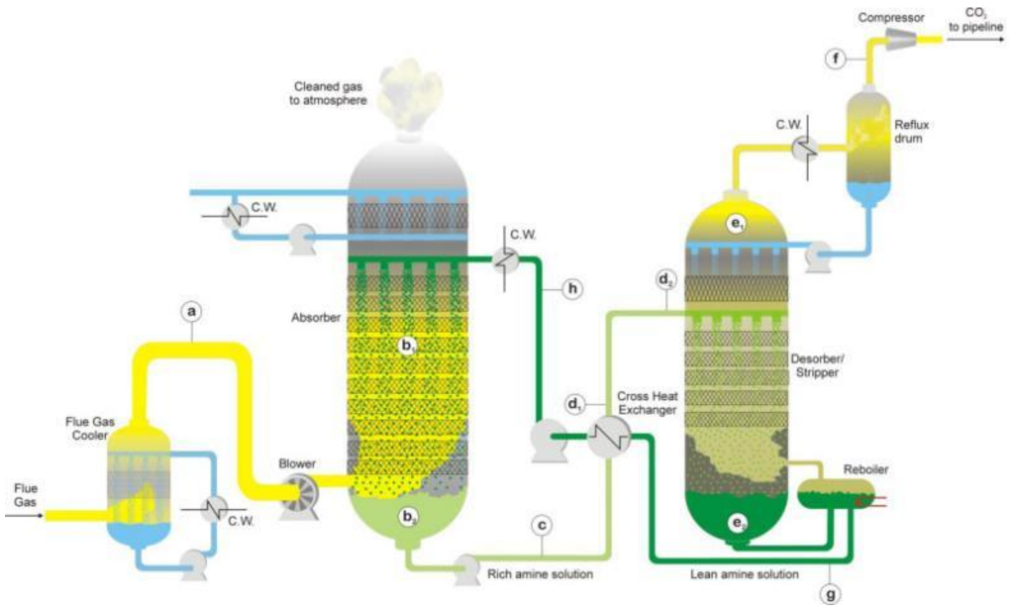
Figure 2. CCU using low-carbon energy is not just a delay in CO_2 emissions but can result in up to 50% emission reduction even when fossil CO_2 is reused

Mertens, Styring et al., Carbon capture and utilization: More than hiding CO_2 for some time, Joule (2023), https://doi.org/10.1016/j.joule.2023.01.005

Theme 1: Emissions Management and Utilisation
State of the Art

Carbon Capture- Current amine technology

Current capture is dominated by using amine as a solvent (Shell, Chevron, Equinor).
This has several problems:
(1) It is **energy-inefficient regeneration** and
(2) The captured CO_2 has to be utilised, with no current large scale solutions in the UK
(3) Amines are unstable



Theme 1: Emissions Management and Utilisation

Carbon Capture- FluRefin

Carbon capture and utilisation offers a pathway towards a cyclical carbon economy wherein CO_2 emissions are recycled as an alternative feedstock for chemical synthesis.

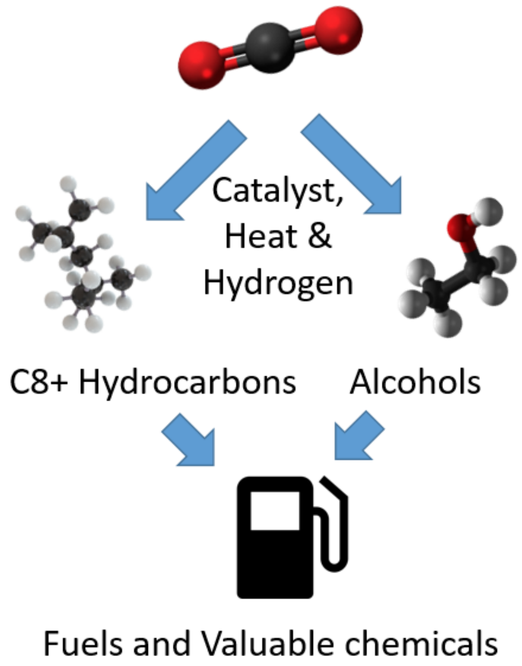
Flexible capture units with small footprint are required for CO_2 capture in steel contexts, in contrast with amine-based approaches that don’t tolerate shifting conditions.

Collaboration with AESSEAL has produced a trailer-based automated capture unit at 40 times the original capture unit scale that can continuously refine a 20% CO_2 stream to 80% (suitable for liquid CO_2 production) at 100kg/day scale. It can also operate off-grid for demonstration or remotely for site testing.

Theme 1: Emissions Management and Utilisation

Utilisation: Thermochemical conversion

Focus is on conversion of CO_2 into value-added products, such as fuels. We shall be investigating whether the 80% CO_2 capture unit output can be directly converted into kerosene/aviation fuel using iron-based catalysts and hydrogen as well as other valuable products like ethanol and Dimethoxyethane



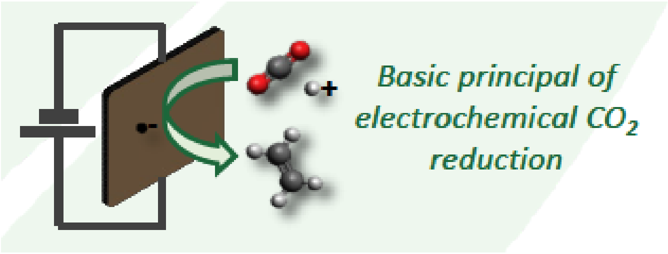
Theme 1: Emissions Management and Utilisation

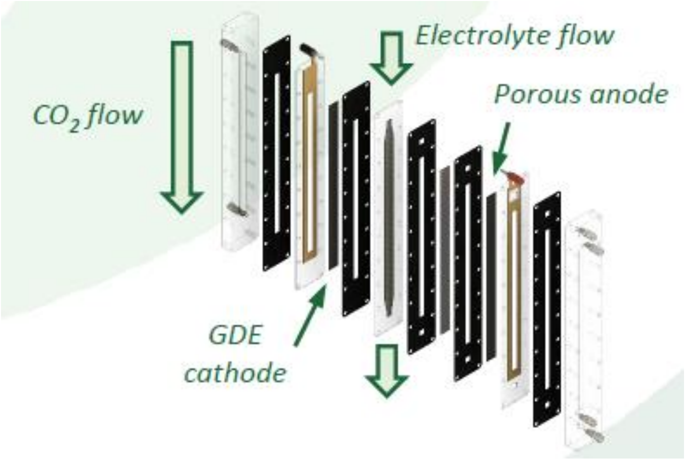
Utilisation: Electrochemical conversion

Electrolysers enable CO_2 valorisation under mild conditions by use of ‘*catalytic gas-diffusion electrodes*’ (GDEs), yet technological challenges persist that limit implementation: presently at TRL 2-3

Aims:

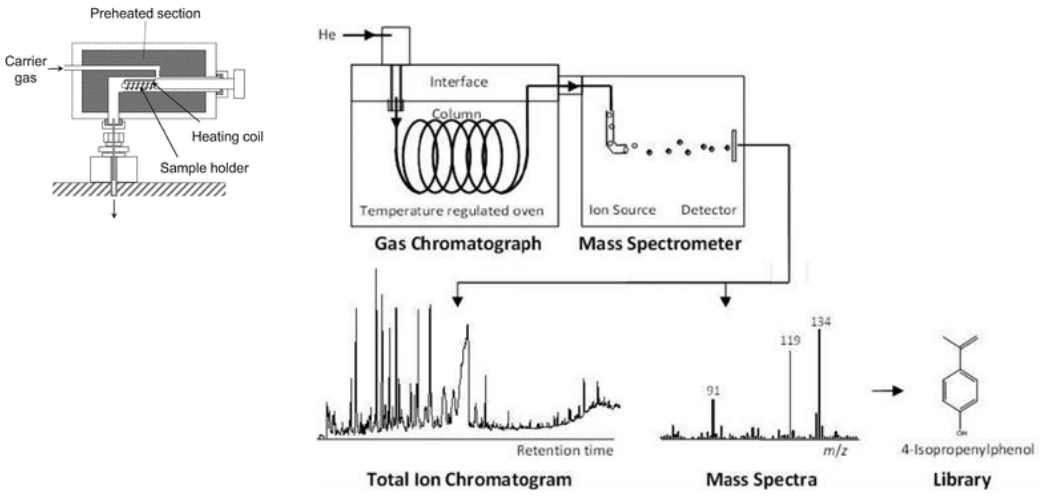
1. Improvement of catalyst selectivity toward ethylene
2. High CO_2 conversion rates of >300 mA cm^{-2}
3. Enhanced operational lifetime and stability of GDEs
4. Electrolyser technology scale-up





Theme 2: Zero Waste Steelmaking Substitutes for Coke

- Ultra-fast, 20,000°C/s pyrolysis to study volatiles released from different Non Fossil Fuel Carbon (FF-C) sources
- Additionally, an ultra-fast thermal imaging system has been developed and has been applied to different ironmaking scenarios and produced some interesting operando style data
- With project partners Tata Steel & British Steel, the team have studied volatile matter for decarbonisation
- Validating the emissions from alternative sources is essential for accreditation for fuel switching



Theme 2: Zero Waste Steelmaking Substitutes for Coke

eCoke is a biomass substitute
Trials with Tata Steel, British Steel and Liberty Steel

Subcoal is a waste paper/plastic substitute (currently used by Voest Alpine)

Recent work has shown that eCoke significantly reduces energy consumption as well as CO_2 footprint (Wang et al., Energy Conversion and Management 102 (2015) 217–226)

Theme 2: Zero Waste Steelmaking

Increased scrap use leads to increased levels of residual elements. Cu is a classic example, which can lead to “hot shortness”, i.e. cracking during hot rolling and poor product ductility

