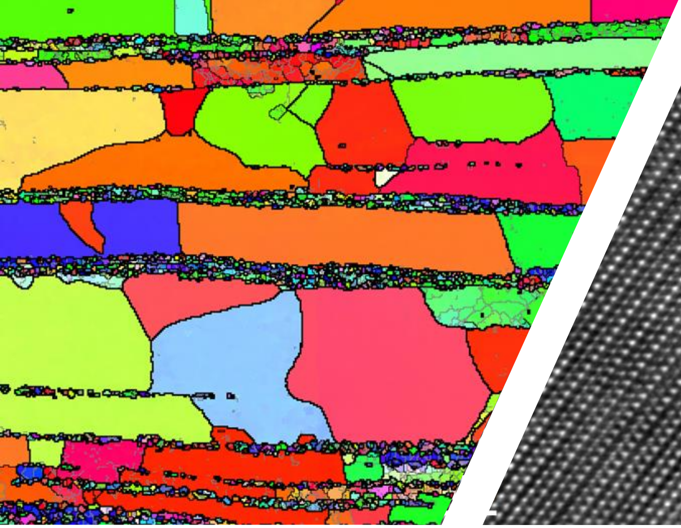
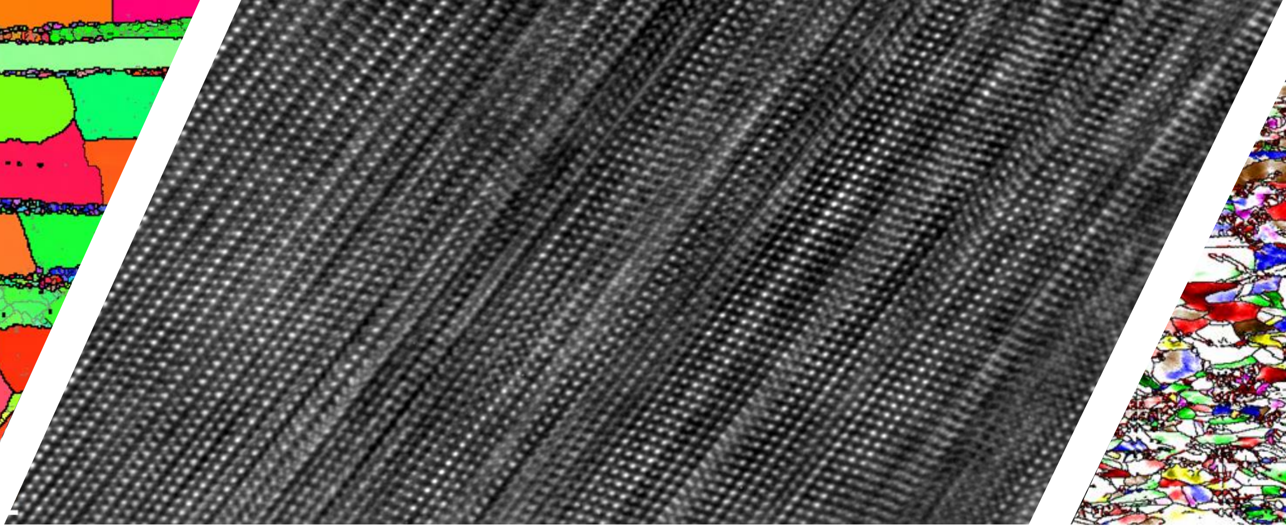
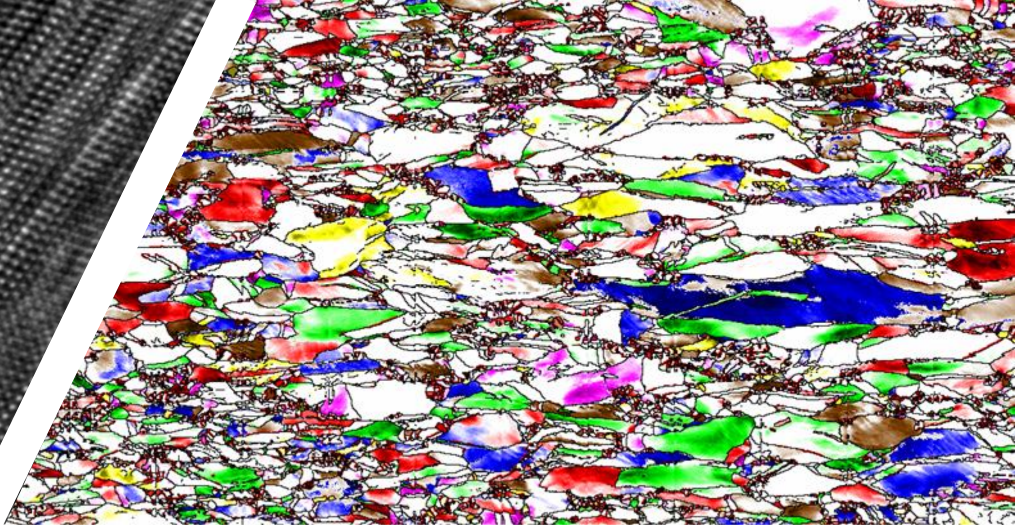
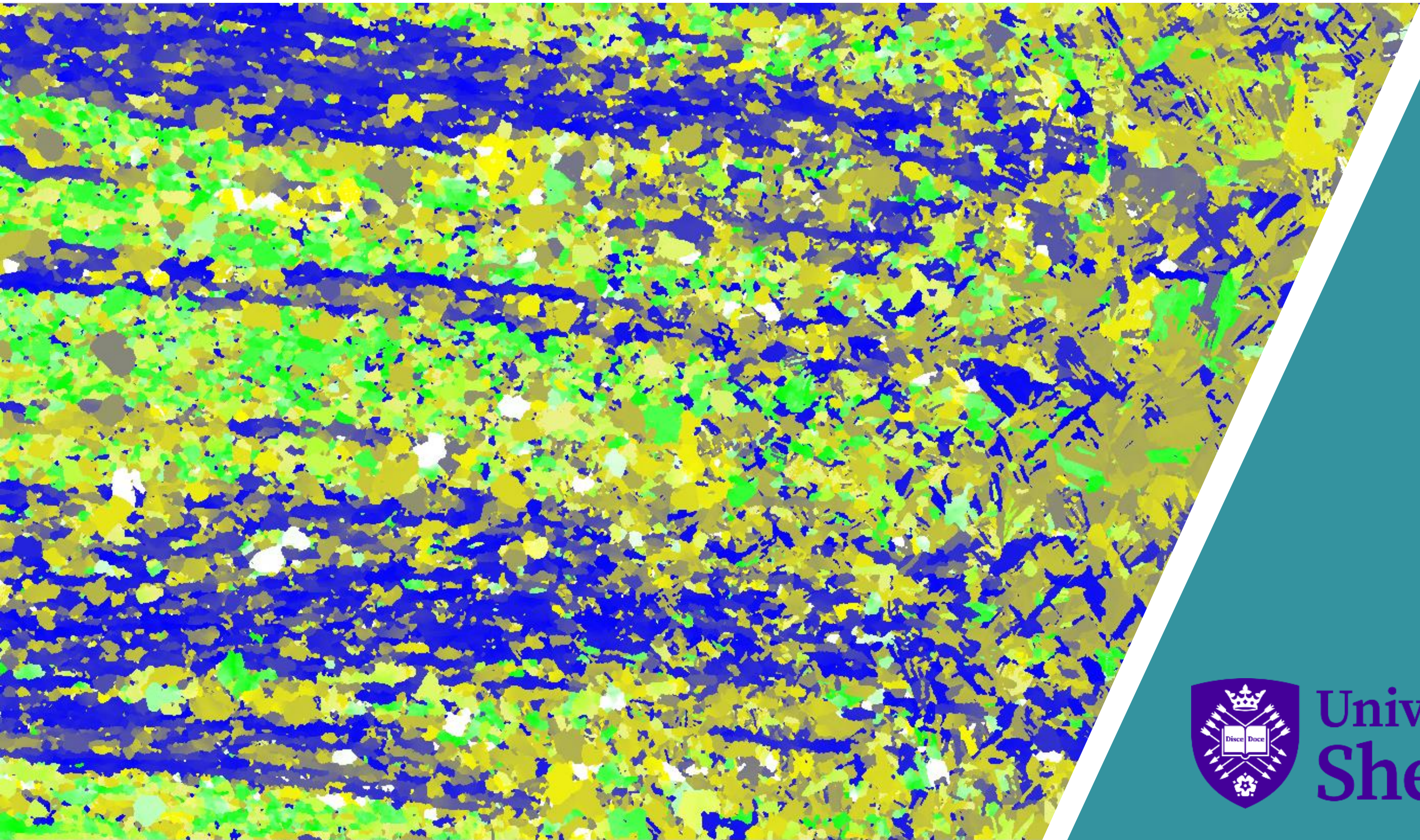





Designing steels for a sustainable low carbon future

Mark Rainforth

University of Sheffield

Acknowledgements- Thanks to these brilliant people who did all the work

- Junheng Gao
- Peng Gong
- John Nutter
- Jiawei Qi
- Karol Rodriguez-Galeano
- Chenghao Yang
- Alfonce Chamisa
- John Hinton
- Yun Wei
- Mike Frolish
- Shengqi Xu
- Jiawei Xi
- Jiawei Xi
- Arnoldo Bedolla
- Jorge Zuno
- Ivo Katzarov
- Andre Turk

University of Sheffield

Acknowledgements- Thanks to these academic and industrial collaborators

- Tony Paxton
- Dave Dye
- Pedro Rivera
- Claire Davis
- Eric Palmiere
- Dave Hanlon
- Arjan Rijkenberg

EPSRC Engineering and Physical Sciences Research Council

BRITISH STEEL

TATA STEEL

LIBERTY STEEL

Rolls-Royce

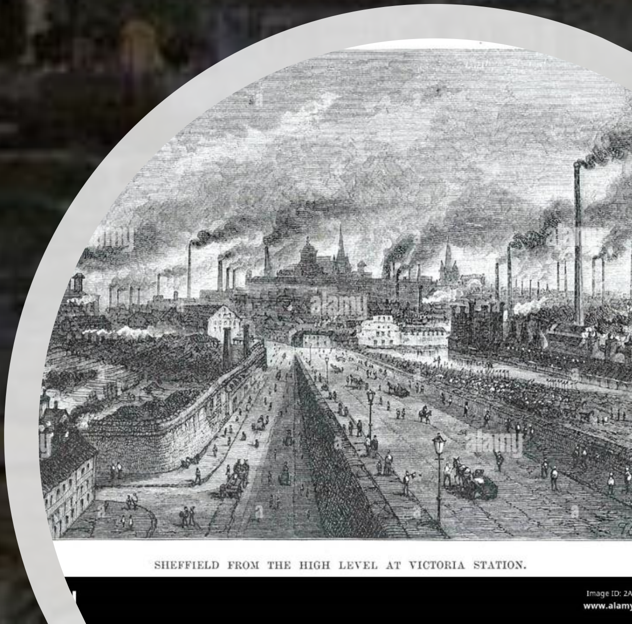
SHEFFIELD FORGEMASTERS

SKF

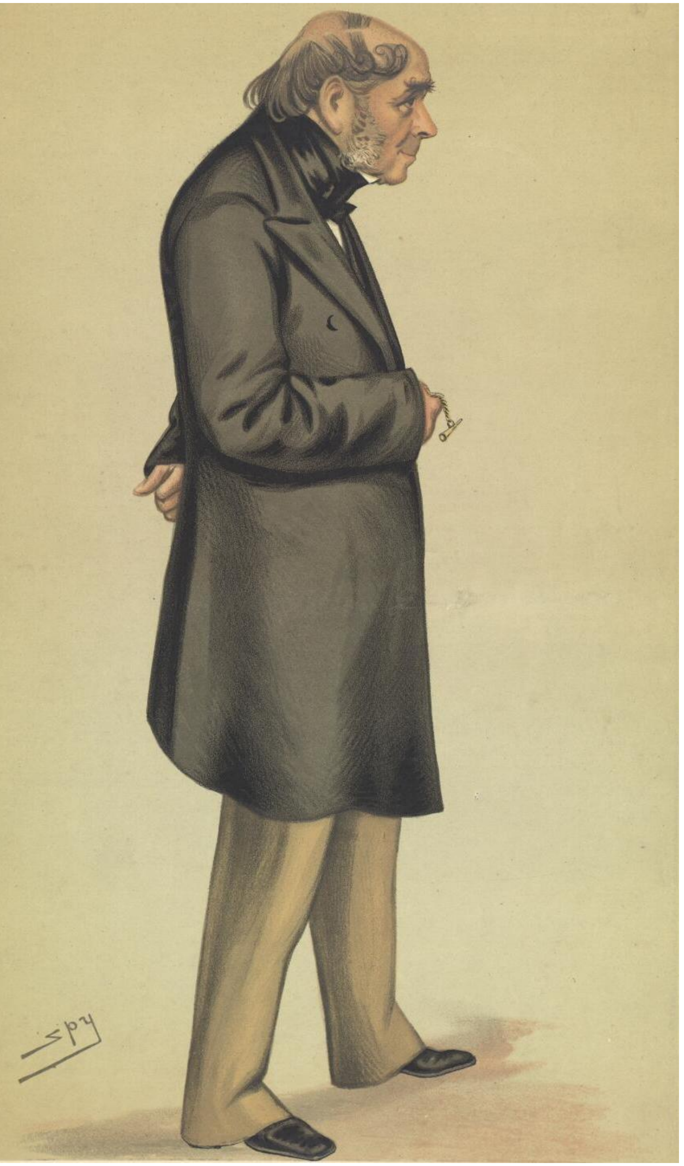
UK Atomic Energy Authority

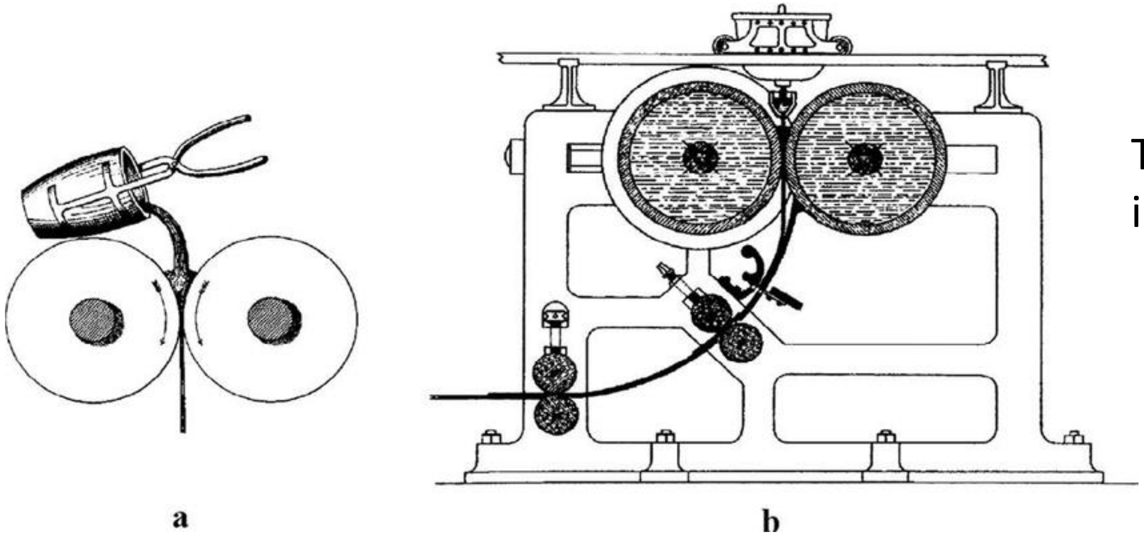
University of Sheffield

Sir Henry Bessemer's Sheffield



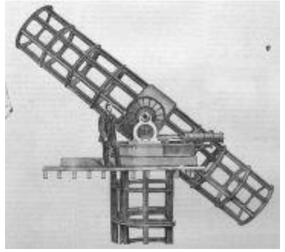
Sir Henry Bessemer's other inventions- 110 patents!