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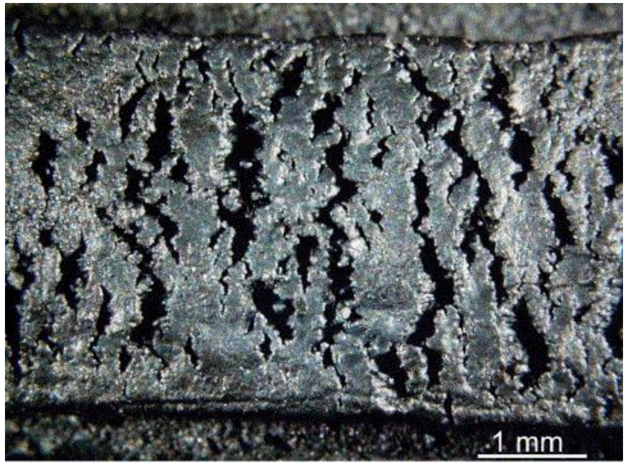
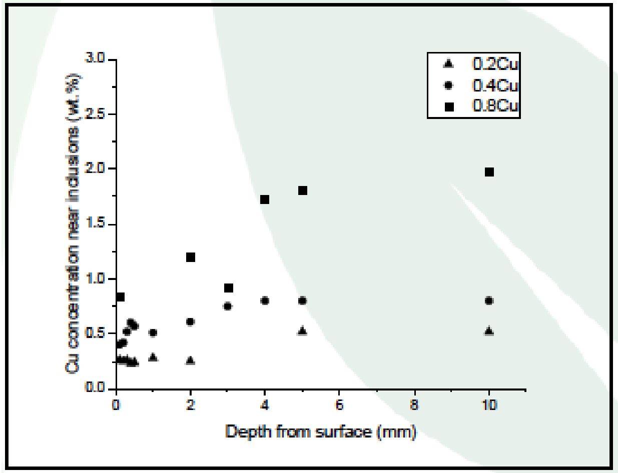
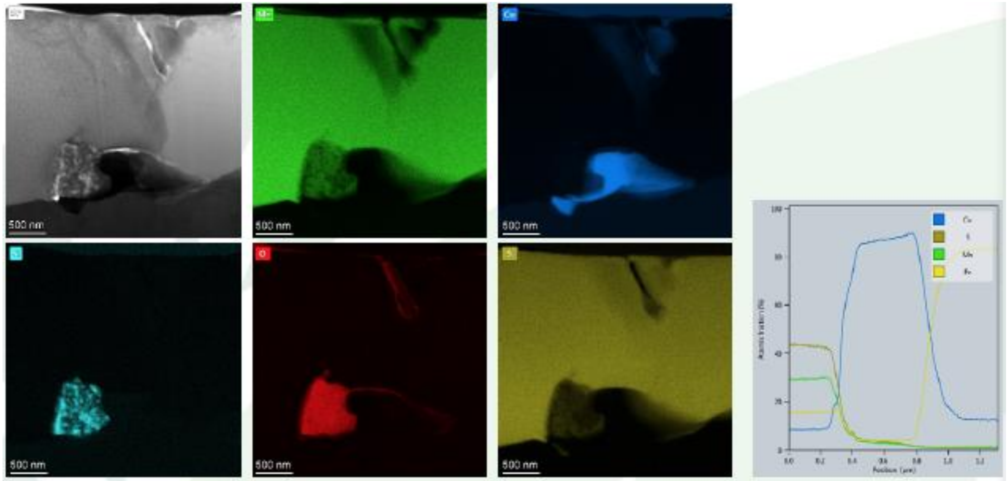


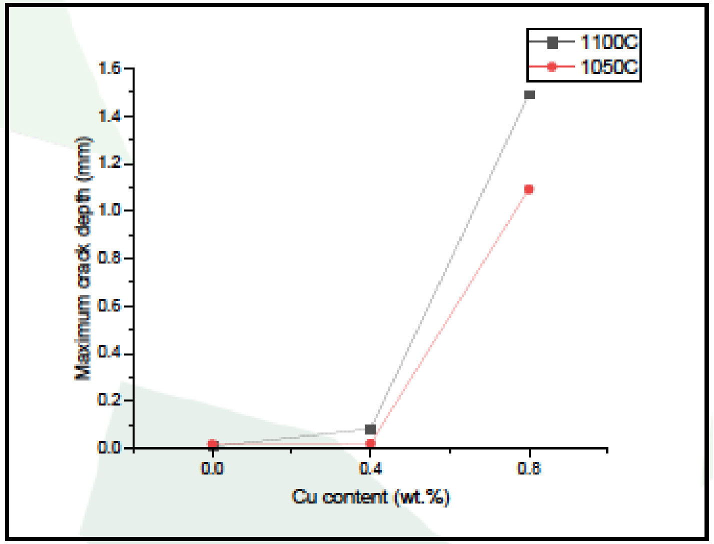


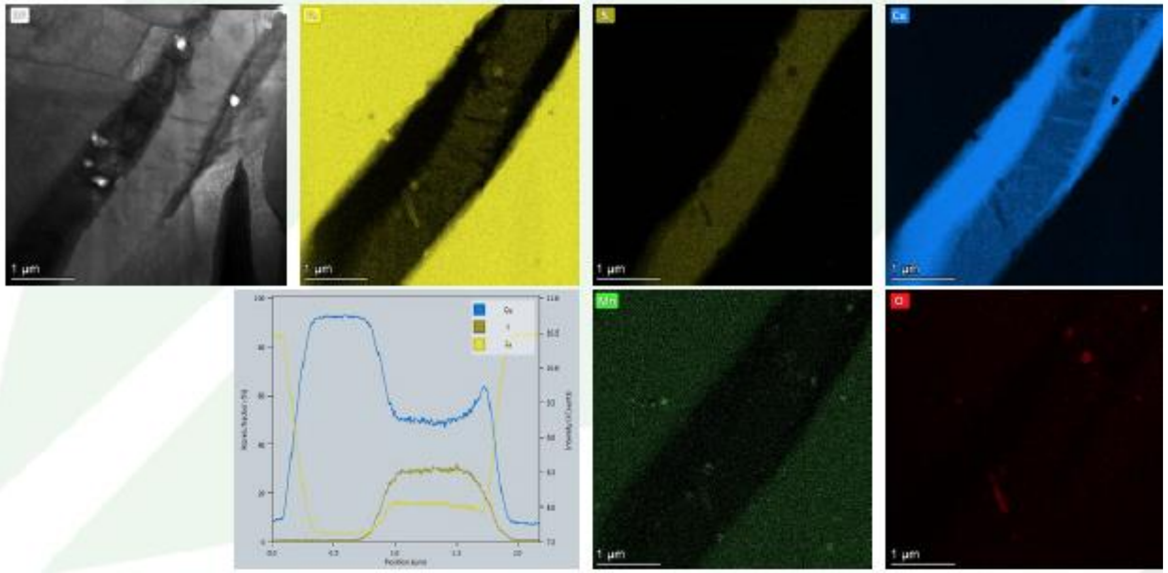


In a free cutting steel, the Cu segregated to the MnS inclusions. These increased with depth from the surface.

Theme 2: Zero Waste Steelmaking

There is remarkably little understanding of the role of residuals. There is particularly little understanding on the role a combination of residuals. Is there scope for alloy additions which reduce the negative effect of residuals?

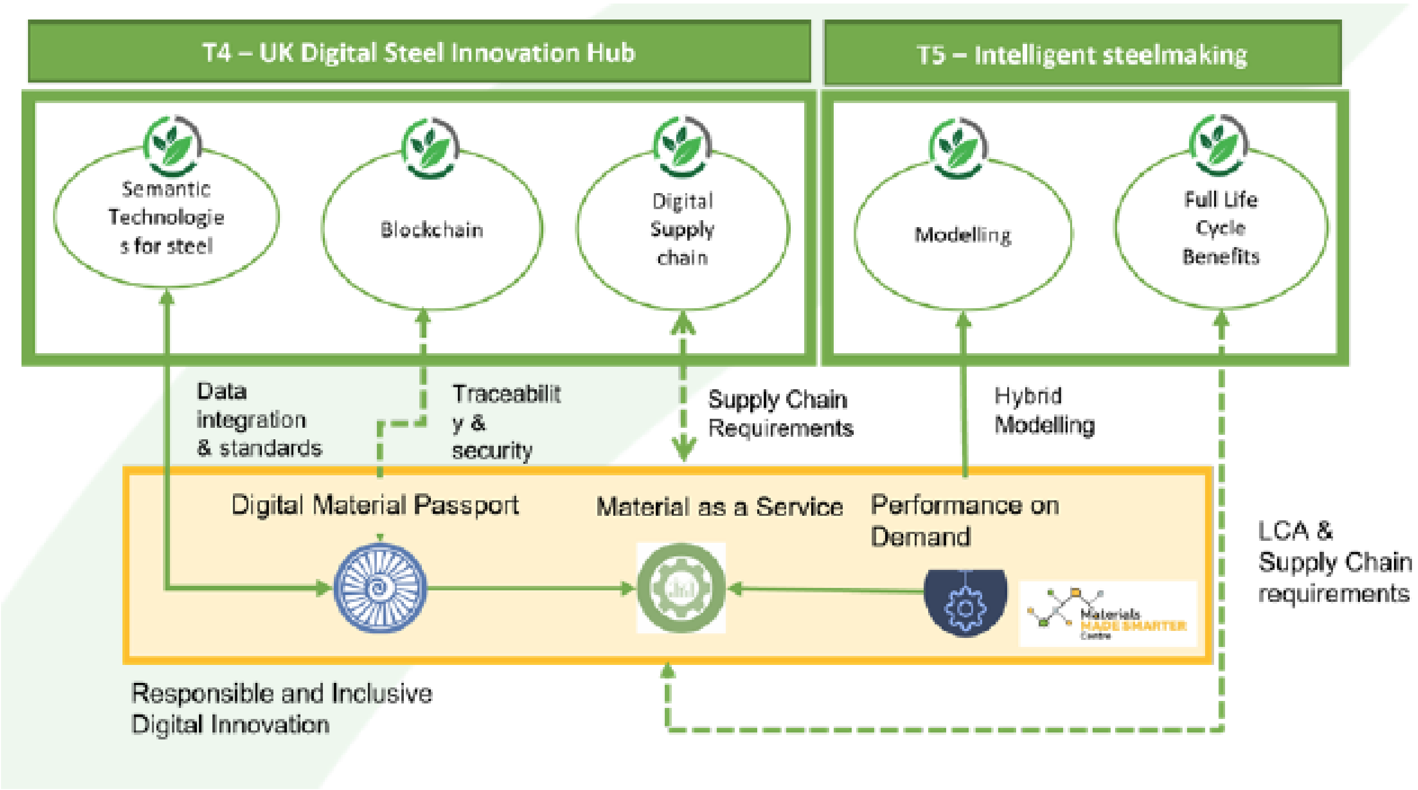




Cu segregated to cracks in a bend test. Cracking strongly depends on the Cu content

Theme 3: Data Driven Innovation

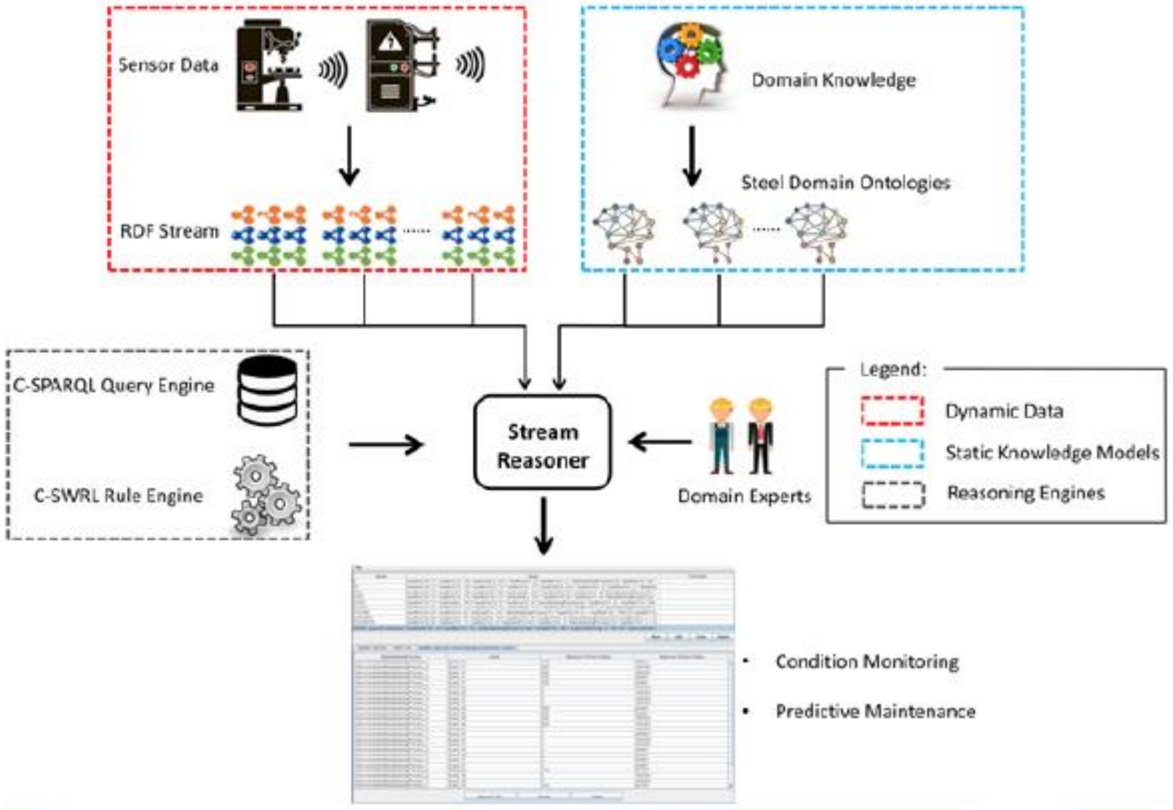
The Digital Steel Innovation Hub (DSIH) is a dynamic network that provides industrial partners with the opportunity to rapidly identify promising data-driven innovations and funding for further development.



Theme 3: Data Driven Innovation

The team's work on Semantic Technologies has developed a Common Reference Ontology for Steelmaking (CROS) and Conceptualization of Stream Reasoner to continuously query & reasoning on real-time data.

There is the potential for the ontology to be adopted as part of the specification for Digital Material Passport

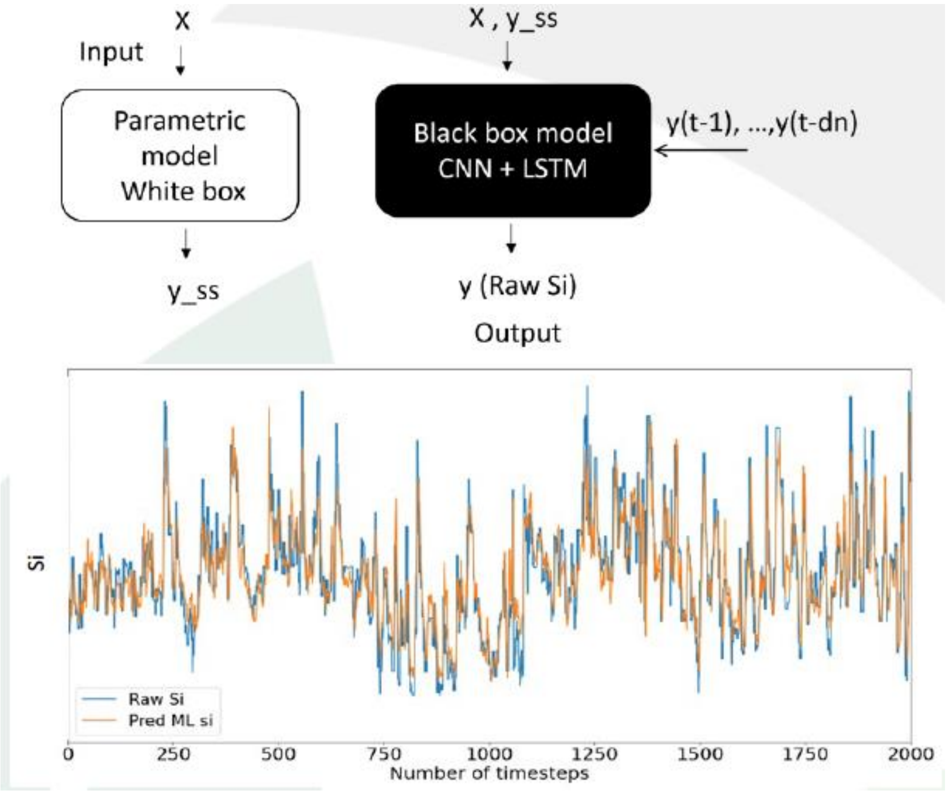


Theme 3: Data Driven Innovation

The team has developed a novel Hybrid Modelling of Blast Furnace for Silicon prediction, the model has been validated using historical data (one year).

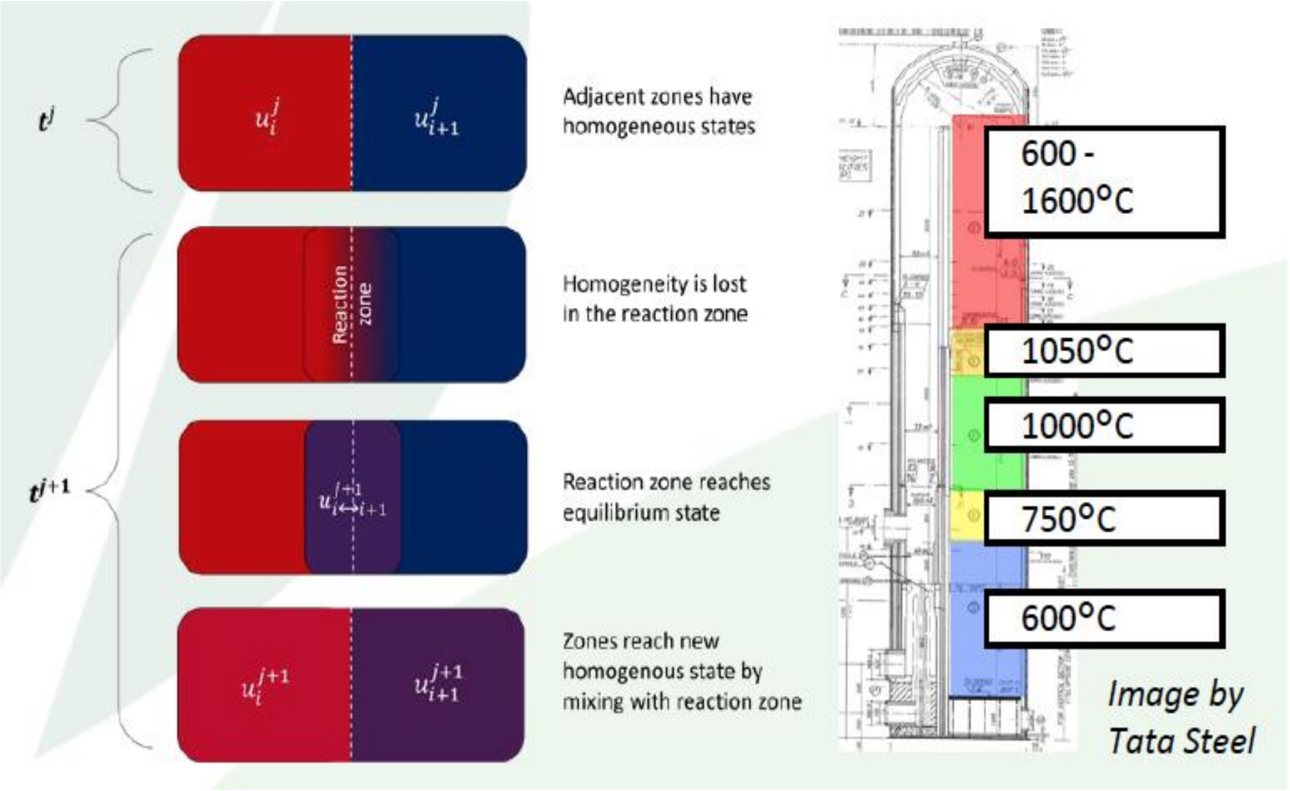
Estimation of the model error is shown to be at an acceptable industry standard.

There is the potential for further trial (currently in discussion with the industrial partner to establish a good timeframe for plant trial)



Theme 3: Data Driven Innovation

Process modelling approach has been developed which combines physics-based modelling with machine learning (LHS) and rough zonal example of a blast furnace stove (RHS). The model serves as a template for further processes in the ”digital refinery”