Twin roll casting machine, invented in 1846

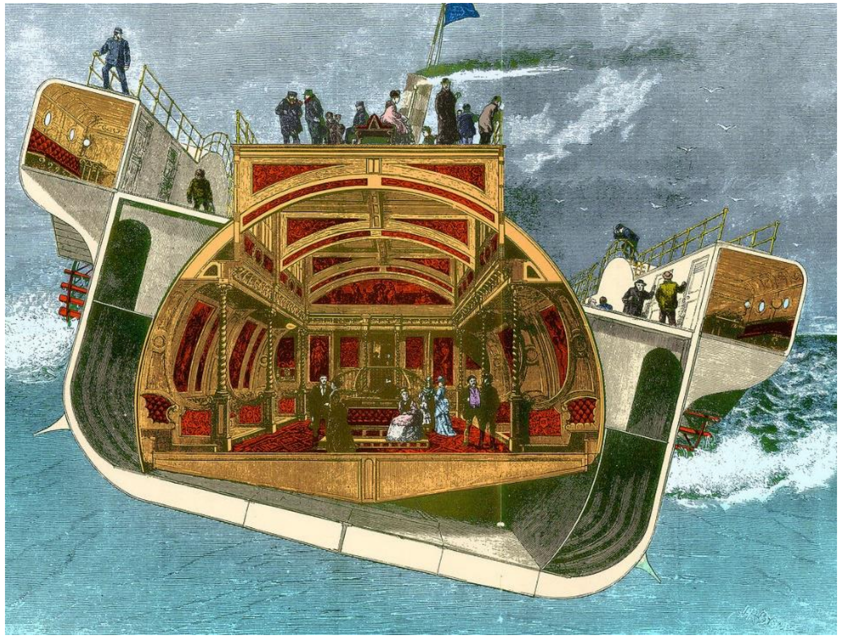
Telescope



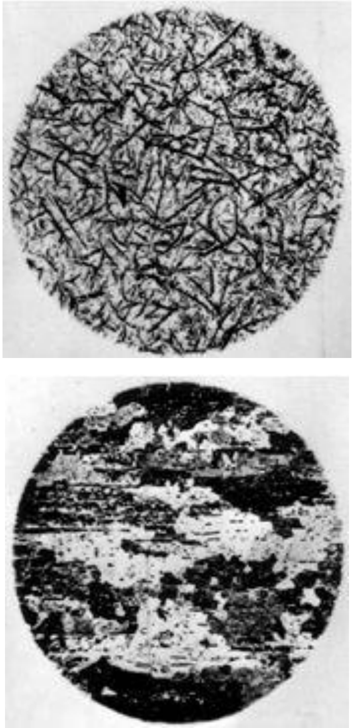
S.S. Bessemer Saloon Steamship. He found investors who stumped up some £250,000. The resulting paddle steamer measuring 350 ft (106.6m).

The gyroscopic apparatus powered by a dedicated steam turbine had been designed and patented by Henry Bessemer himself.

It never worked…. (and years later the tilting train…..)



Henry Clifton Sorby (1826-1908), FRS, Sheffield microscopist, president of the Royal Microscopical Society and elected president of Firth College



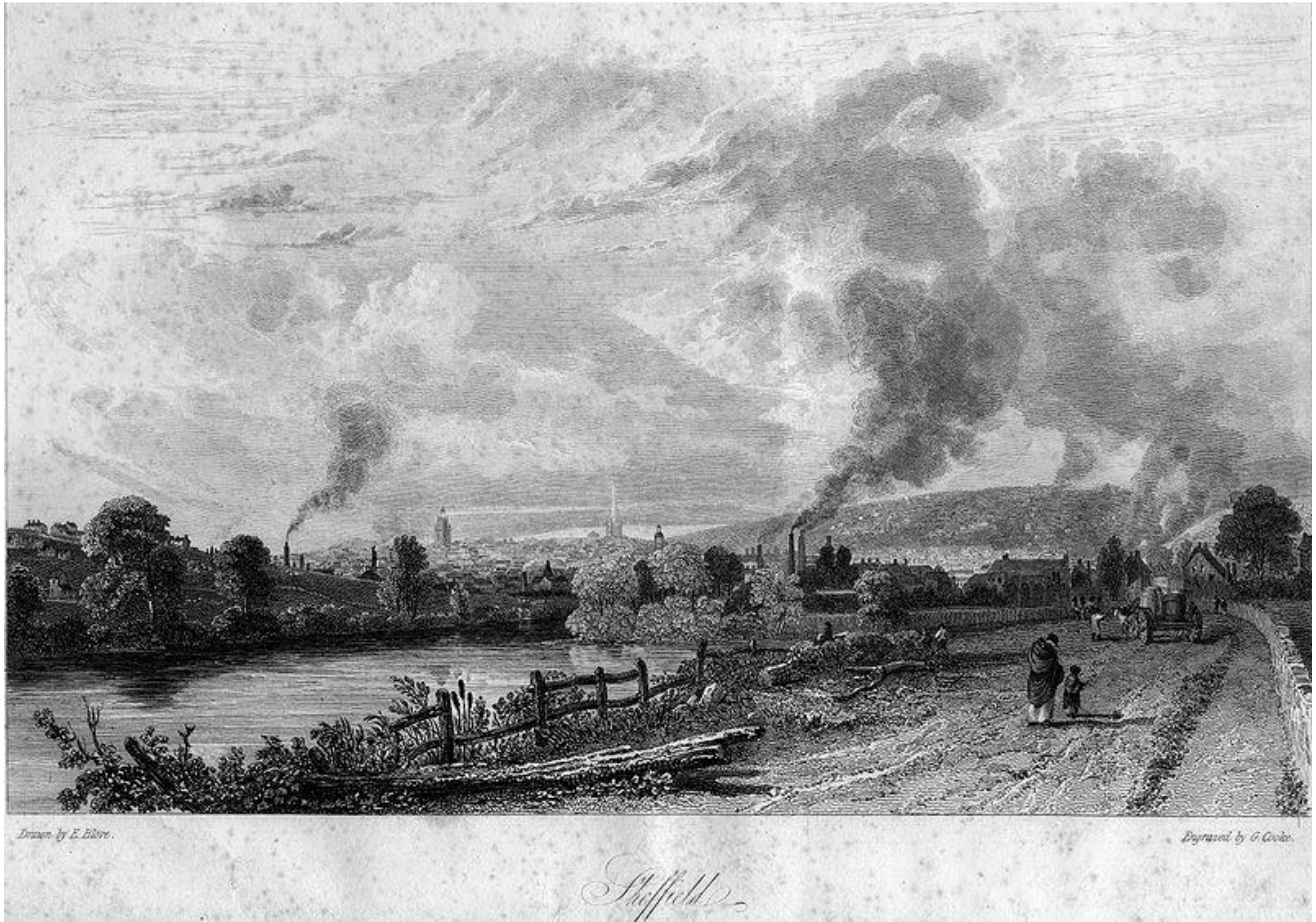
Etched cast iron;

iron armour

The first optical microscopy of metallic samples

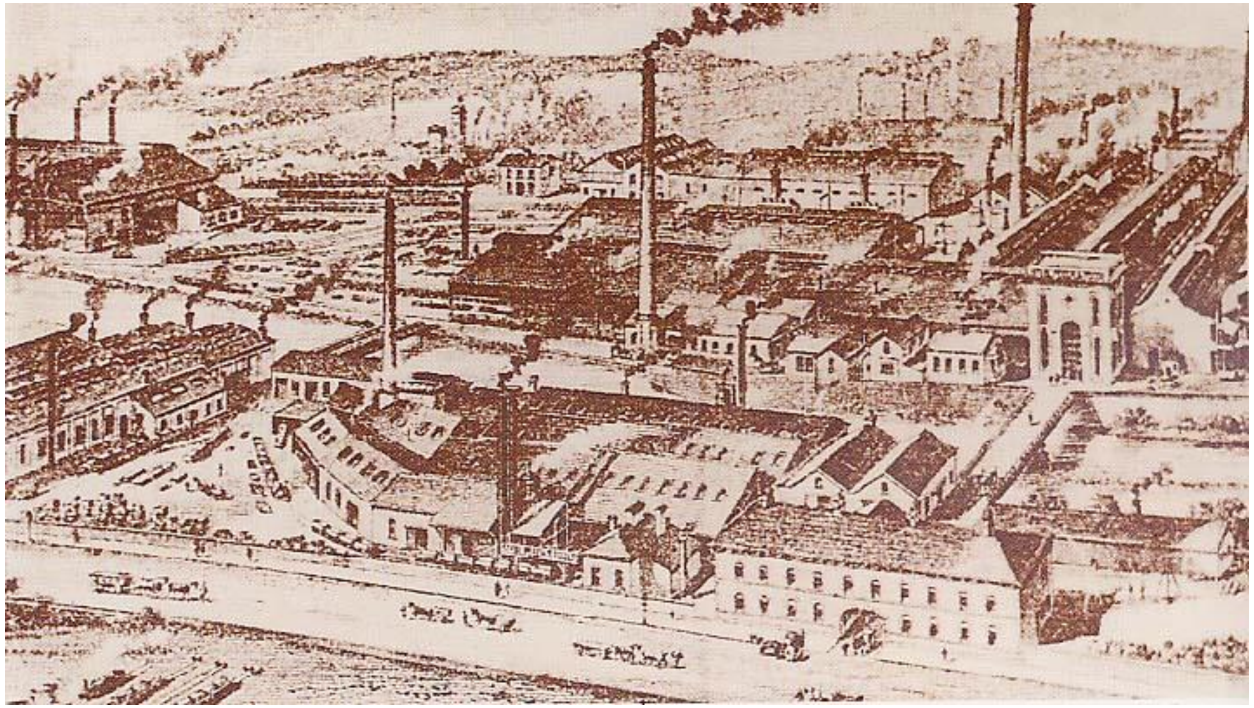
University of Sheffield

Sheffield in Sorby's time- contemporary with Bessemer



University of Sheffield

Steel making in Rotherham/Sheffield



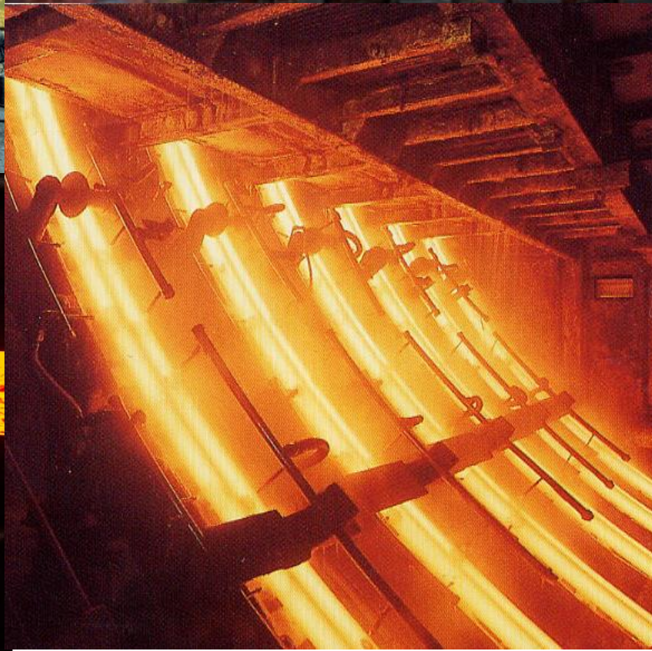
Steel Peech & Tozer, Ickles works, 1890

The Steel, Peech and Tozer Templeborough Steel Works, Templeborough, 1949

University of Sheffield

Our long proud history of steelmaking in Sheffield/Rotherham - which molded my early years

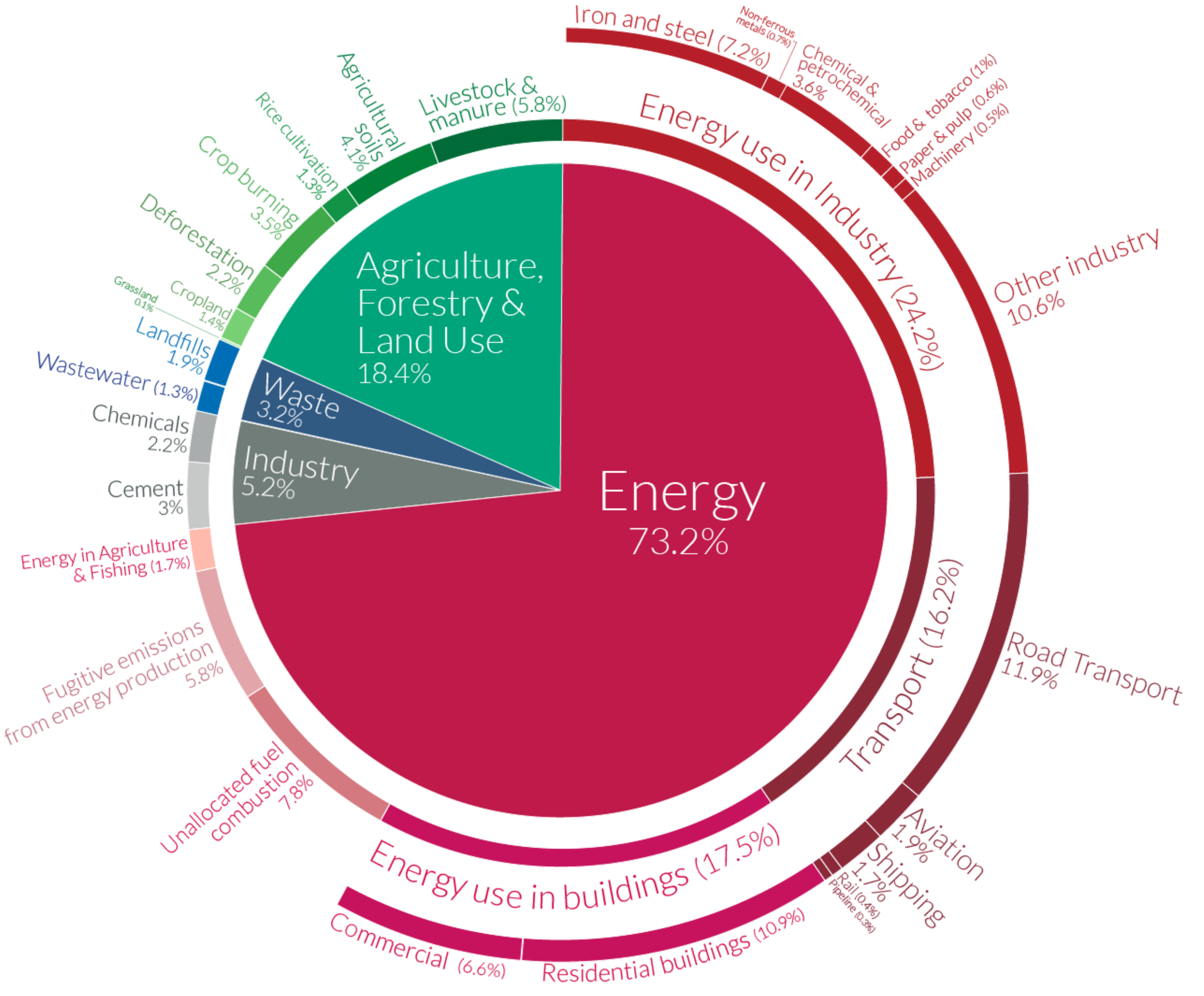
Templeborough-the first UK site for a special steels billet caster in 1981



University of Sheffield

World CO_2 emissions by sector

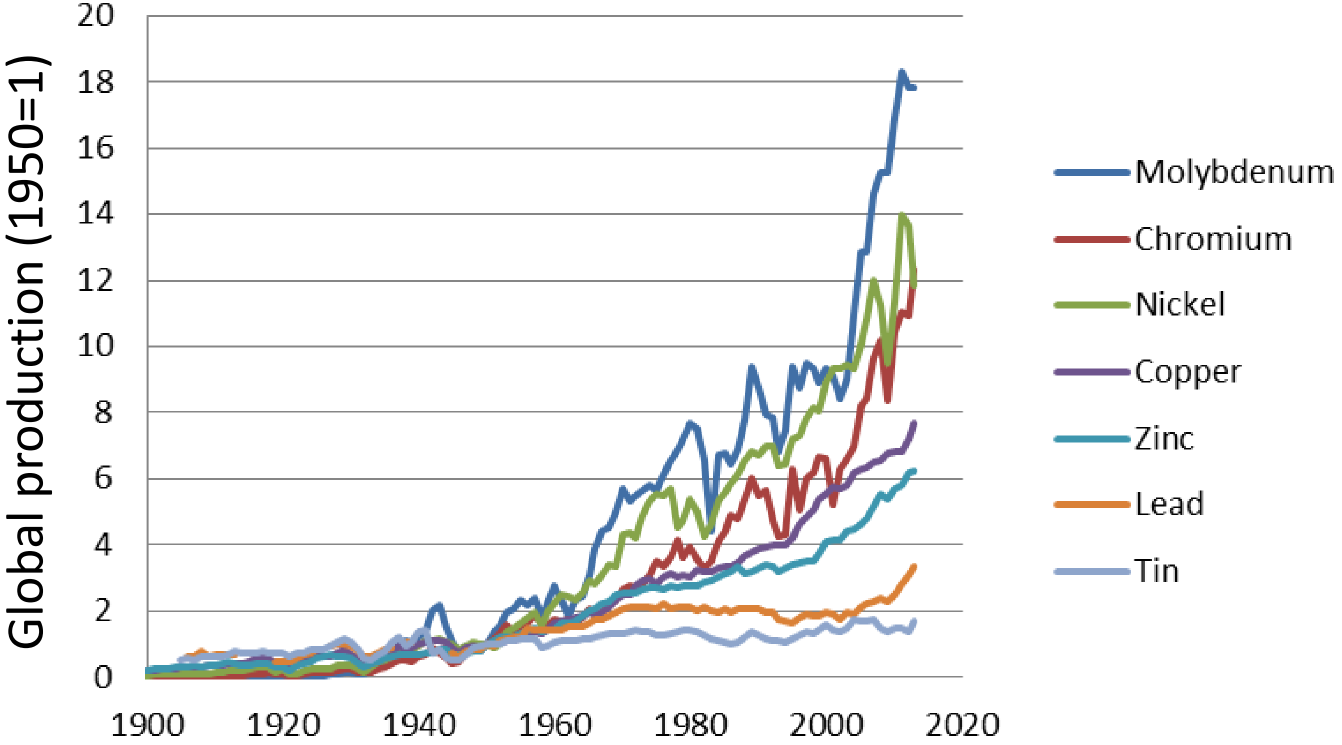
Metals production consumes about 5% of global energy use and is responsible for 40% of industrial greenhouse emissions



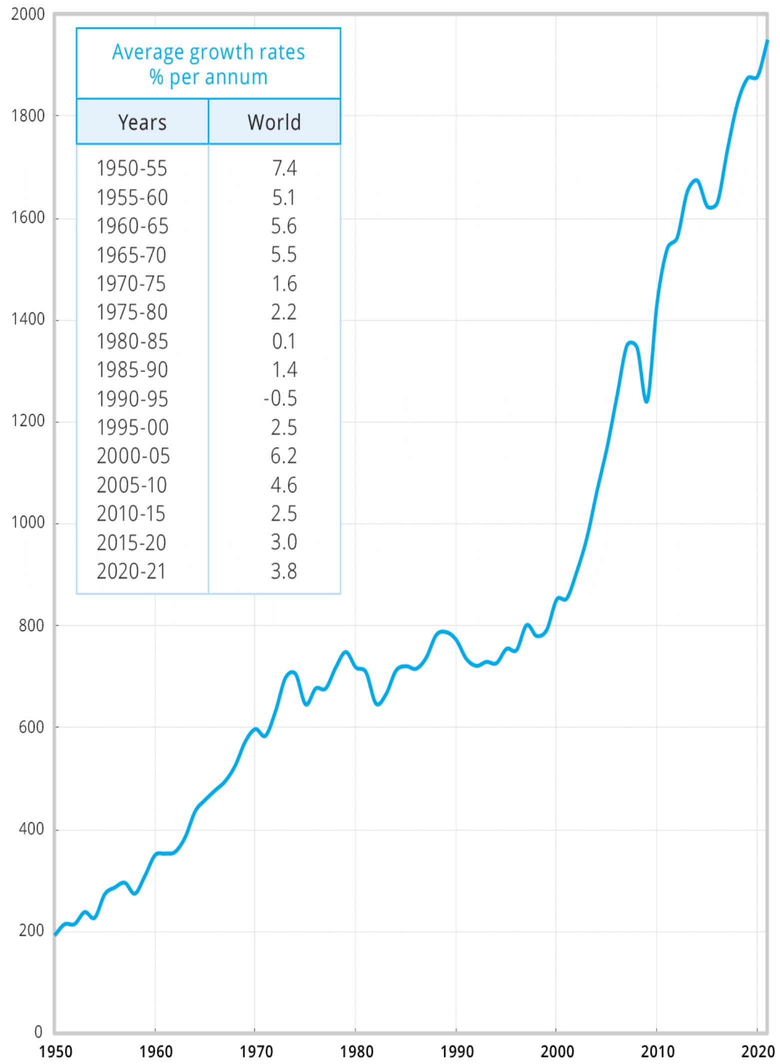
OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020).

University of Sheffield

An OECD forecast suggests that consumption of most raw materials will double by 2060



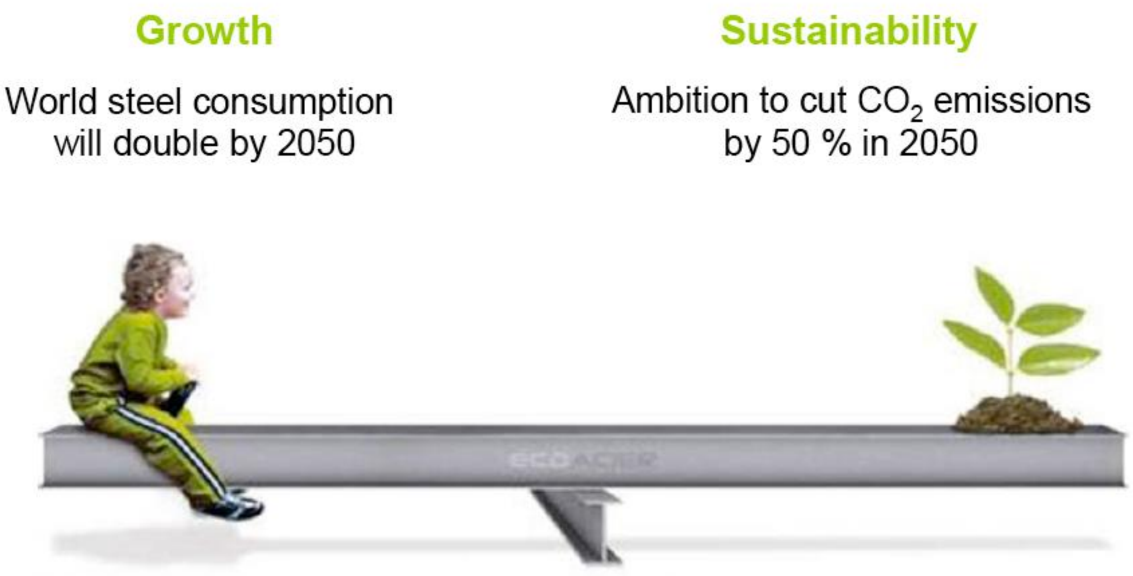
Million tonnes world crude steel production



University of Sheffield

The Sustainability Challenge

TATA

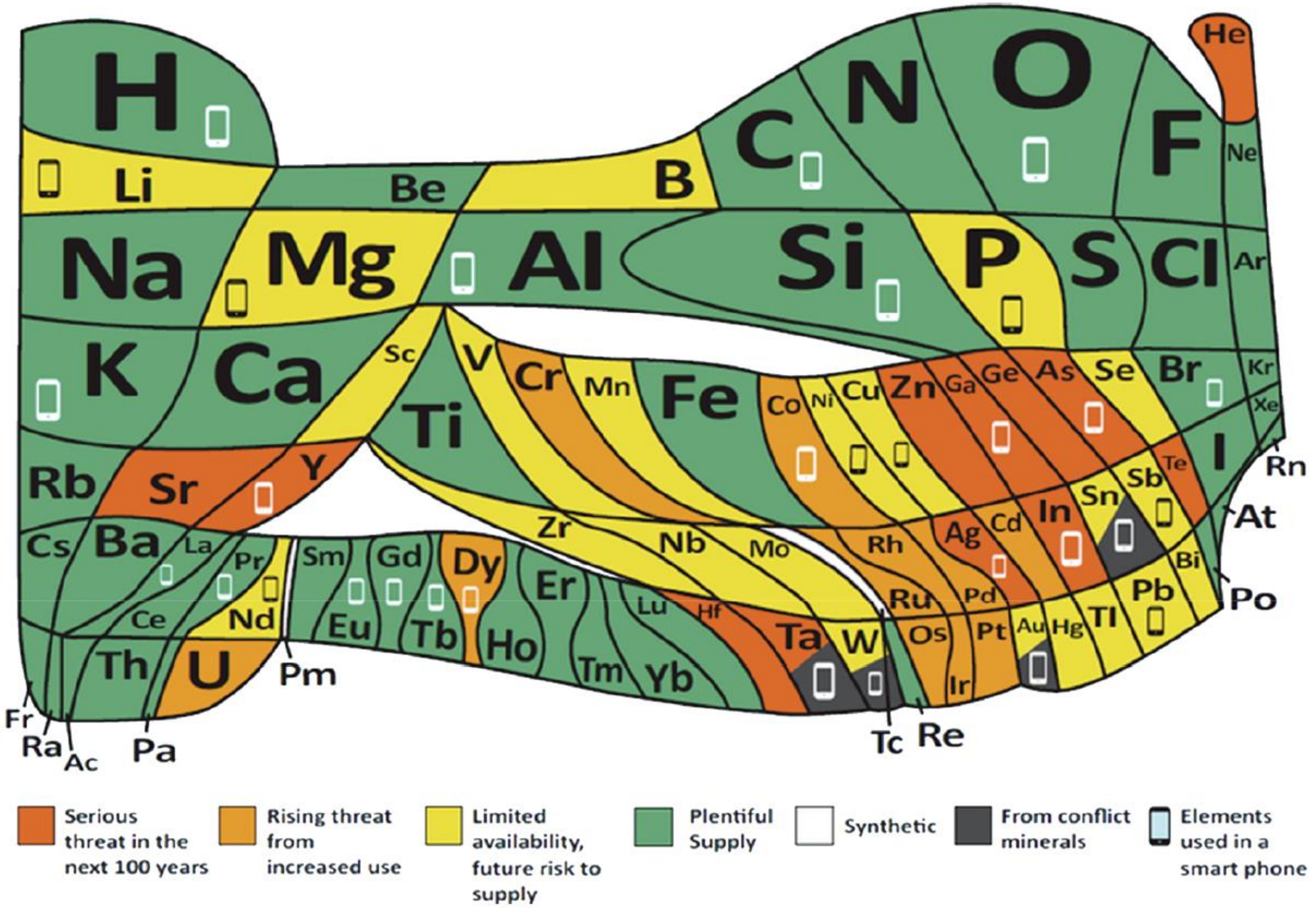


This means that the metallurgical (and generally the materials) sector cannot be exclusively built on circular economy principles, simply because there is not enough scrap and waste material available

University of Sheffield

OECD: Organization for Economic Co-operation and Development. Copyright 2019, OECD

Periodic table of the element abundance



University of Sheffield

Steel has changed more rapidly than any other material on this planet

MAKE uk
The Manufacturers' Organisation

The future of steel is changing rapidly

- Government has targeted a 95% emission reduction from steelmaking by 2050.
- New Net Zero steel production will increase electricity use, but industrial electricity prices are a key barrier, as UK steelmakers currently pay almost 60% more than their European counterparts.
- UK demand for steel is expected to grow by 2030, presenting an opportunity to reindustrialise and create green jobs.
- Any route to Net Zero steelmaking must include creating a market for Net Zero steel, ensuring that imported, high-emission steel does not undermine domestic investment.
- Globally, a long way off decarbonised steel production

"Green steel" Basic challenges to make steel more sustainable:

1) Green steel is defined as steel manufactured without fossil fuels.
2) Switch to green steel production includes:
   - Better collection and sorting of scrap.
   - Improving recycling of intensely mixed scrap where element recovery is very challenging.
   - Change alloy design to make materials compositionally more robust and thus better suited for recycling
3) It is not just the removal of fossil fuels in production, but also the substitution of less sustainable alloy additions by more sustainable ones
4) Re-use of steel, extra longevity

University of Sheffield

Major investments in the UK

TATA STEEL

- Tata Steel and the UK government announced a proposal to invest in state-of-the-art Electric Arc Furnace steelmaking at the Port Talbot site with a capital cost of £1.25 billion inclusive of a grant from the UK Government of up to £500 million. The largest investment in the UK steel industry for decades.
- Using electric arc furnace technology, Tata Steel could reduce carbon emissions from its Port Talbot site by 5 million tonnes a year by 2030 – equivalent to the carbon footprint of almost 2 million homes in the UK (almost one in ten of all homes in England and Wales).
- **Blast furnace No 4 closed on 29th September 2024**. EAF some way off, large job losses

SUSTAIN

Future Steel Manufacturing Research Hub

University of Sheffield

Major investments in the UK

- British Steel unveiled ambitious plans for the biggest transformation in its history – a £1.25-billion proposal to become a clean, green and sustainable business by adopting electric arc furnace steelmaking.
- The new furnaces could be operational by late 2025 and would replace the aging iron and steelmaking operations in Scunthorpe which are responsible for the vast majority of the company's CO_2 emissions. The company proposes maintaining current operations until a transition to electric arc steelmaking.