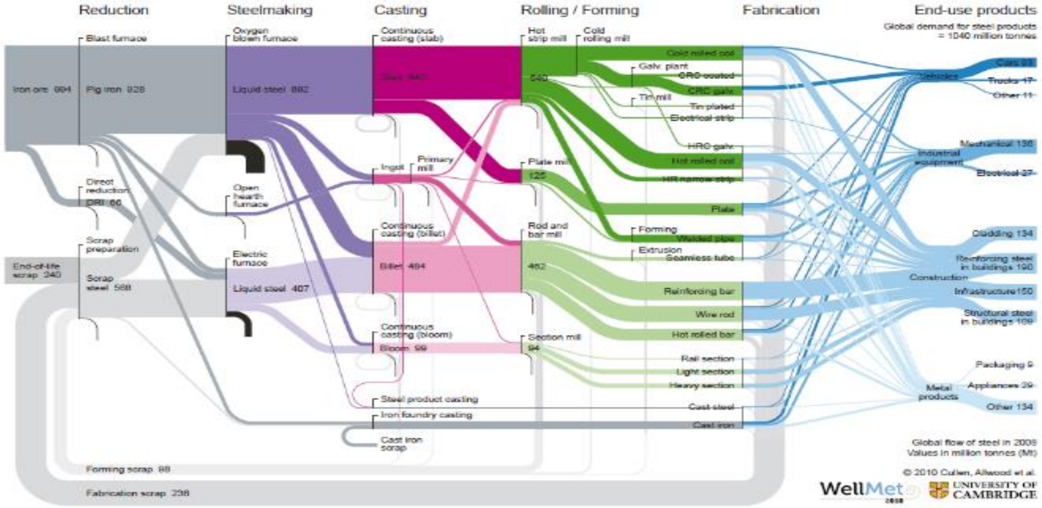


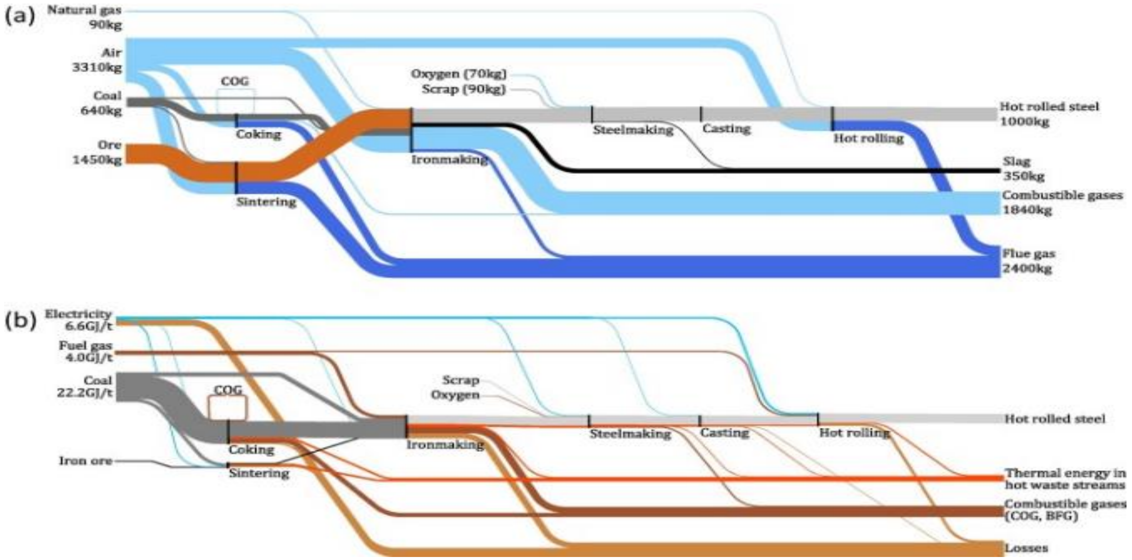
Theme 3: Data Driven Innovation

LCA

Preliminary work has shown that combining biomasses with existing materials such as coal and coke have the potential to improve energy efficiency and reduce gaseous emissions in ironmaking. However, there are concerns about the viability of the supply chain for these new materials, as well as the environmental impact of using these biomasses, and so work needs to be carried out to understand more about these factors

There are many ways to recover zinc from EAF dust, but some of these recovery mechanisms may have a more harmful environmental impact than using primary zinc, and there are few (if any) large scale UK based facilities available. Various recovery mechanisms have shown promise at small scale, but there remain issues with the viability of scaling up to meet demand.





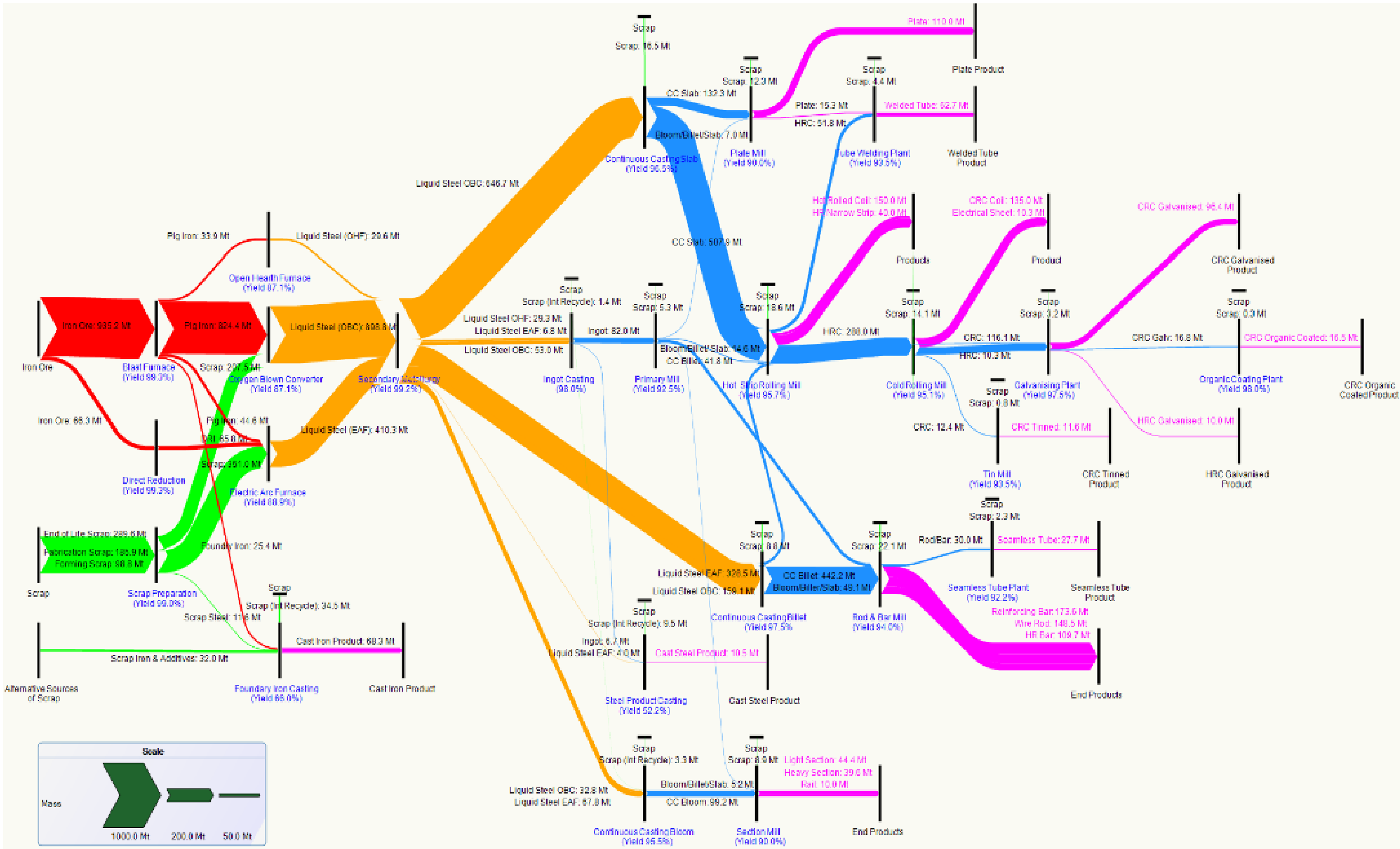
Theme 3: Data Driven Innovation

The current volatility of key raw material prices means that there is a need to

(i) identify mechanisms for the recovery of expensive alloying elements such as manganese and copper from BOS slag and

(ii) increase the recyclability of some of the various refractory materials used in steelmaking

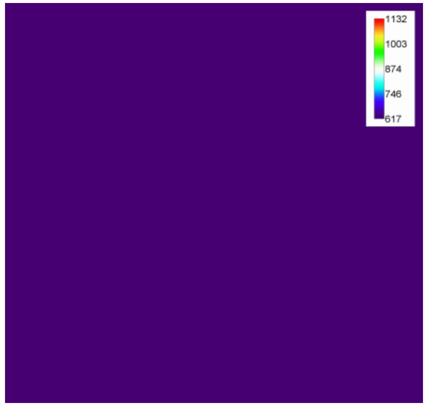
(iii) understand more about the environmental impact of using ferroalloys in steelmaking.



Theme 4: Smart Low Energy Production

Demand

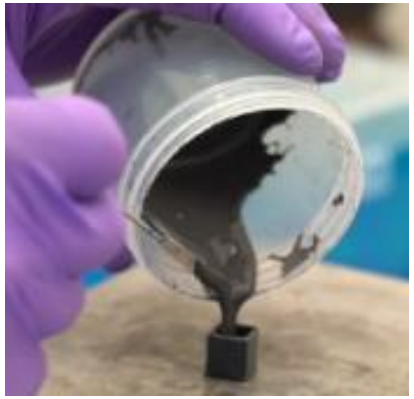
Insulation (Refractories)
1538ºC > Steelmaking



Heating
$\gamma > \alpha$ (A3) > (Re)Heating (Radiant)

Utilisation

Thermoelectric (Surfaces)
Net-shaped & integrated



Thermochemical (Gases)
Inter-seasonal & mobile

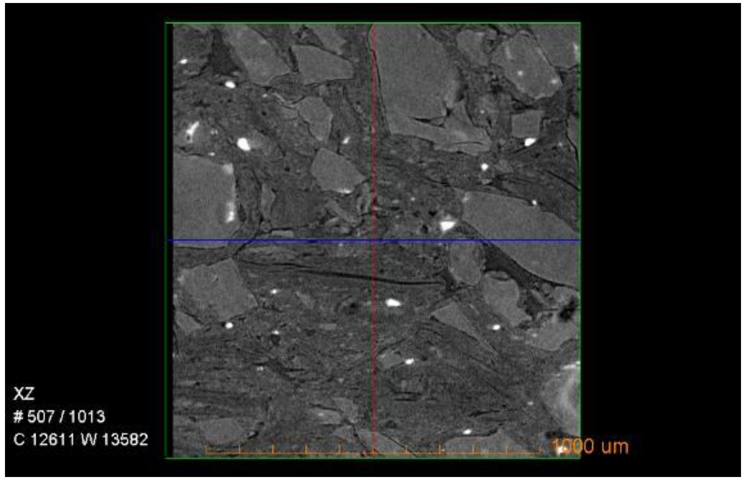
Aims and objectives

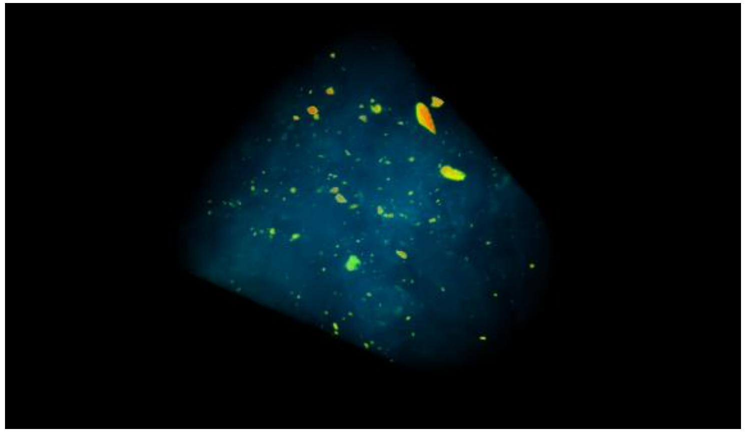
- Develop as multiscale ex-situ structural characterisation approach for refractories.
- Improve understanding of structure-property relations in carbon bonded refractories.
- Develop robust, cost effective Sn-Se thermoelectric materials / devices for integration into refractory linings.
- Build UK academic skill base in the field of refractories.
- Improve steel re-heating efficiency.
- Develop robust, energy efficient thermochemical heat storage materials suitable for steel production processes.