Future Steel Manufacturing Research Hub

Investment in Europe in "Green Steel"

- **9/14/2023 - Voestalpine has broken ground on a EUR450 million electric arc furnace (EAF) at its Donawitz plant in Austria, the first of two that the steelmaker will build, the company has said.** The plant will be capable of producing 850,000 metric tons of steel annually, and commissioning is to take place in three years.

- **10/26/2023 - The European Commission and the Italian Ministry of Enterprises are throwing support behind a research project that aims to establish a fully hydrogen-fuelled steelmaking plant.** The pilot facility, which is to open in 2025, will include a direct iron ore reduction (DRI) tower, which will use hydrogen as its primary reducing agent, as well as an electric furnace and a reheating furnace.

- **7/20/2023 - The European Commission has signed off on EUR2.85 billion in state aid that will go to decarbonization efforts at thyssenkrupp and ArcelorMittal.** The funding consists of a EUR550 million grant to thyssenkrupp, along with a conditional payment of up to EUR1.45 billion. The funding will support a direct reduction plant and two melting units.

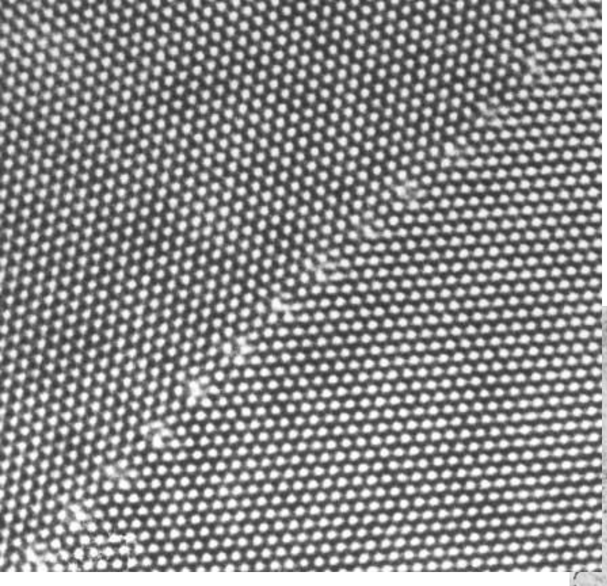
- **6/2/2023 - SSAB's board of directors has greenlighted construction of an electric arc furnace at its Oxelösund mill, a SEK6.2 billion (US$575.6 million) investment that is projected to reduced Sweden's national CO2 output by 3%.**

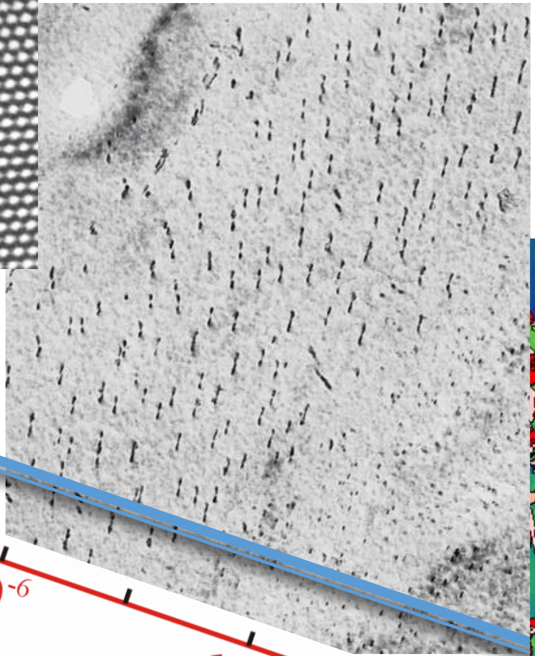
University of Sheffield

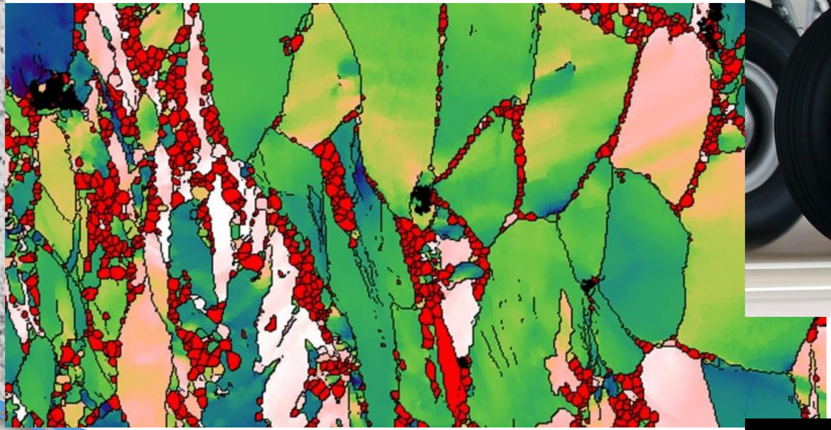
Thanks to Prof Claire Davis for gathering the information

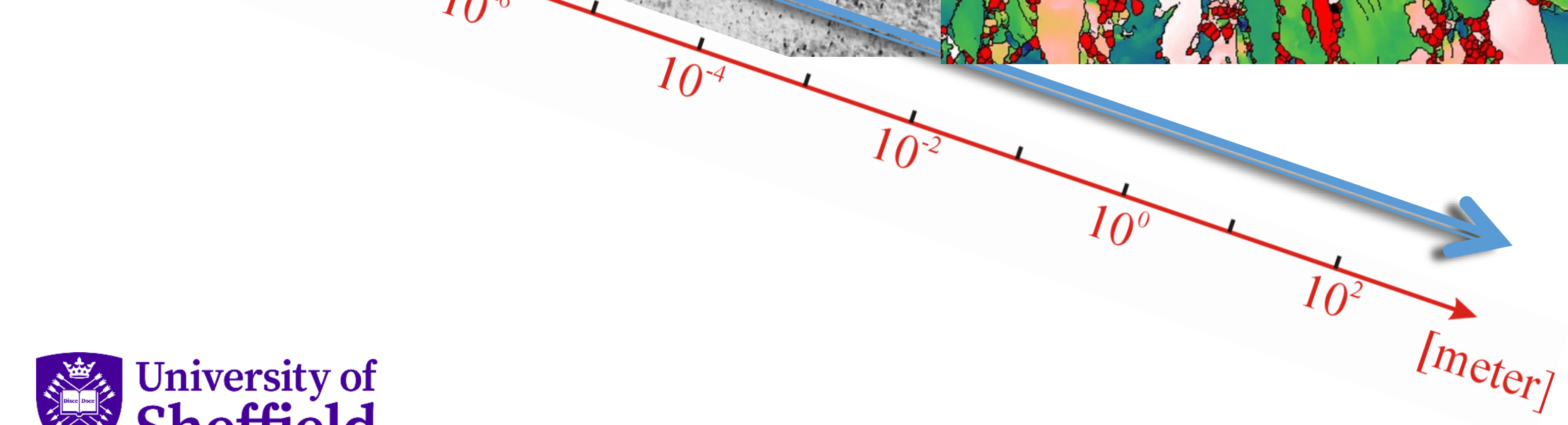
SUSTAIN
Future Steel Manufacturing Research Hub

Microstructure determines properties. But there are massive length scales involved- changes at the atomic scale determine properties at the macroscopic scale



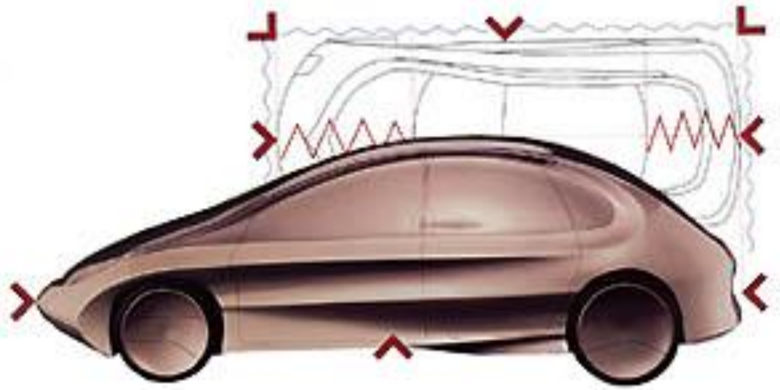






University of Sheffield

Steels in automotive- a major success story!

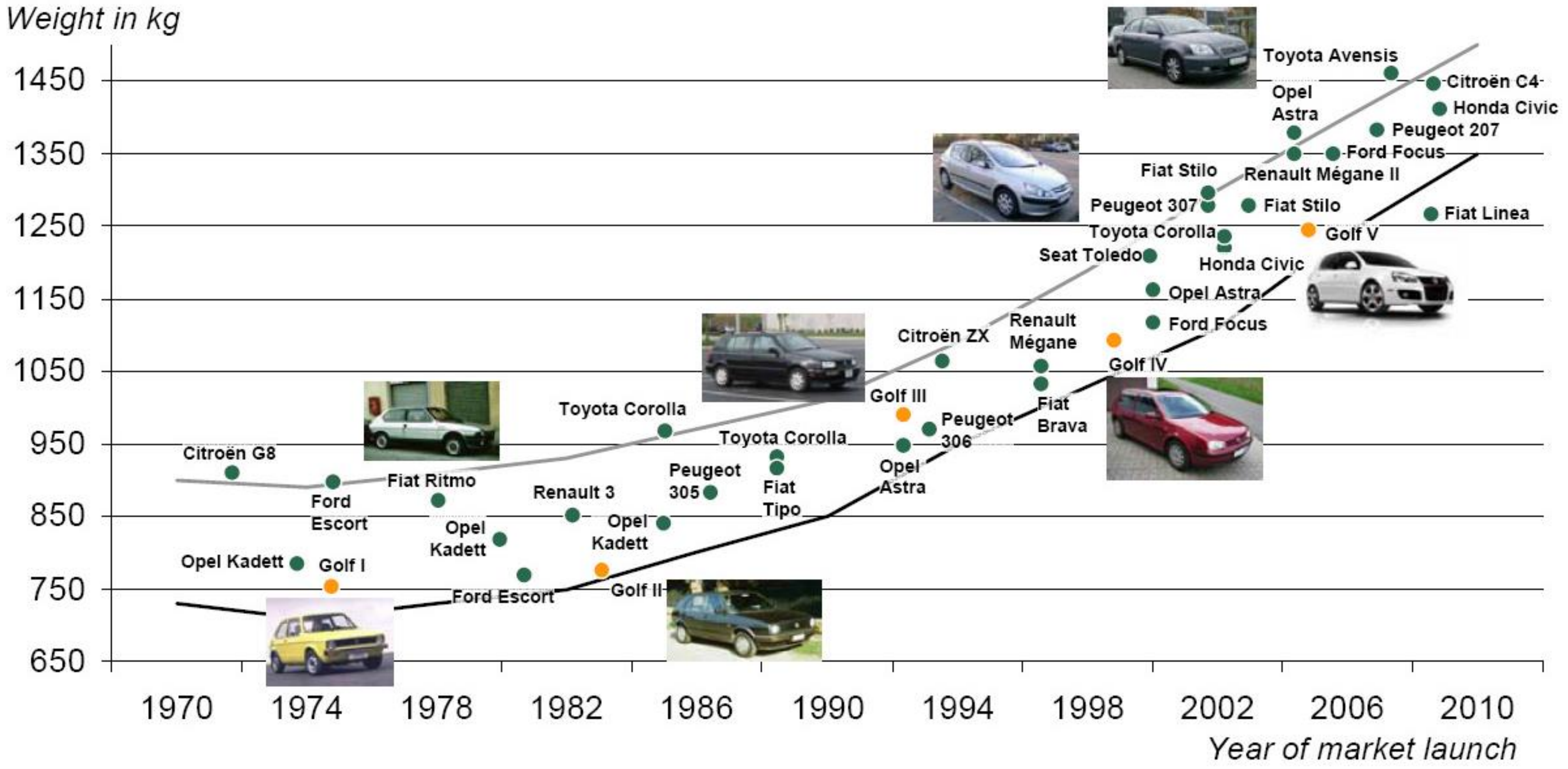


high strength, low weight components for automotive applications

University of Sheffield

Old and new.....

Increase in car kerb weight-cars in Europe

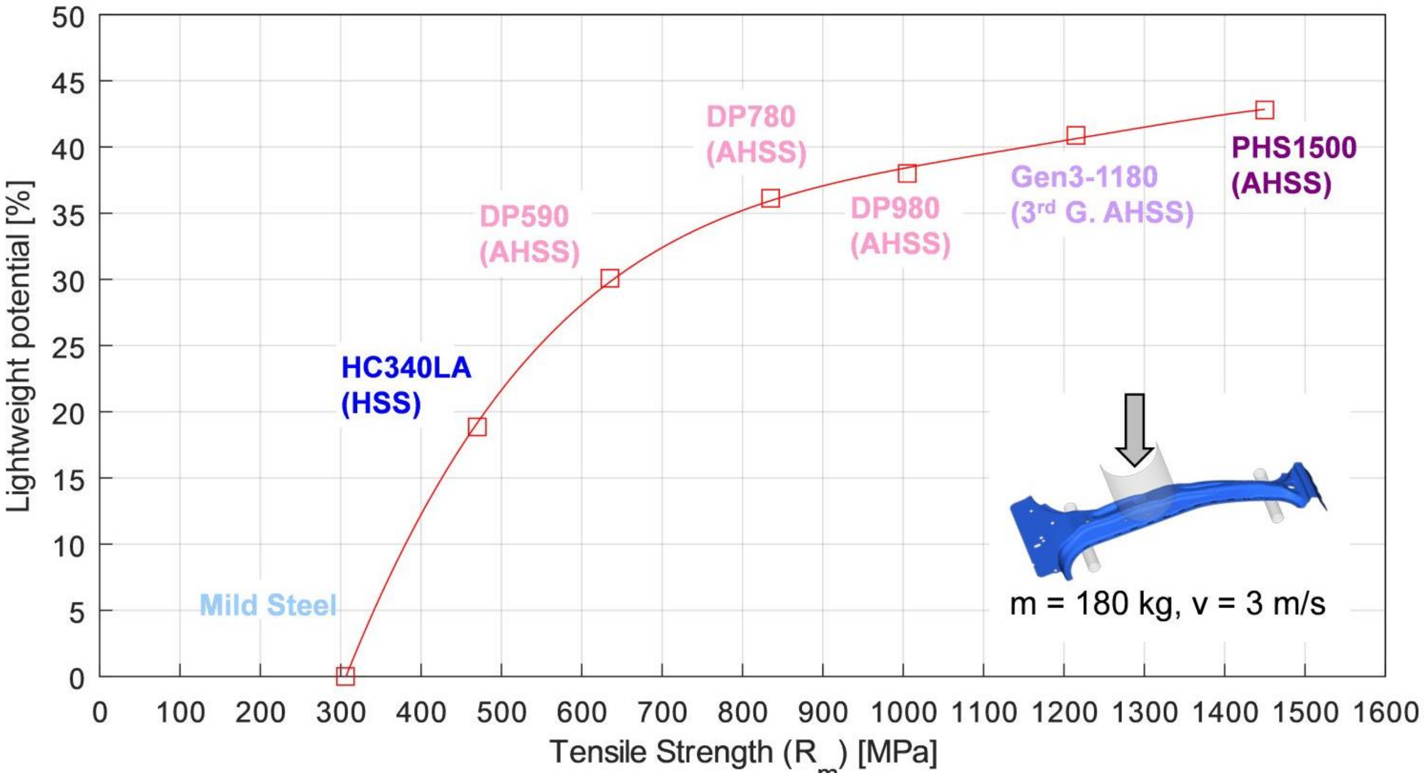


Sorurce: Handelsblatt Tagung, Stuttgart, 3.-4. Juli 2007

University of Sheffield

DARE
DESIGNING ALLOYS for RESOURCE EFFICIENCY

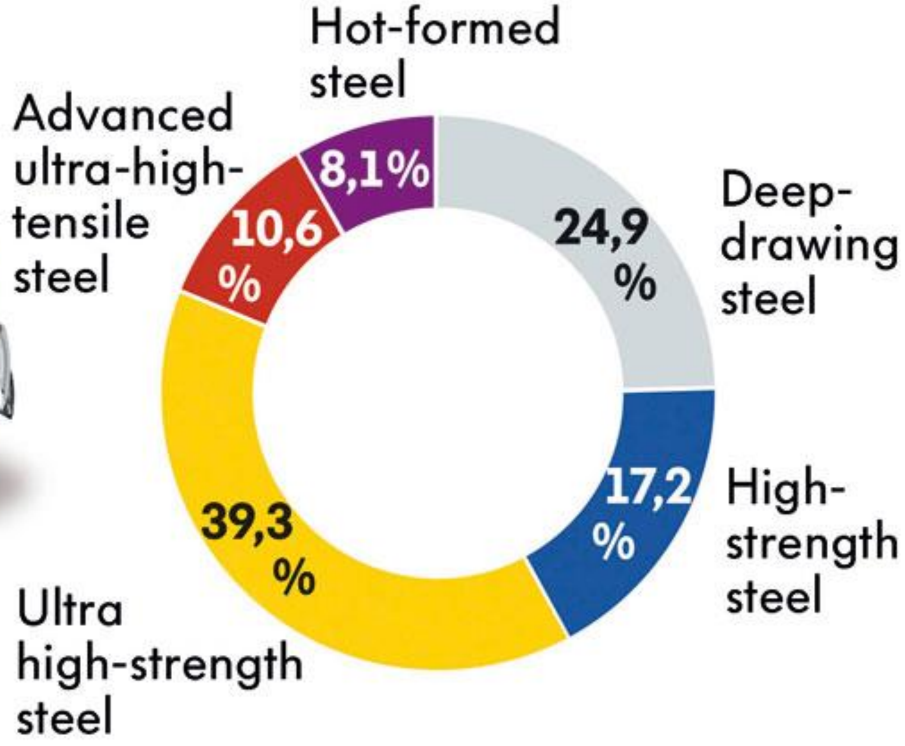
The need to invent new steels with higher strength- Automotive steels increased in strength by ~100MPa per year over a decade



University of Sheffield

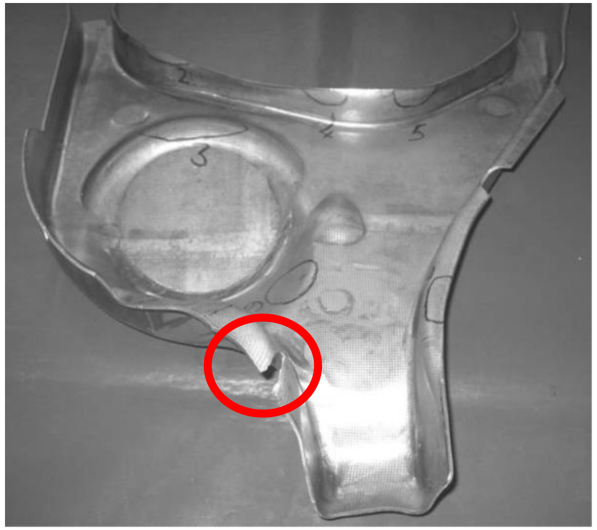
DARE
DESIGNING ALLOYS for RESOURCE EFFICIENCY

Rapid invention of new high strength steels to reduce the weight of the “body in white”

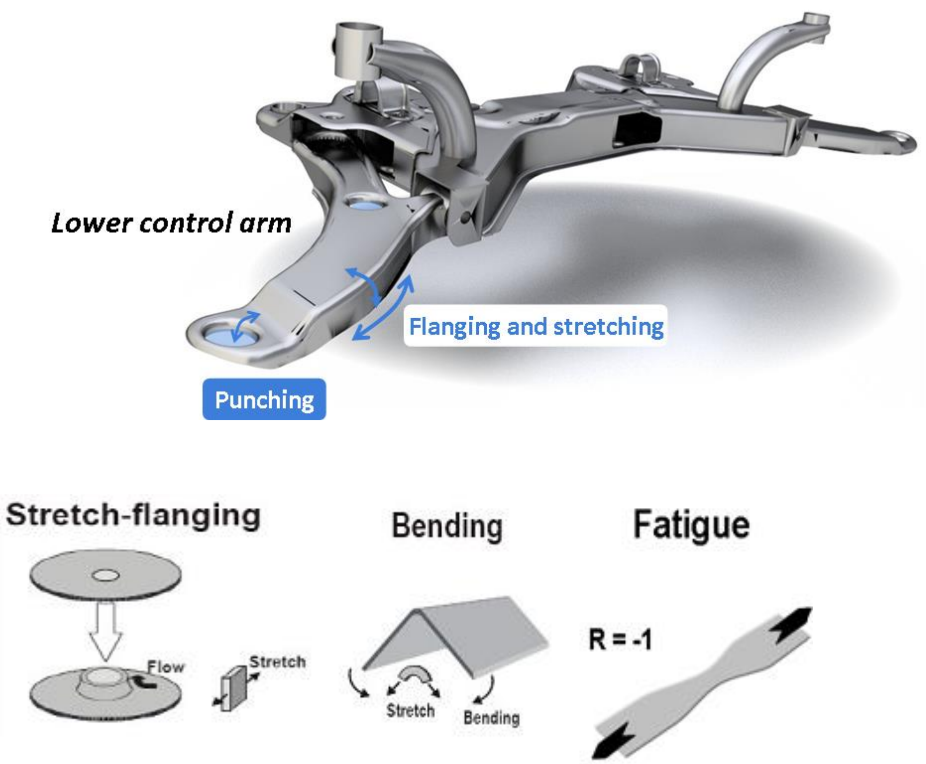


Source VW

Design of nanoprecipitation steels to deliver strength and formability



Edge splits waste a lot of time and money



- The need is for:
  - ✓ *High yield and tensile strength*
  - ✓ *Improved combination of hole-expansion and elongation*
  - ✓ *Good bendability*
  - ✓ *Good fatigue strength*
  - ✓ *Good weldability*

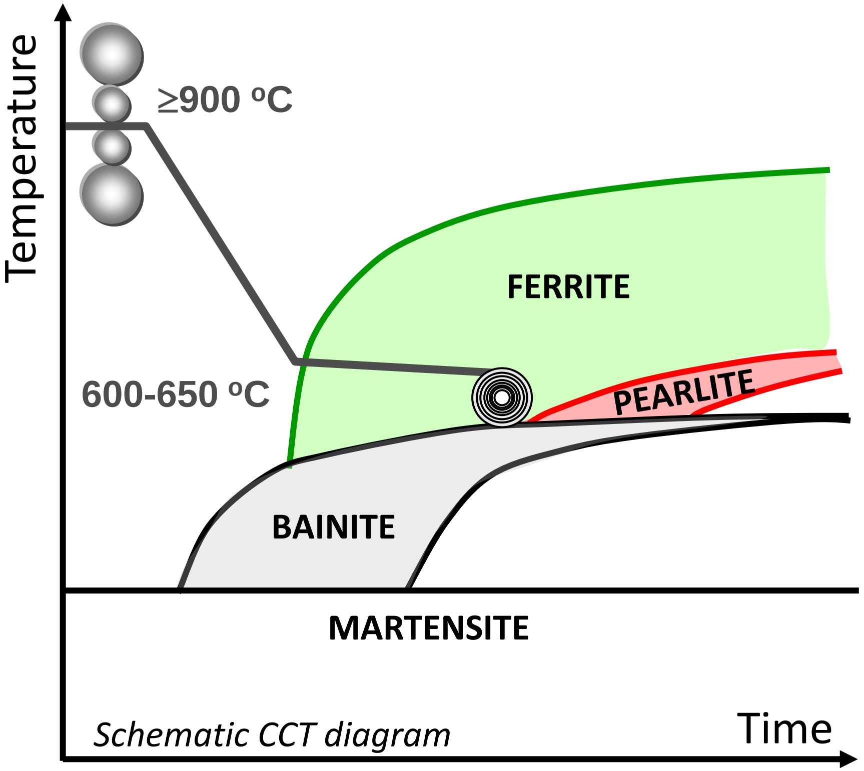
In association with Tata Steel

University of Sheffield

SUSTAIN Future Steel Manufacturing Research Hub

DARE DESIGNING ALLOYS for RESOURCE EFFICIENCY

Nano-precipitation strenghtened single-phase ferrite microstructure- using existing production facilities

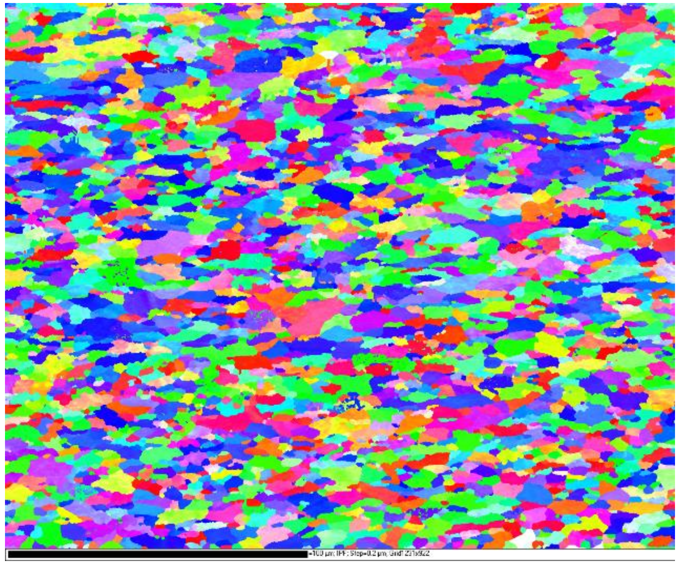


University of Sheffield

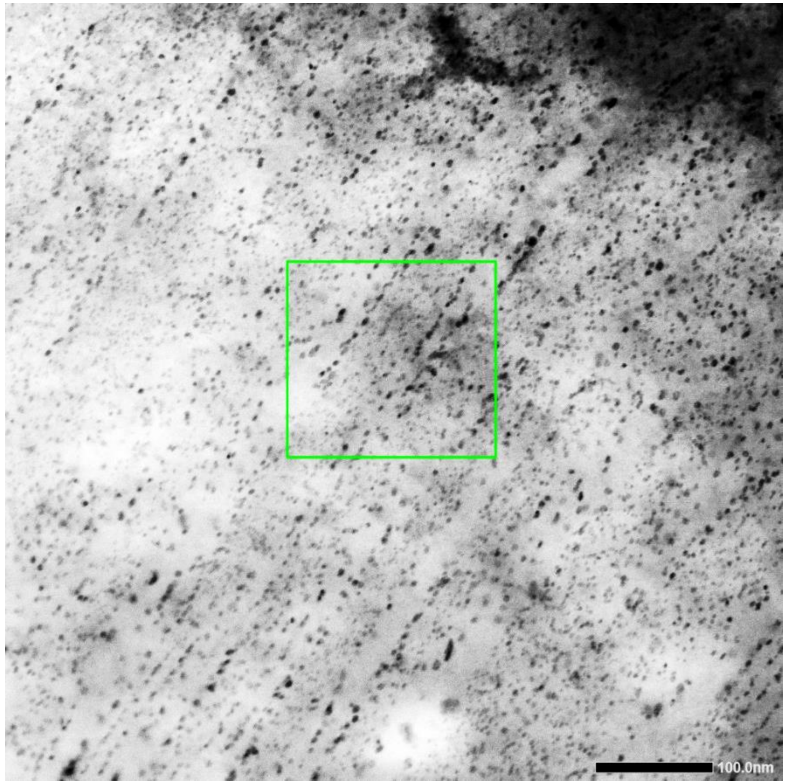
SUSTAIN
Future Steel Manufacturing Research Hub