Theme 4: Smart Low Energy Production

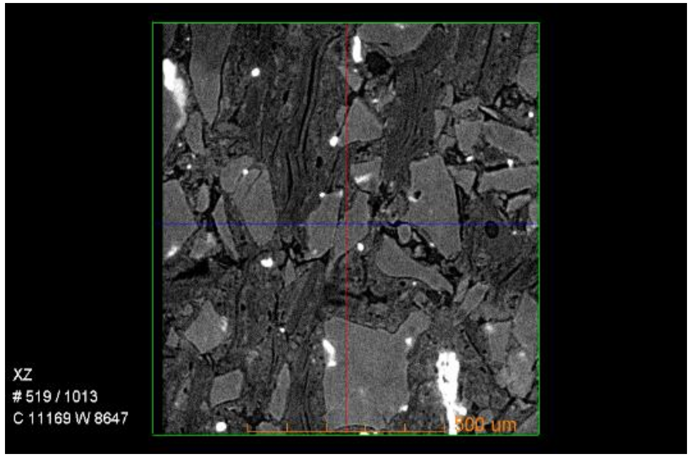
- Refractories contain high carbon contents to prevent thermal stress and reduce corrosion
- New refractory material being developed with Vesuvius
- Focus upon recycling of refractory materials and on-line diagnostics
- Potential to deliver multi-£m savings for individual steelmaking facilities

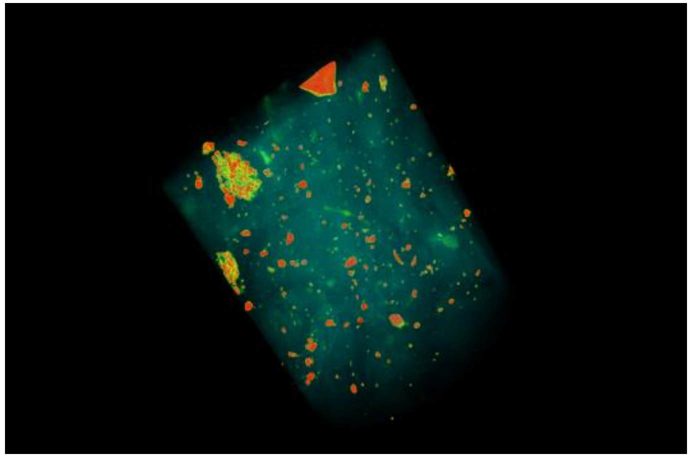
Control





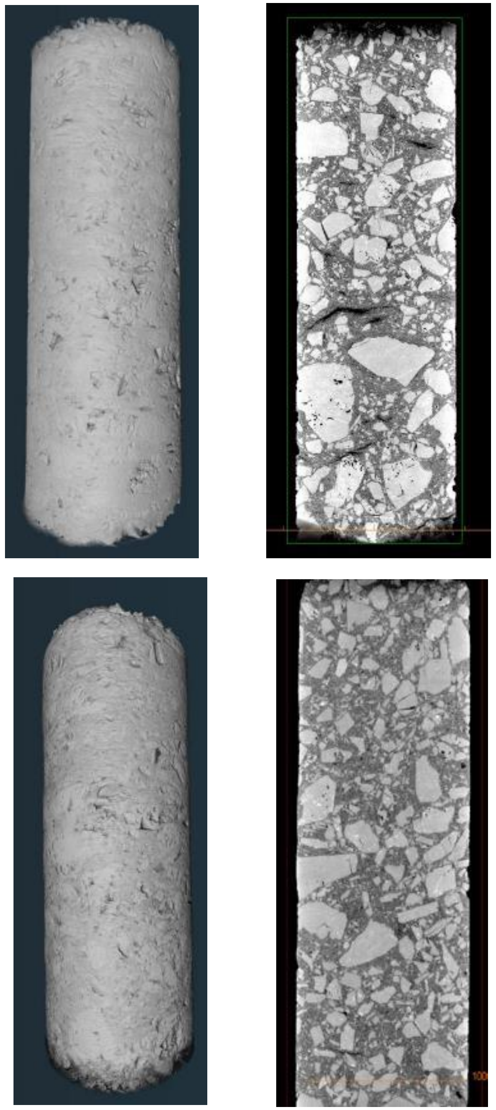
Oxidised

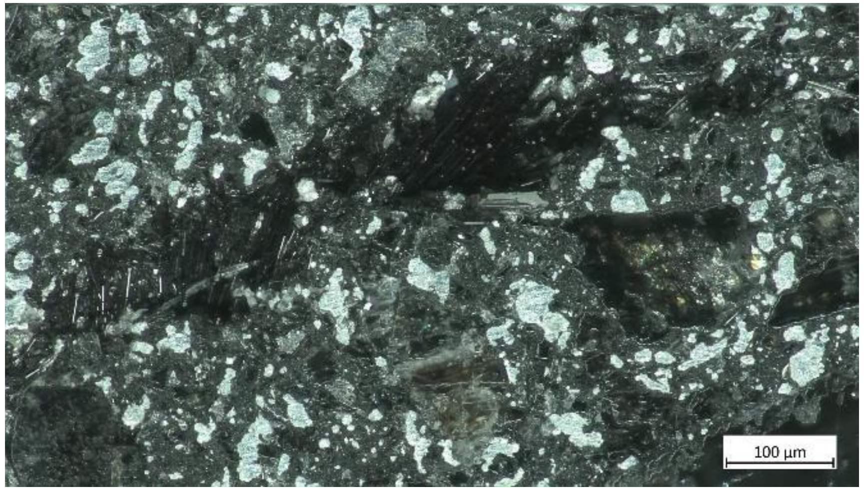


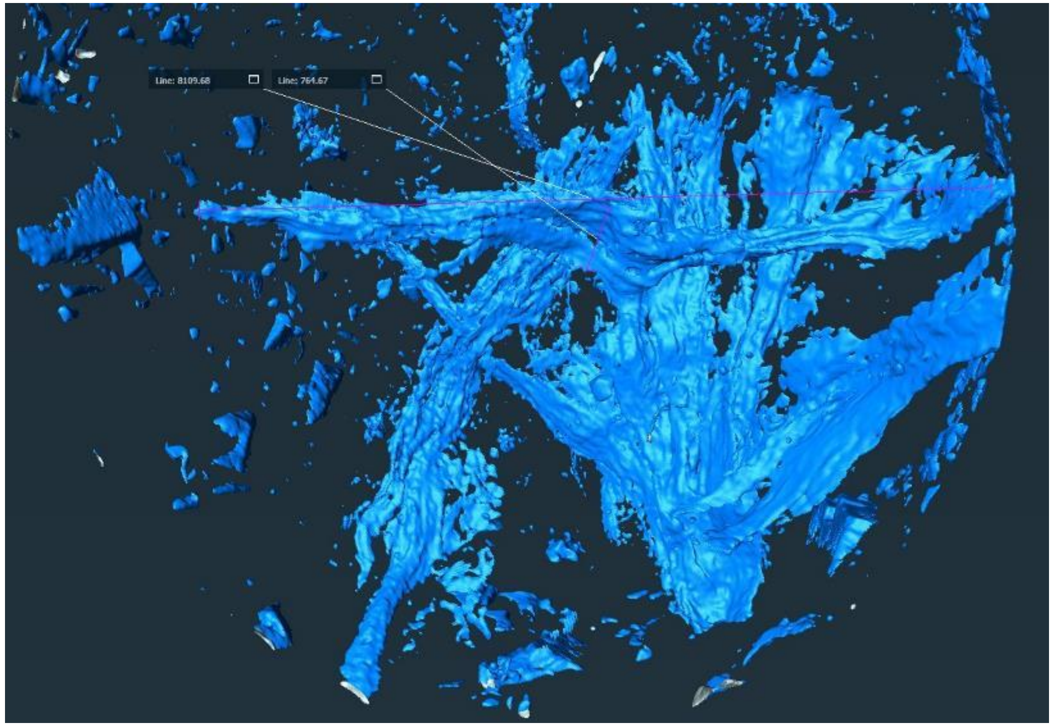


Theme 4: Smart Low Energy Production

Next generation refractories





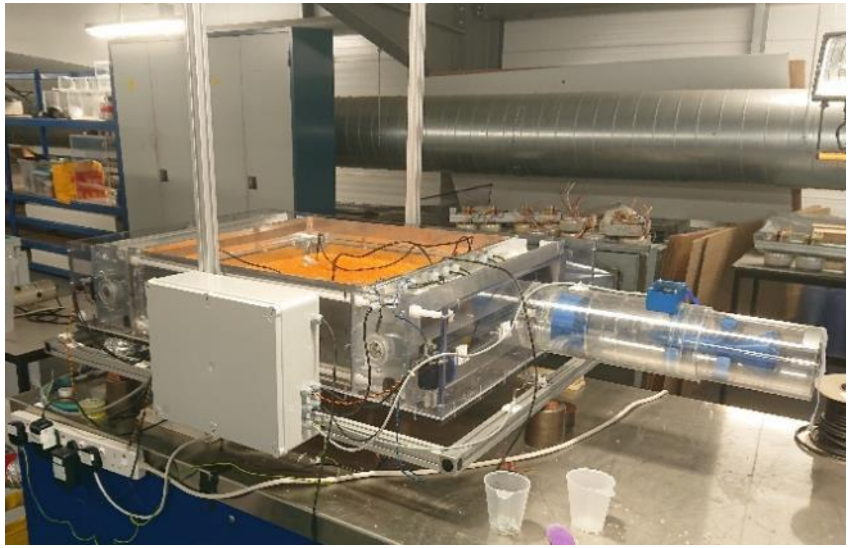


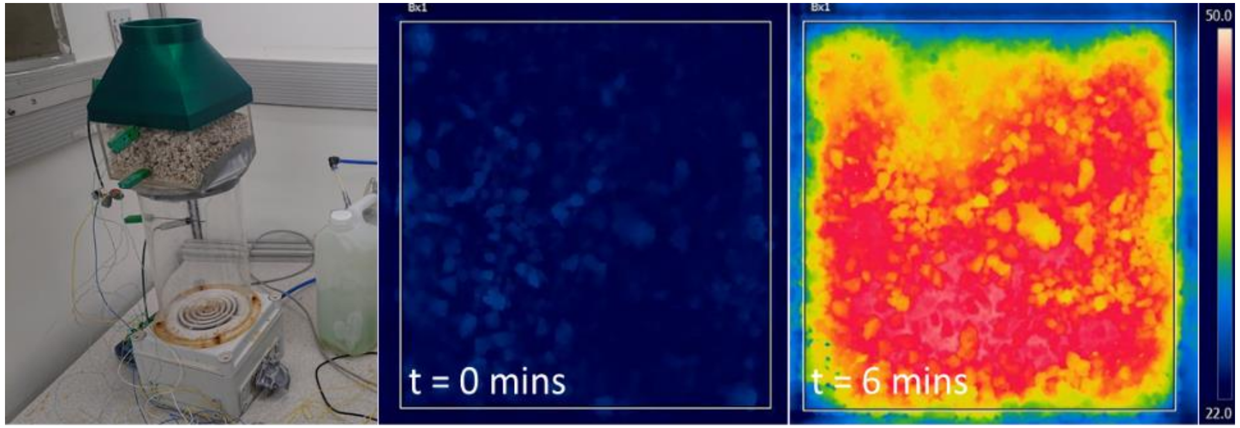
X-ray µ-CT 3D volume analysis, investigating effects of mixing processes on fibre distribution in refractory materials from Vesuvius, a) standard; b) intensive.

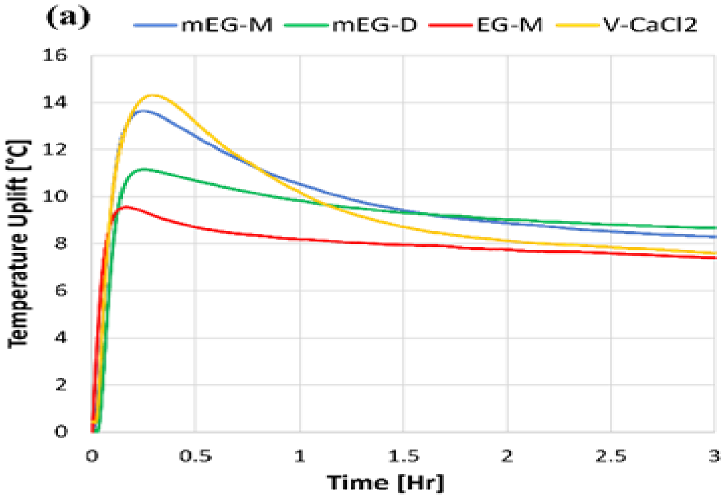
Even the most complex 3D microstructures can be fully quantified

Theme 4: Smart Low Energy Production
MESH – Thermochemical Heat Storage

- Develop materials to harvest waste heat energy within selected temp ranges
- Optimise heat capture and reutilisation with lab scale reactors
- Model system energy flows from industry to determine efficiency, capacity and impact, both ecologically and economically.







IDRIC The Industrial Decarbonisation Research and Innovation Centre.

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FLEXIS
SMART ENERGY FOR OUR FUTURE
YNNI CALL AR GYFER EI'N DYFODOL

Theme 4: Smart Low Energy Production

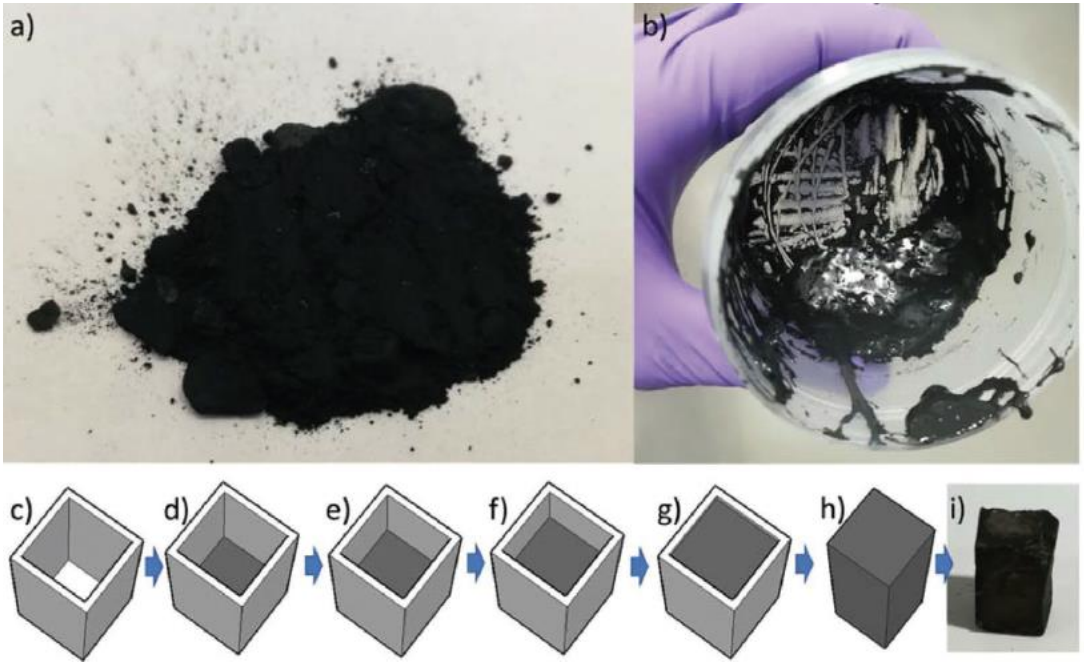
Thermal energy (heat) is stored by passing hot air over the Active Material, creating a chemical reaction that locks the energy into the material. The reverse reaction is exothermical, meaning that heat is released, and is instigated by passing humid air over the material. This is being developed for industrial gas waste streams. Port Talbot steel energy flow review targeted ranges of 50-200°C and 600-800°C.

Theme 4: Smart Low Energy Production Targeted Thermo-electrics

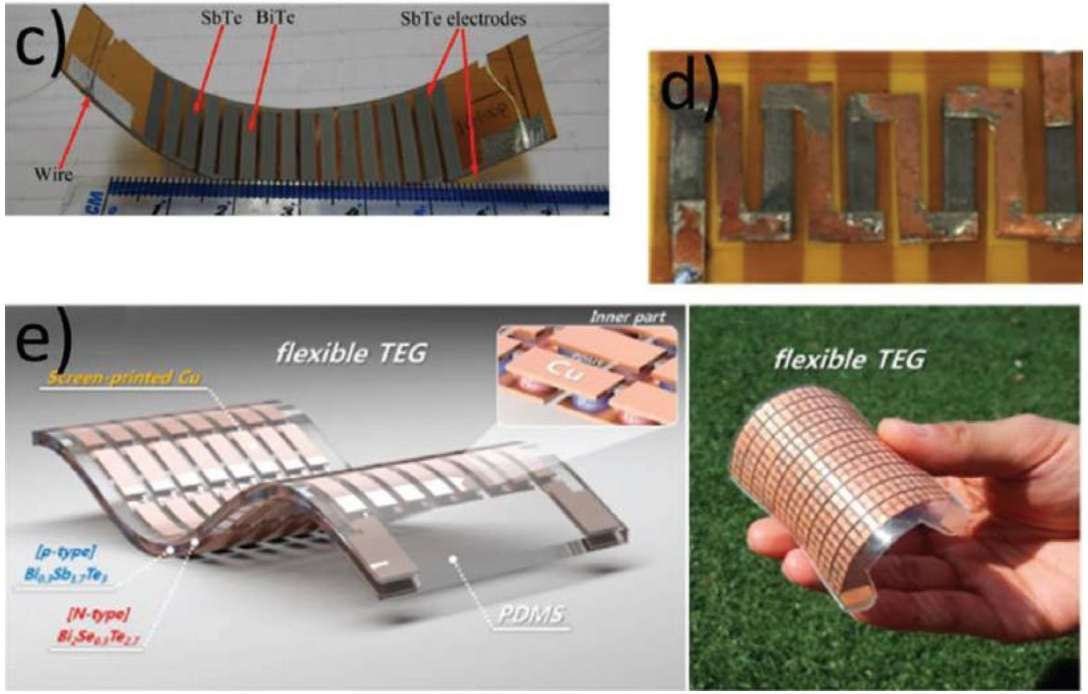
Thermo-Electric Generators (TEGs)

- Develop affordable printed / castable earth abundant TEGs
- Integrate these devices for integration into refractory linings

- Novel net-shape printing method designed & proven on N&P-type Sn-Se materials (Fig.7.).
- High temperature stable cementitious binders created with minimal efficiency penalties.
- ECR (Burton) has progressed to consider earth abundant P&N type Half Heusler economically scalable material options.



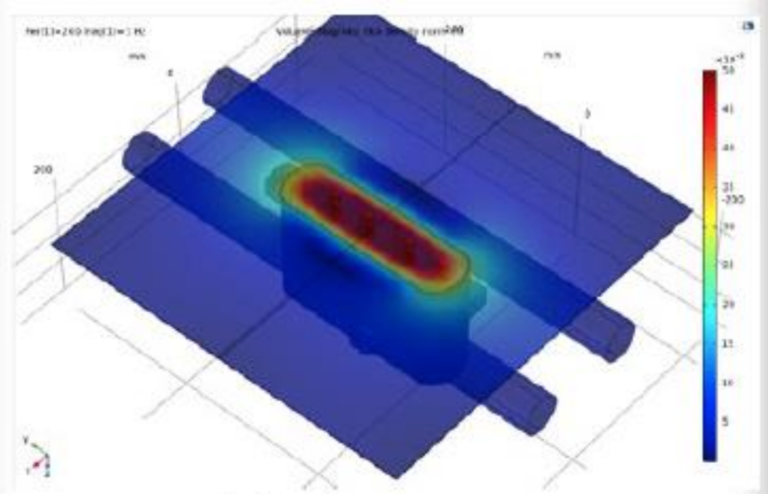
Novel casting method for thermoelectric legs (SnSe pictured)



Burton et al. Adv. Mater. 2022, 34, 2108183

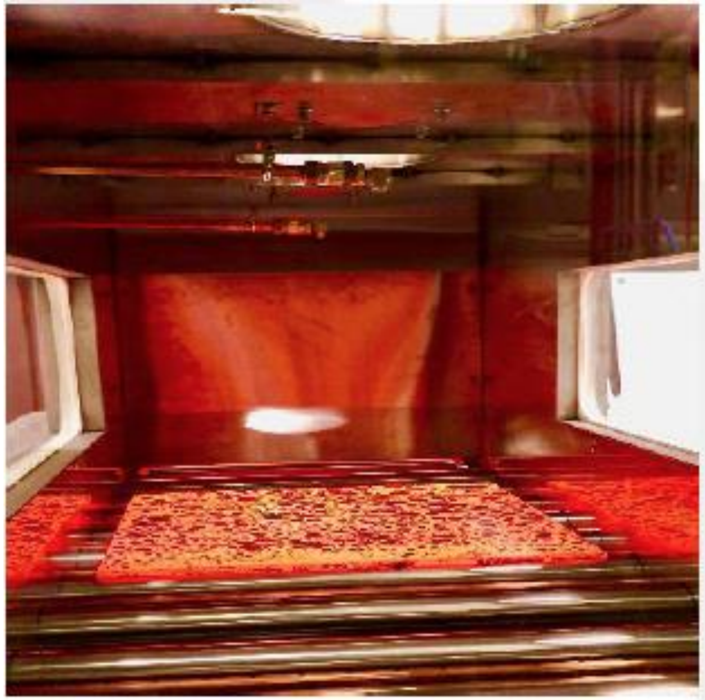
Theme 5: New Processes for New Products
Sensors

Design, build and install an EM sensor array into a furnace-run-out table, and carry out modelling and experimental studies to link sensor signal to magnetic properties and microstructures for specific complex geometry steel products (such as wire/rod and narrow strip). To develop an improved fundamental understanding of the link between magnetic signals and microstructure as a function of temperature