DARE
DESIGNING ALLOYS for RESOURCE EFFICIENCY

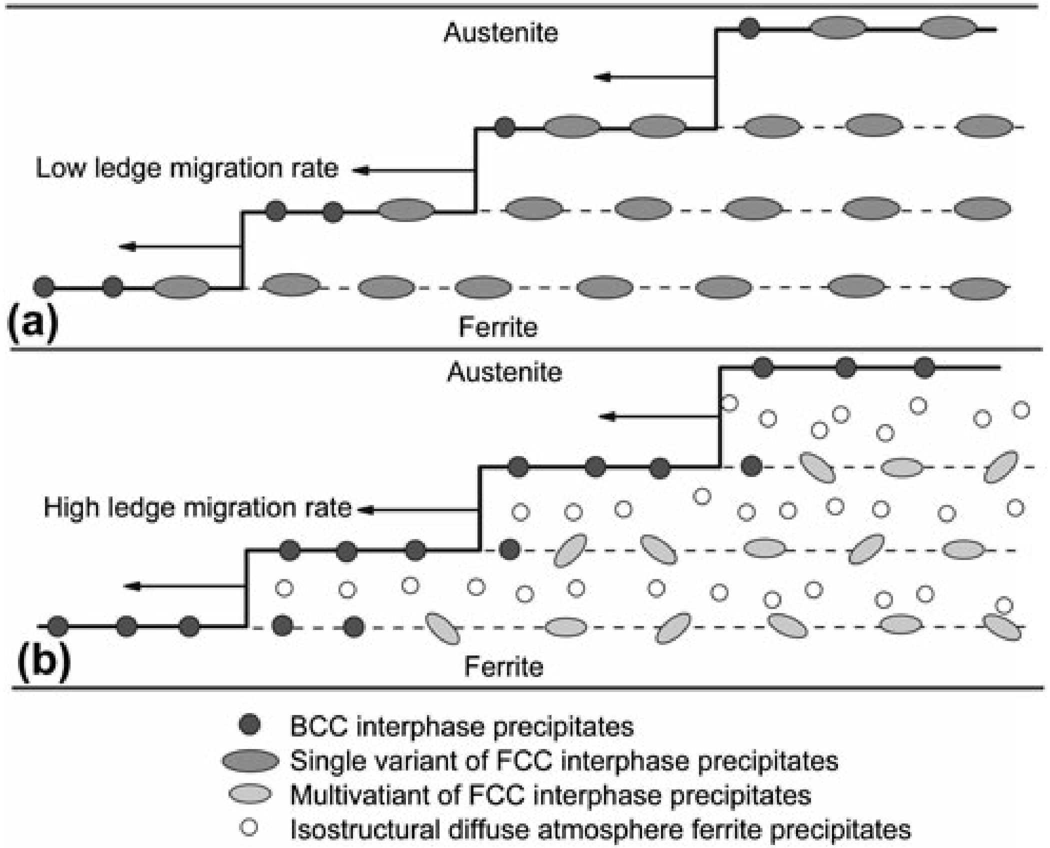
Old knowledge updated- interphase precipitation in a lean steel



Fine grain size, ~2μm



Ultra fine precipitation



Gong, Rainforth et al. Acta Materialia, 2018

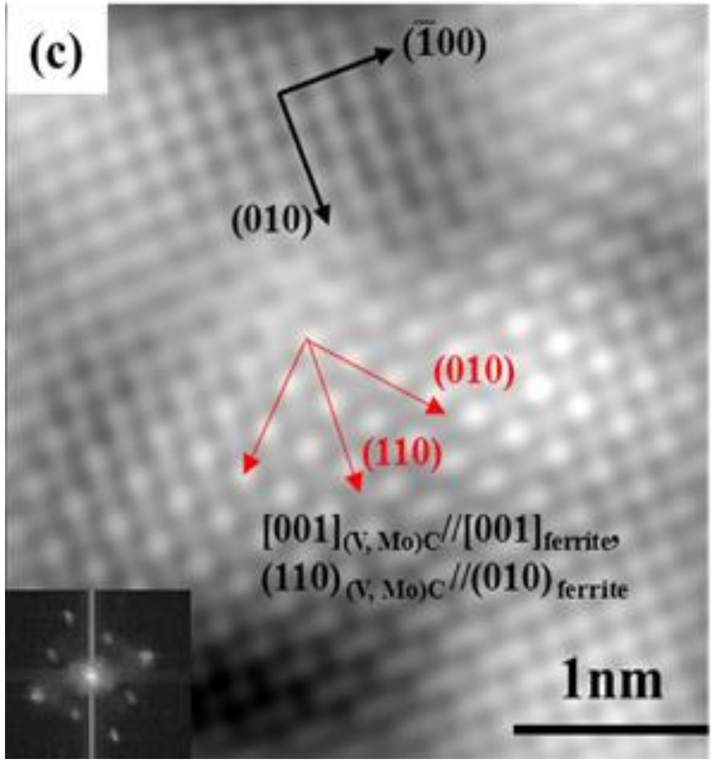
Fe-0.1C-1.6Mn-0.5Mo-0.2V

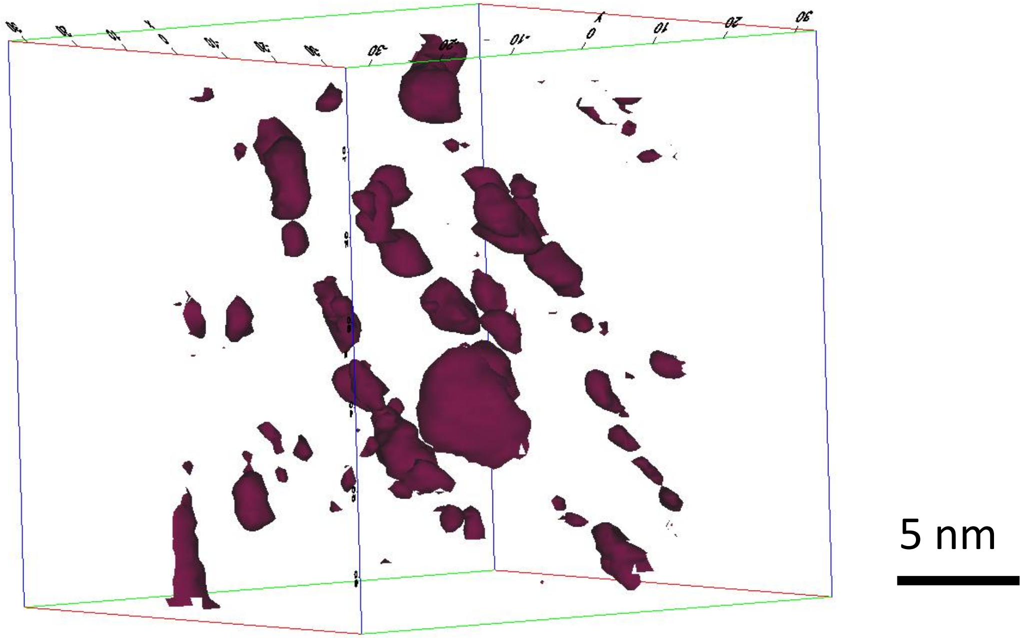
University of Sheffield

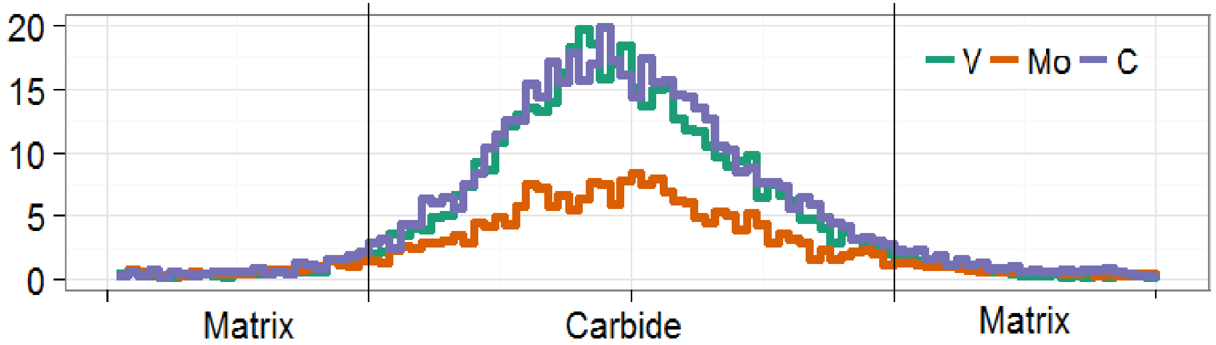
SUSTAIN
Future Steel Manufacturing Research Hub

DARE
DESIGNING ALLOYS for RESOURCE EFFICIENCY

Atomic scale engineering of nanoscale $V(Mo)_xC_y$

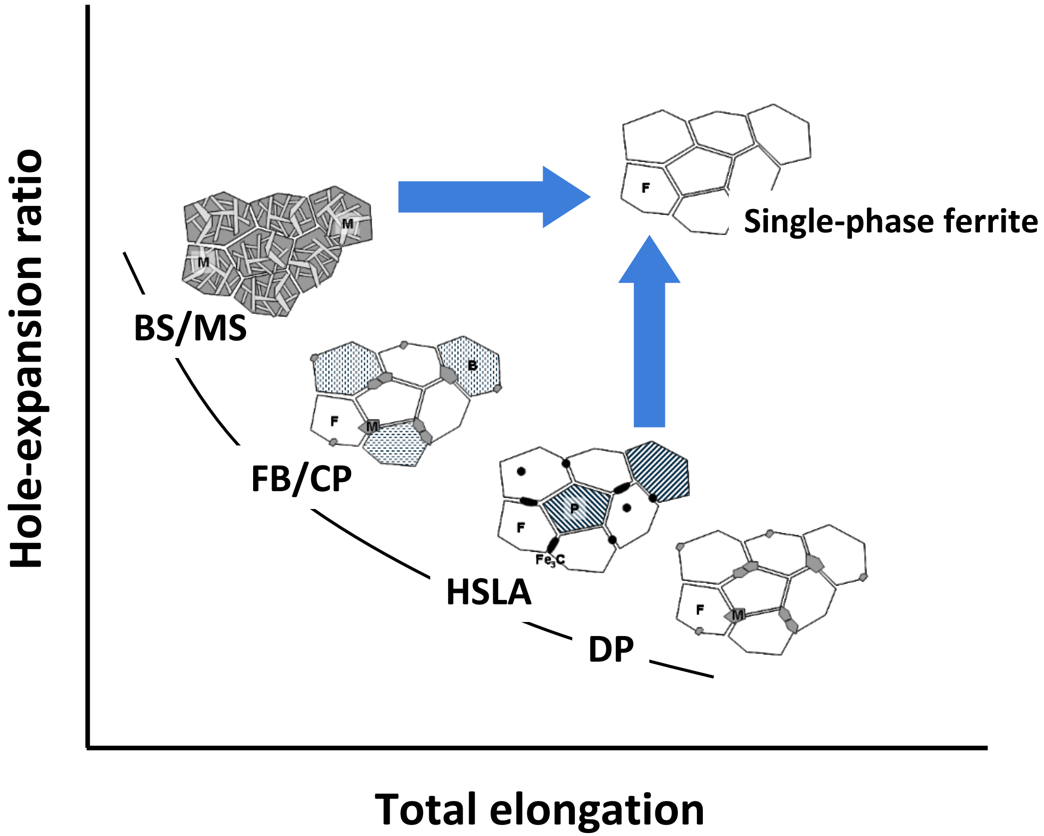


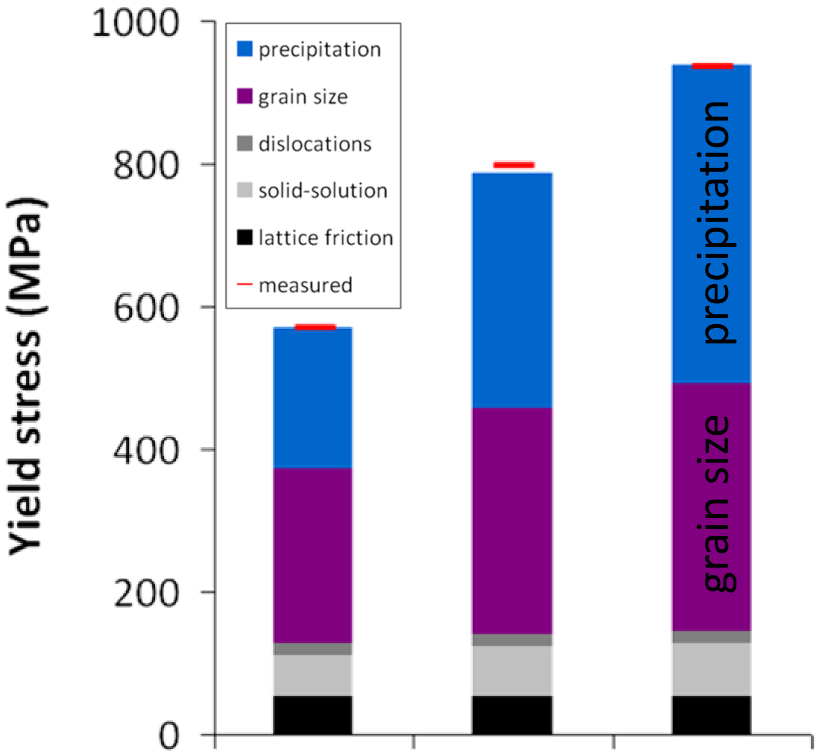




University of Sheffield
UNIVERSITY OF OXFORD
SUSTAIN
Future Steel Manufacturing Research Hub
HEMS
Hydrogen in Metals
DARE
DESIGNING ALLOYS for RESOURCE EFFICIENCY

Ultra-high yield strength of **1000MPa** a result of fine grain size and precipitation hardening; Using minimal alloying and standard processing