FE model of sensor array

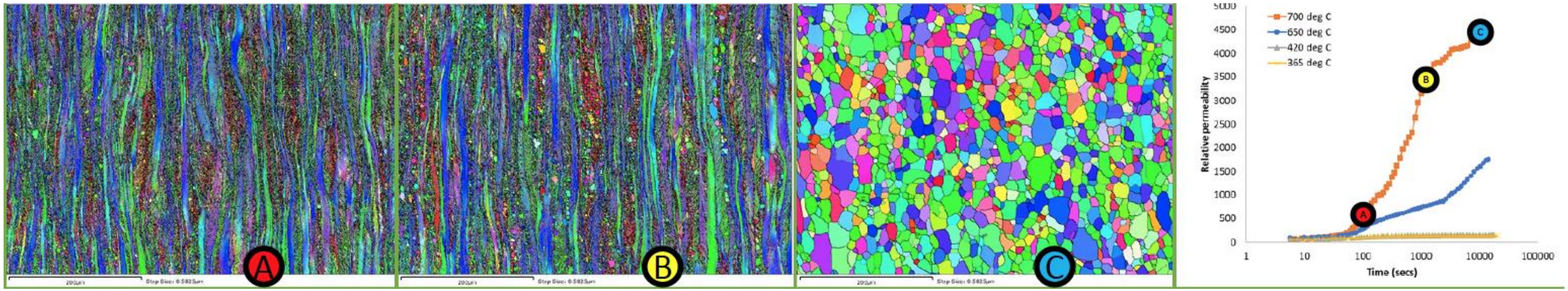
FE model has been validated against samples of known magnetic properties



Hot steel passing above sensor

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

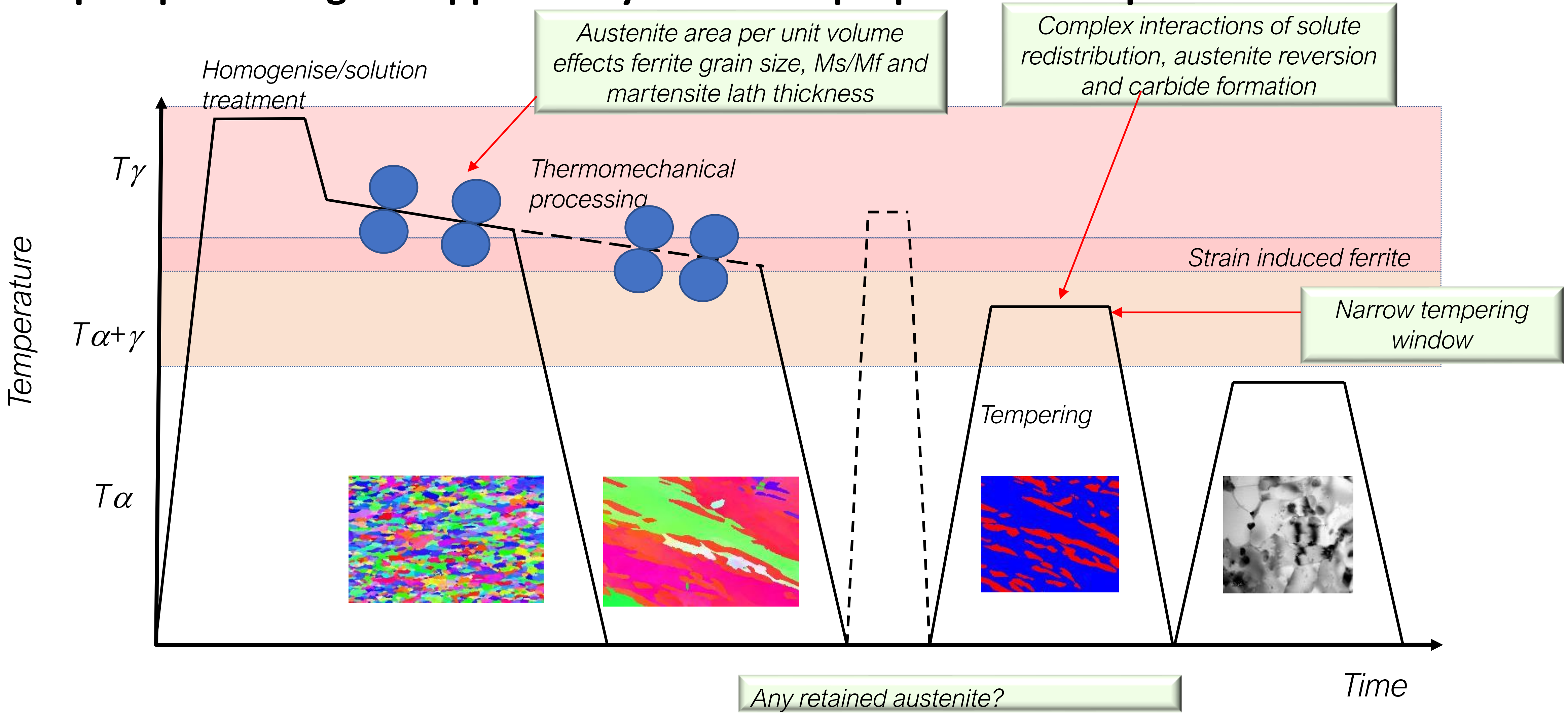
Theme 5: New Processes for New Products
Sensors



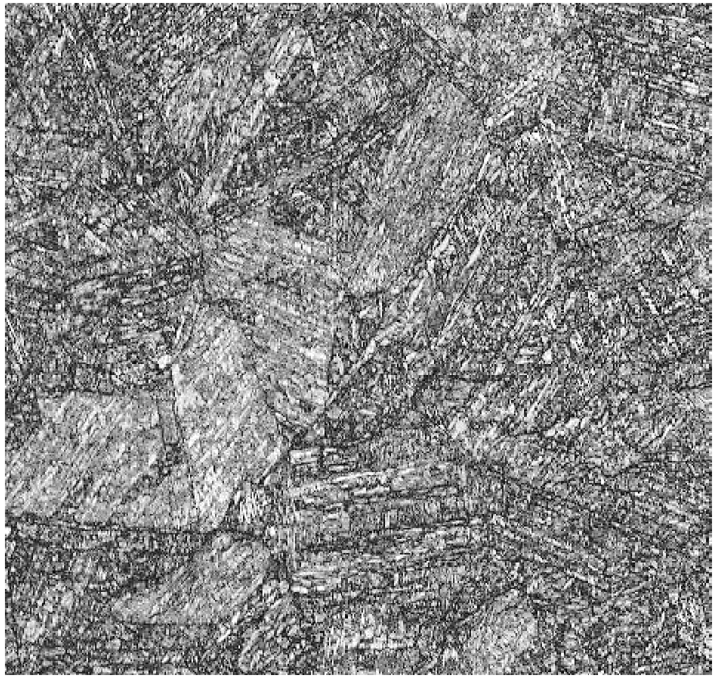
A: EBSD of deformed steel after 3mins 700ºC, limited recovery, initiation of recrystallisation, B: As A after 30mins, with some recrystallisation, C: Full recrystallisation after 210mins.
EM sensor signal monitoring these changes, showing progress of recrystallisation and how much slower the process is at 650ºC compared to 700ºC.

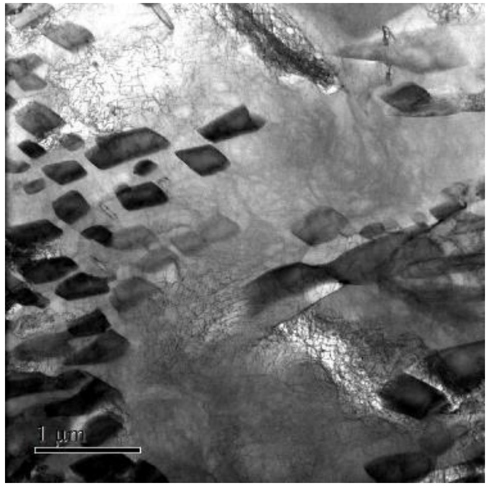
Theme 5: New Processes for New Products
Late Stage Differentiation

Complex processing- an opportunity to control properties as required

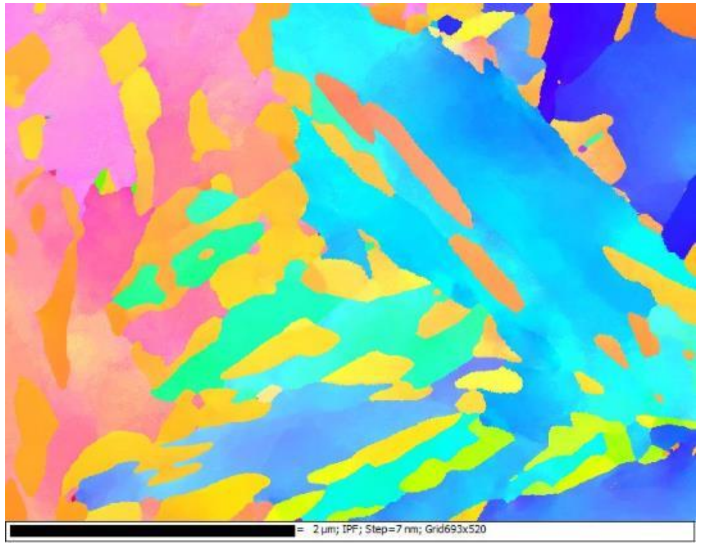


Theme 5: New Processes for New Products
Late-Stage Differentiation

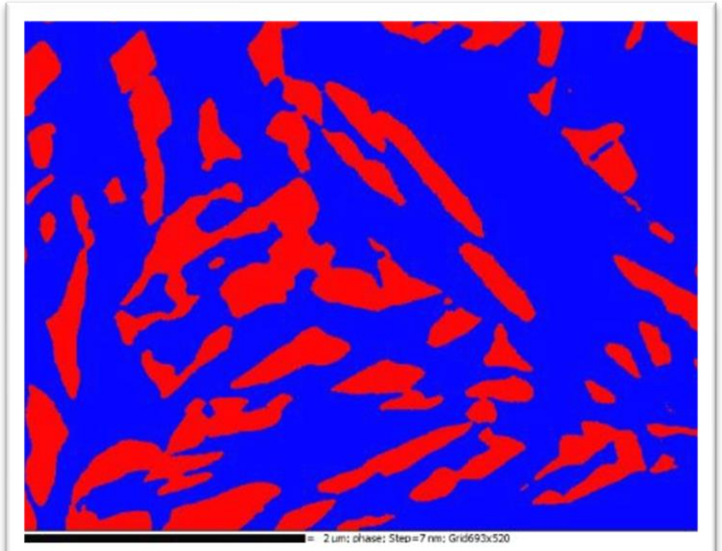




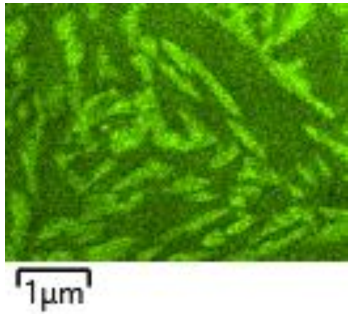
Crystal orientation



Phase distribution (red is austenite, blue is ferrite)

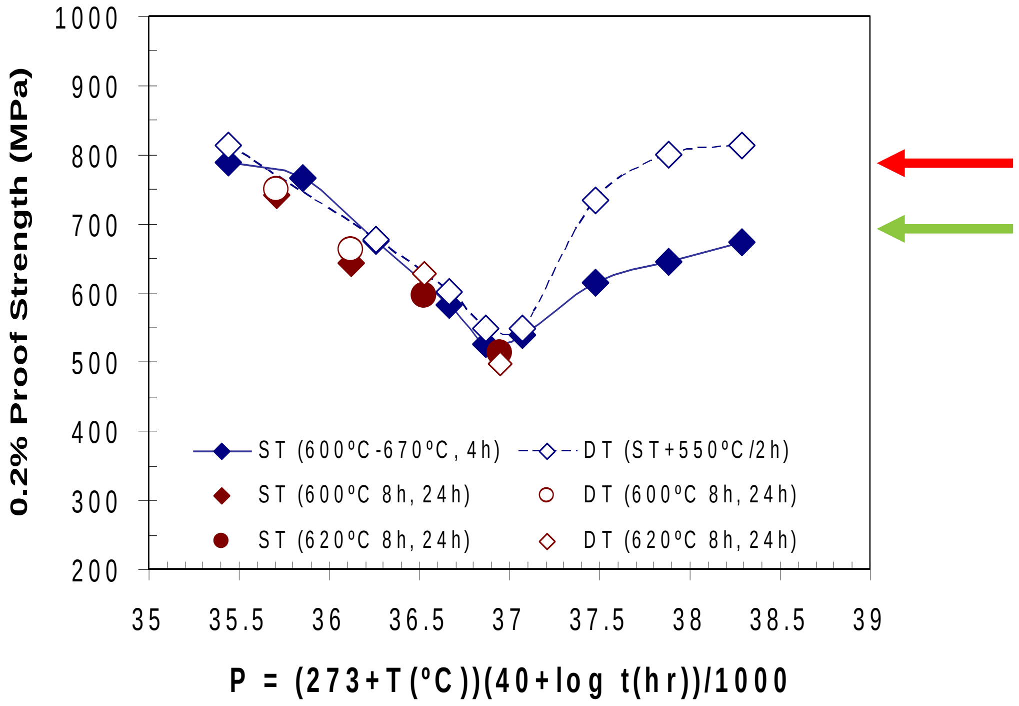


Ni



Super 13Cr steel. Complex mixture of martensite, reverted austenite and carbide

Theme 5: New Processes for New Products

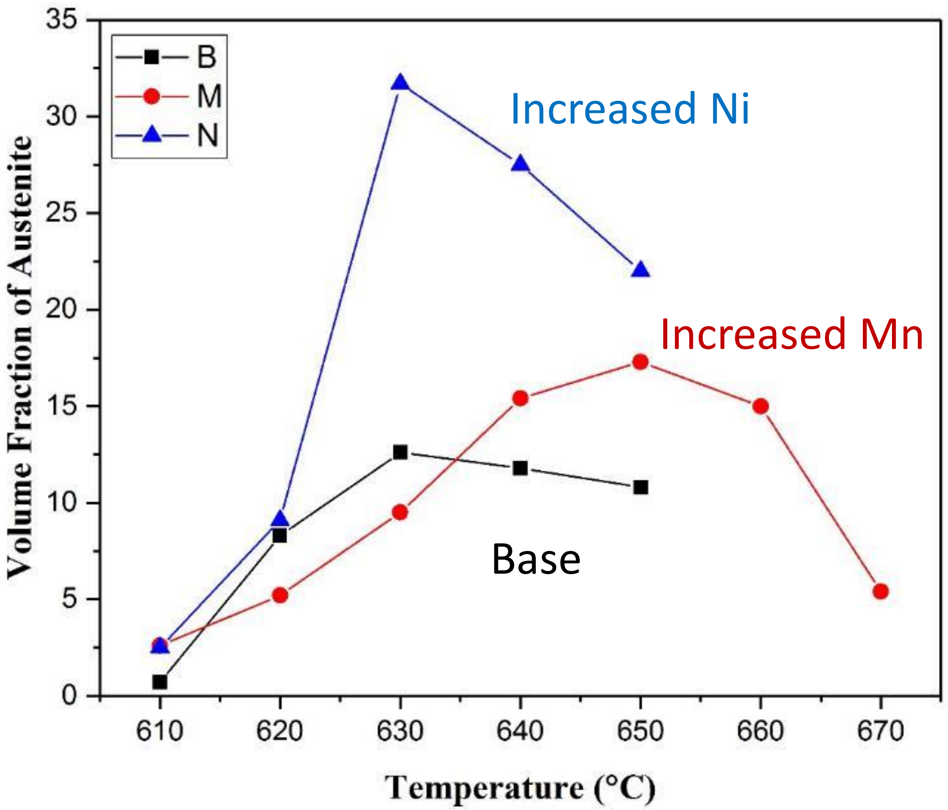


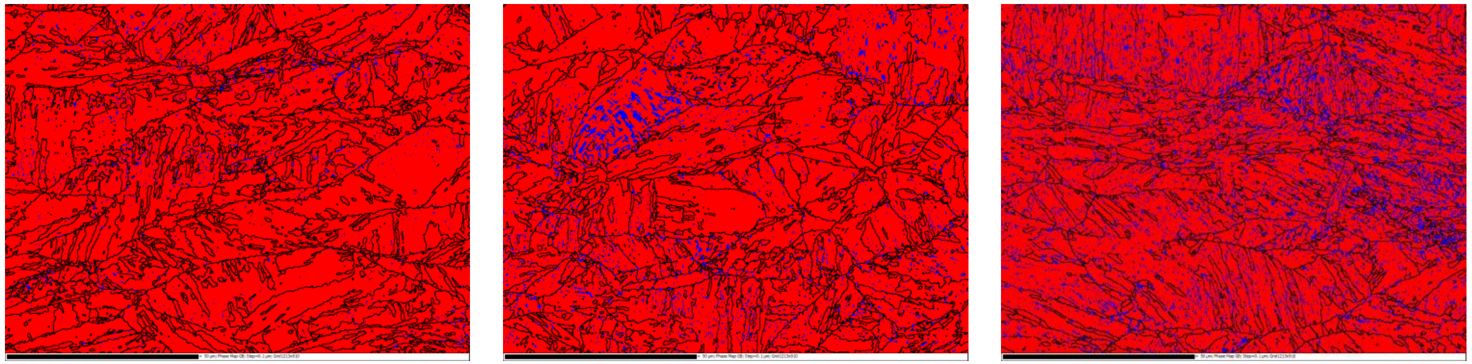
Time/temperature input

Sample	% austenite	Proof strength (MPa)
C	16	786
E	28	670

Small changes in process conditions leads to substantial changes in mechanical properties

Theme 5: New Processes for New Products

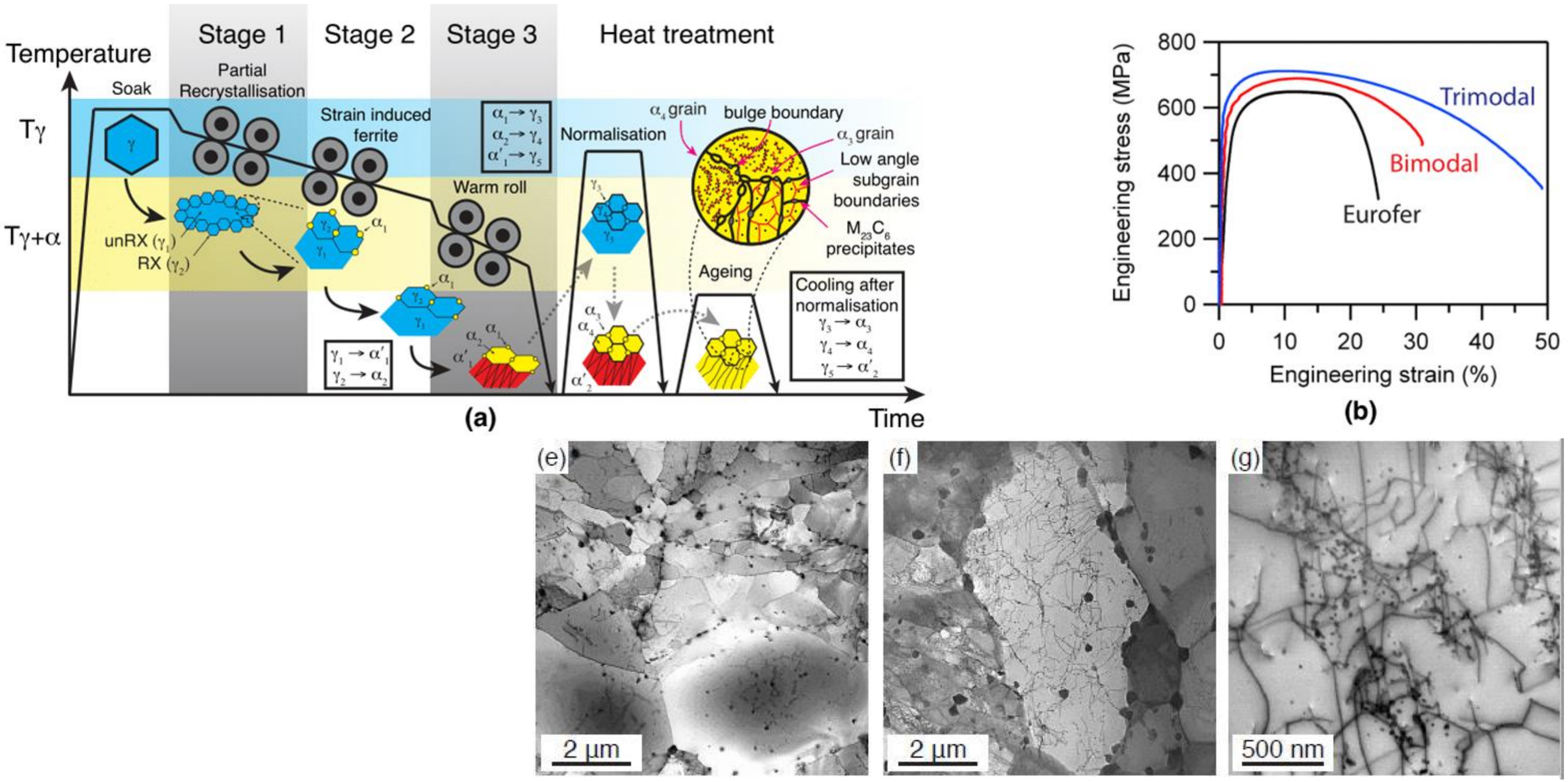




Small changes in composition (Ni and Mn) allow major improvements in composition

Theme 5: New Processes for New Products

New RAFM Steel



The new understanding allowed the design of a new thermomechanical process route for an existing reduced activation ferrite/martensite (RAFM) steel which has greatly improved mechanical properties

SUSTAIN Phase 2