XPF steel- Tata steel

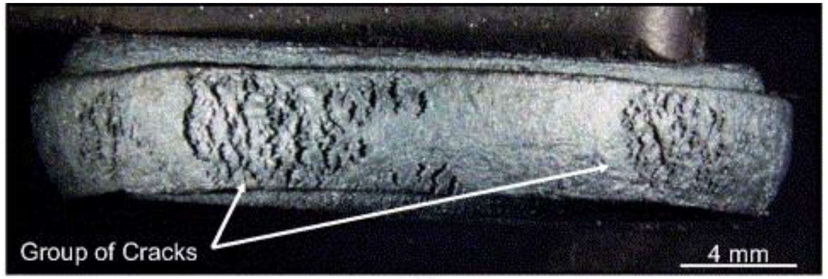
SUSTAIN

Future Steel Manufacturing Research Hub

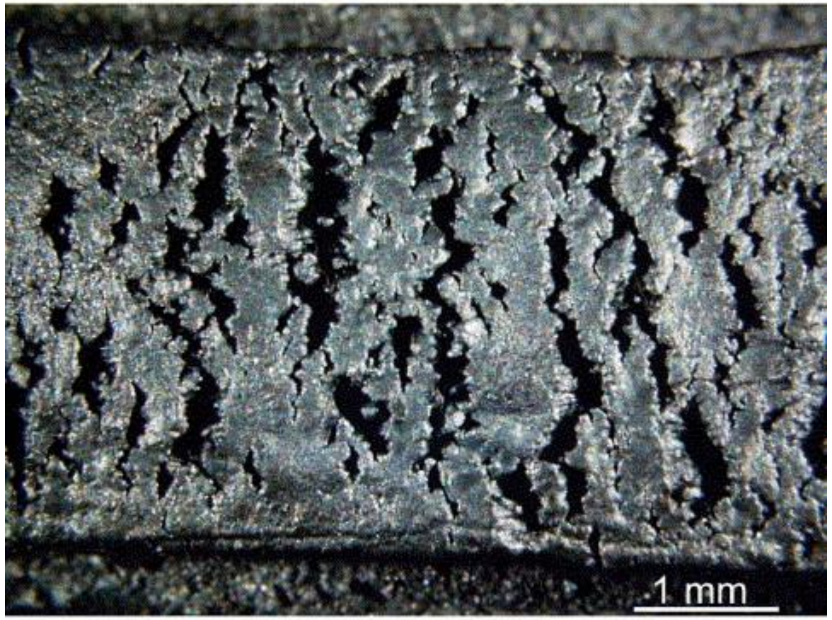
Recycling is a key strategy for sustainability

University of Sheffield

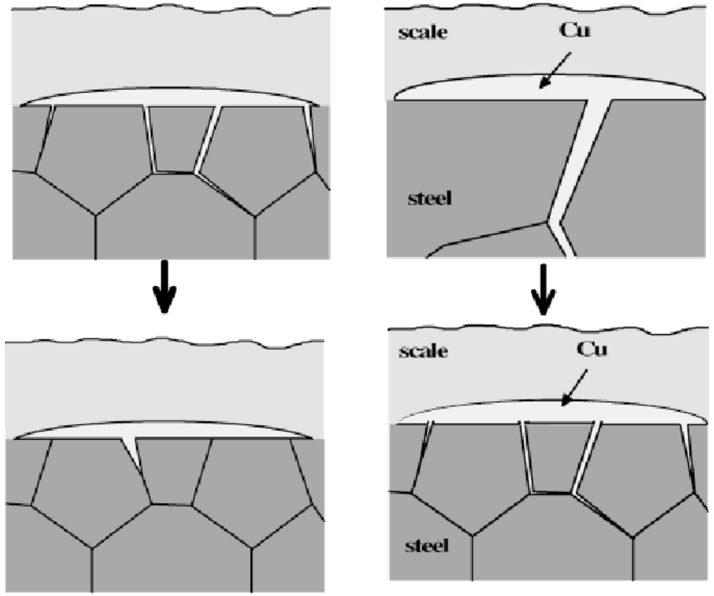
Copper in steel-major recycling issue
Hot shortness and degradation of mechanical properties

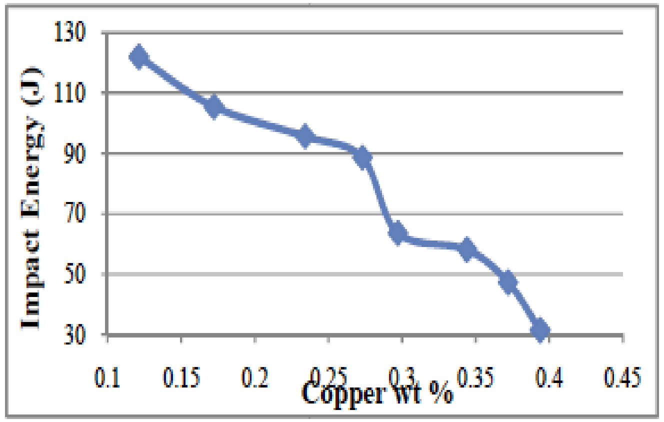


(a)



(b)





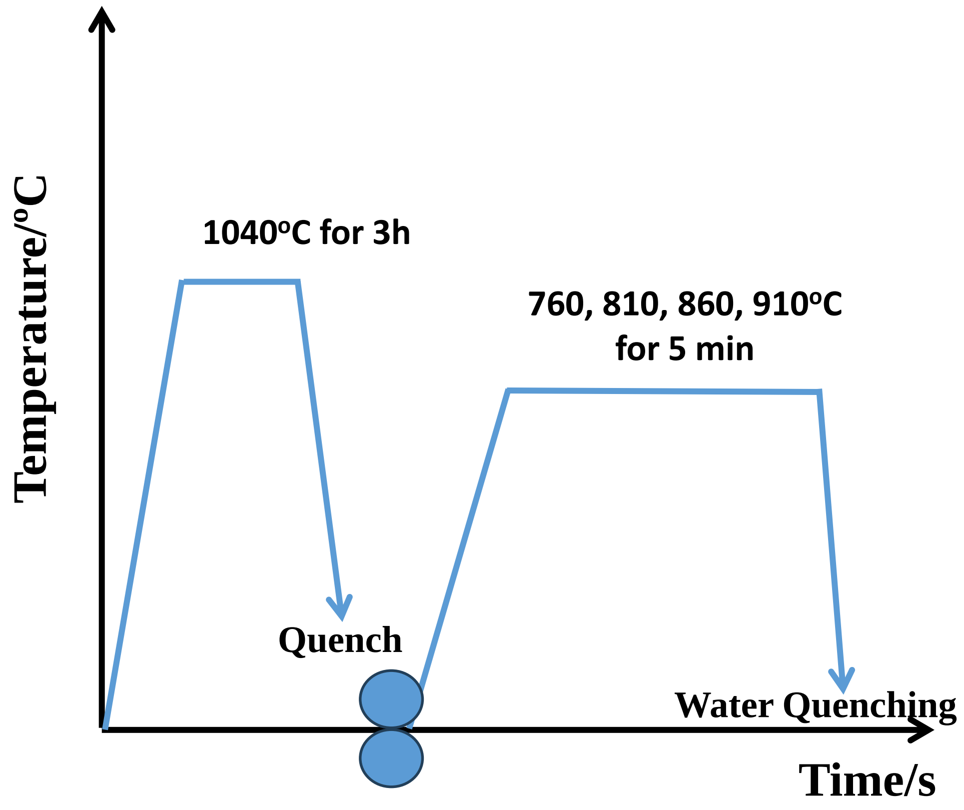
University of Sheffield

SUSTAIN
Future Steel Manufacturing Research Hub

Can a steel be designed with high Cu, high strength and can be processed in a straightforward way?

Fe-0.6C-15Mn-3Cu

Fe-0.6C-15Mn-4Cu



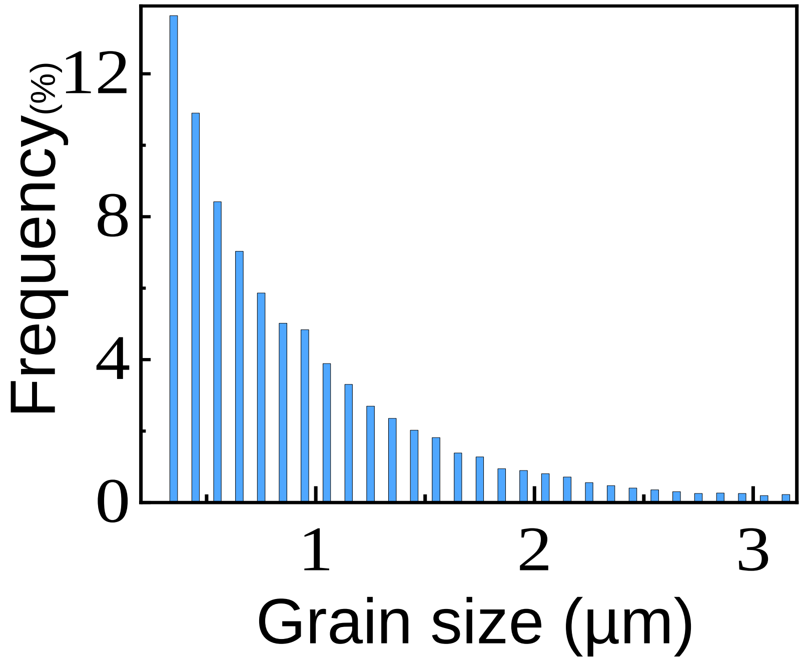
Cold roll 6mm
to 1.5mm

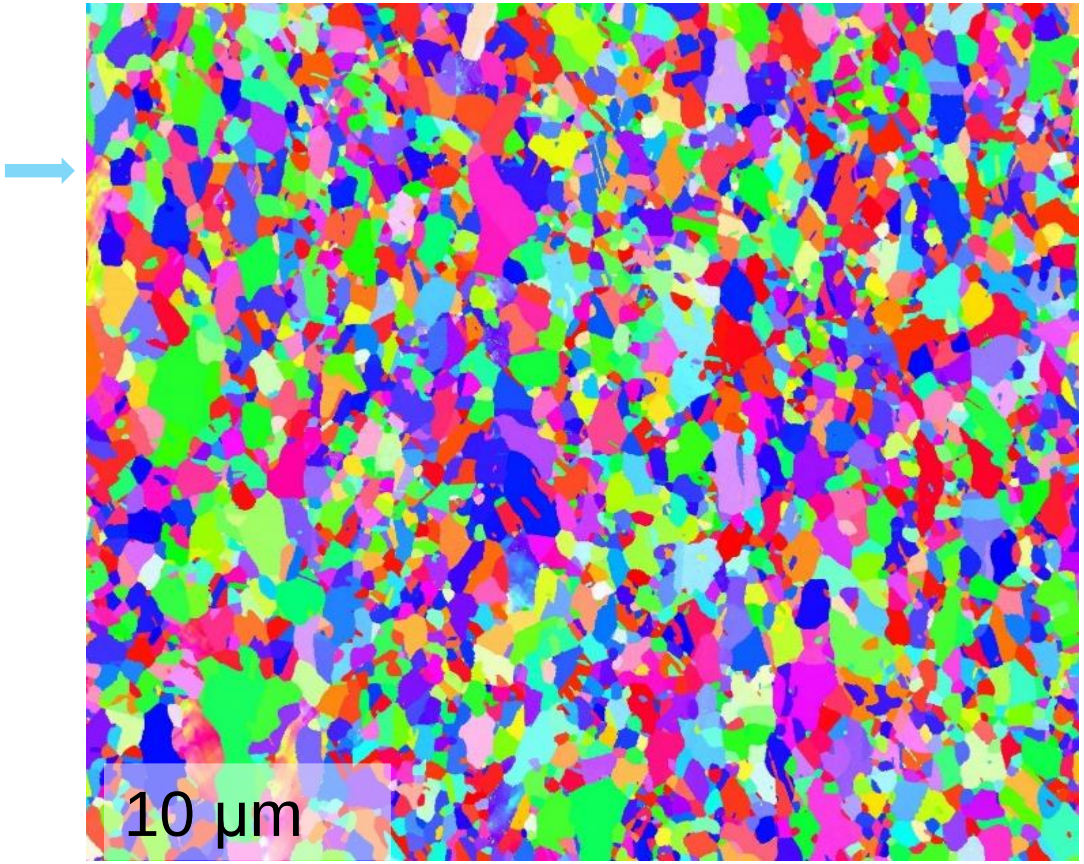
University of Sheffield

DARE

SUSTAIN
Future Steel Manufacturing Research Hub

A unique steel structure- the average grain is 800±400nm





Gao, Rainforth et al. **Nature**, 590 7845 (2021) 118538

Gao, Rainforth et al. **Acta Materialia**, 243 (2023) 262-267

University of Sheffield

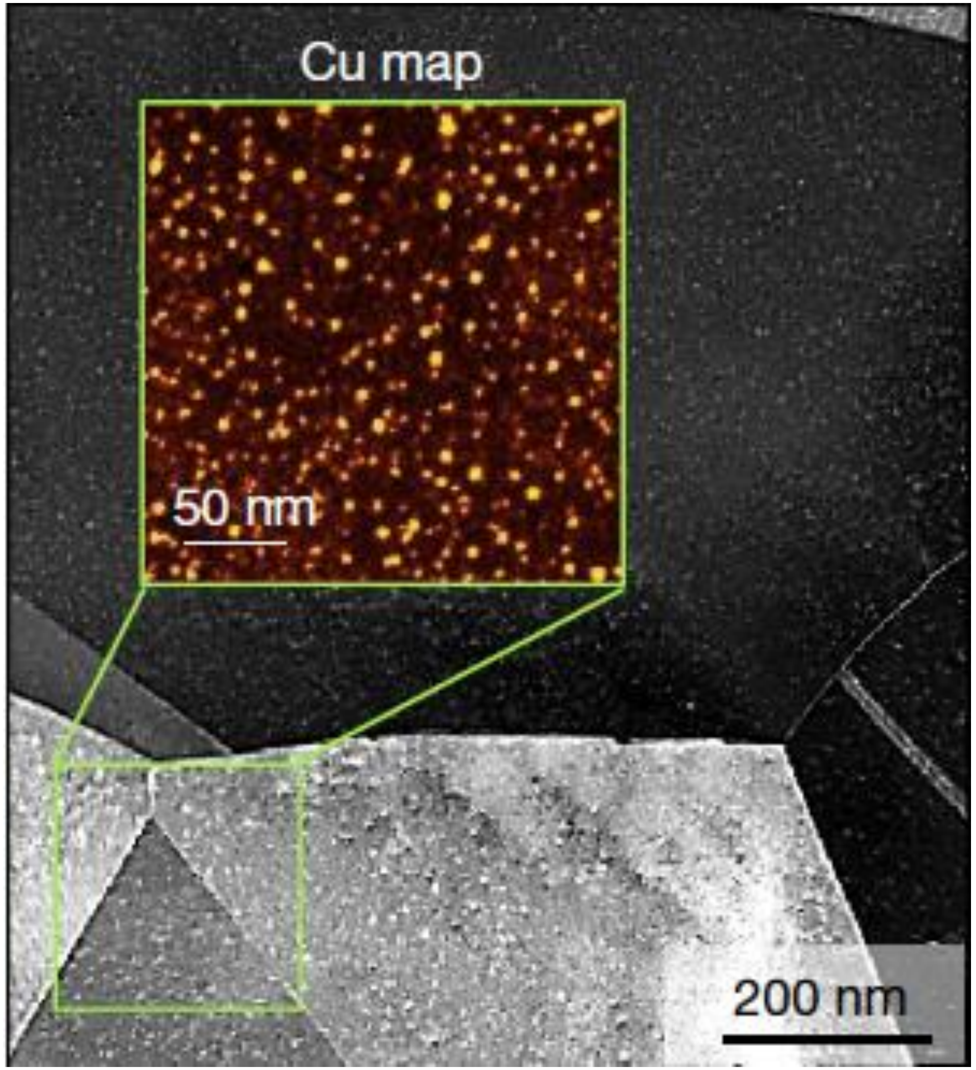
SUSTAIN Future Steel Manufacturing Research Hub

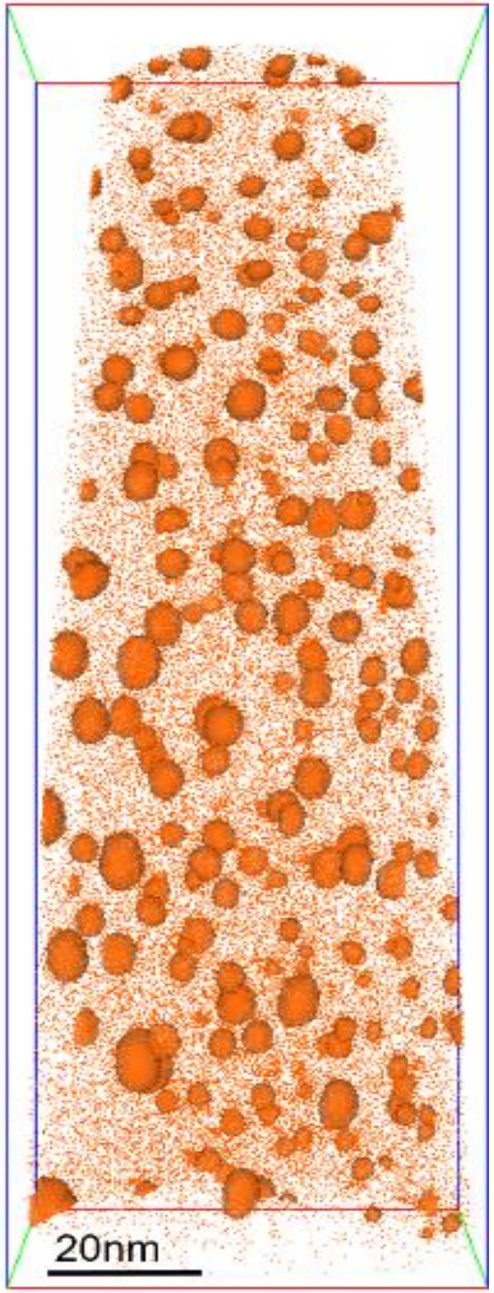
DARE

A very high density of fine Cu rich precipitates

Average precipitate size 4.5 nm with a number density of $6.1 \times 10^{23}\ m^{-3}$

TEM



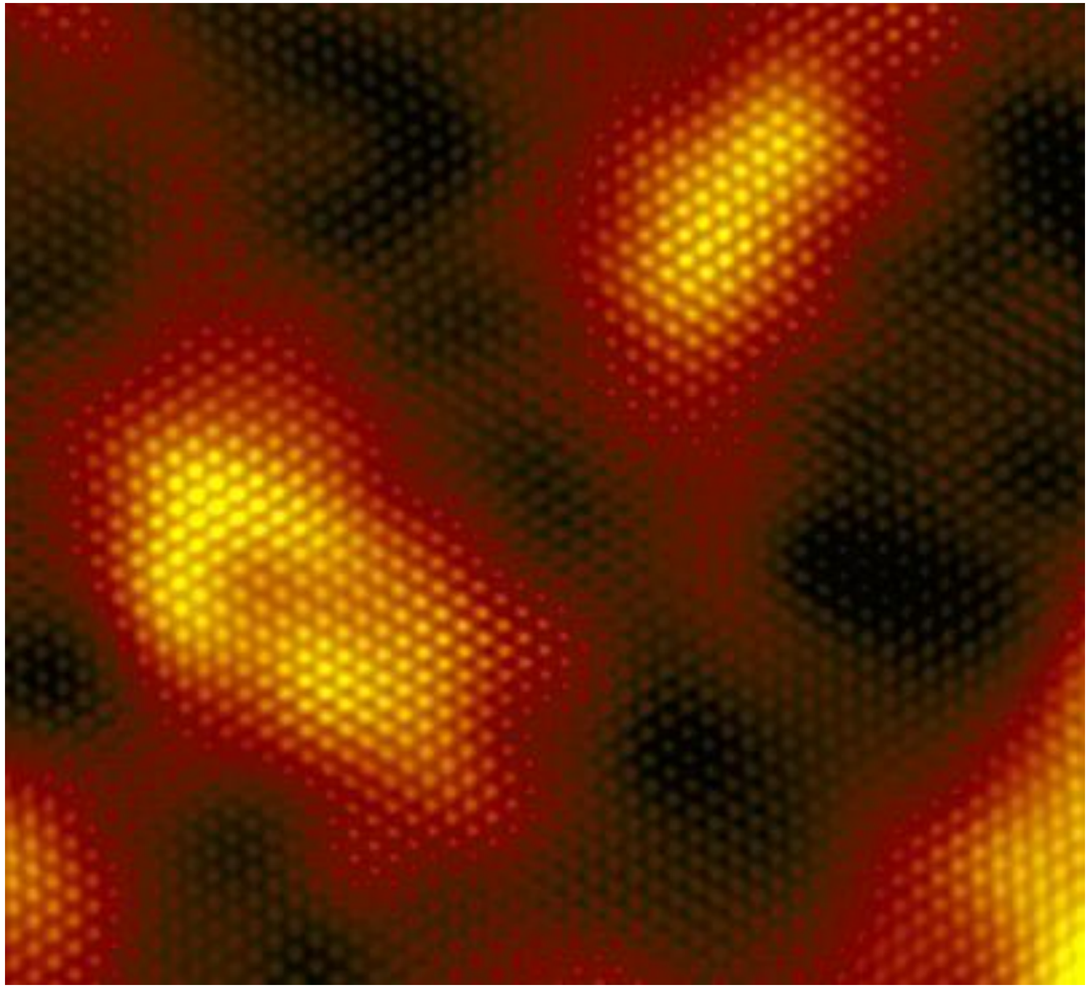


Atom Probe

Gao, Rainforth et al. **Nature**, 590 7845 (2021) 262-267

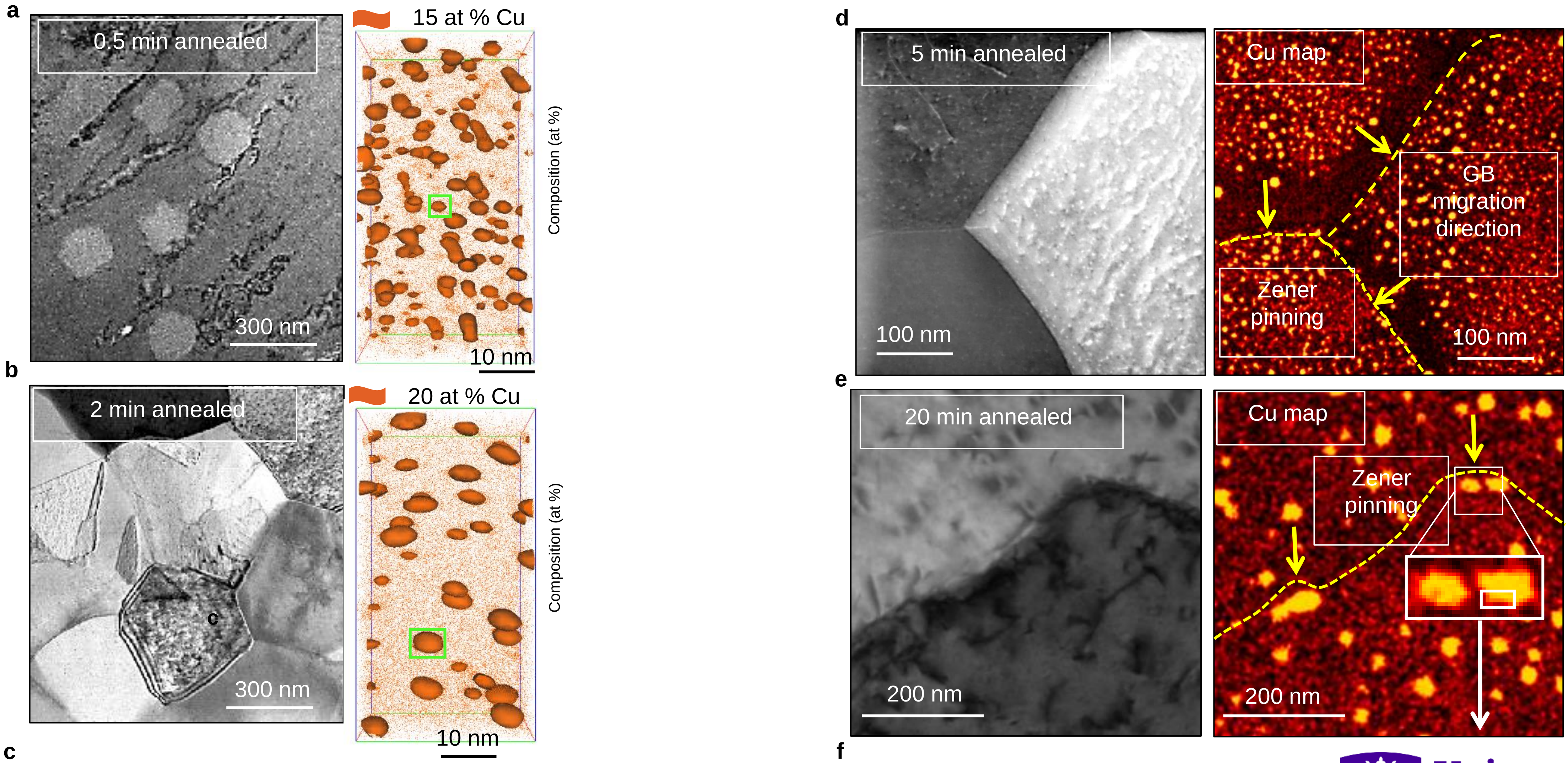
University of Sheffield

Cu-rich precipitates are fully coherent with the matrix, have the same crystal structure and a diffuse interface



Average precipitate size 4.5 nm with a number density of 6.1×10^{23} m^{-3}

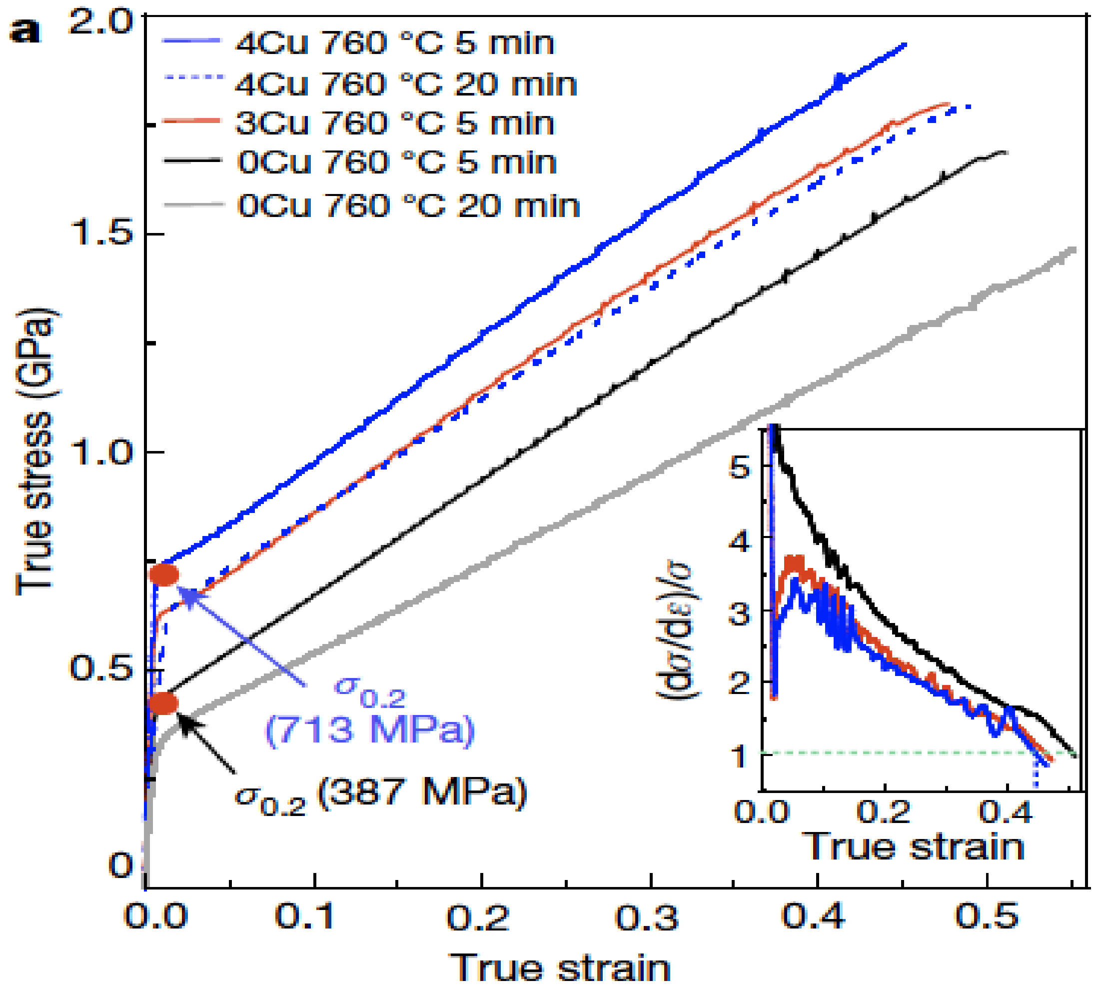
Key point: Recrystallisation occurs concurrently with precipitation. The precipitates provide Zenner pinning, preventing grain growth



Gao, Rainforth et al. **Nature**, 590 7845 (2021) 262-267

University of Sheffield

Sustained work hardening is achieved to very high strains. The Cu addition greatly increases the yield strength

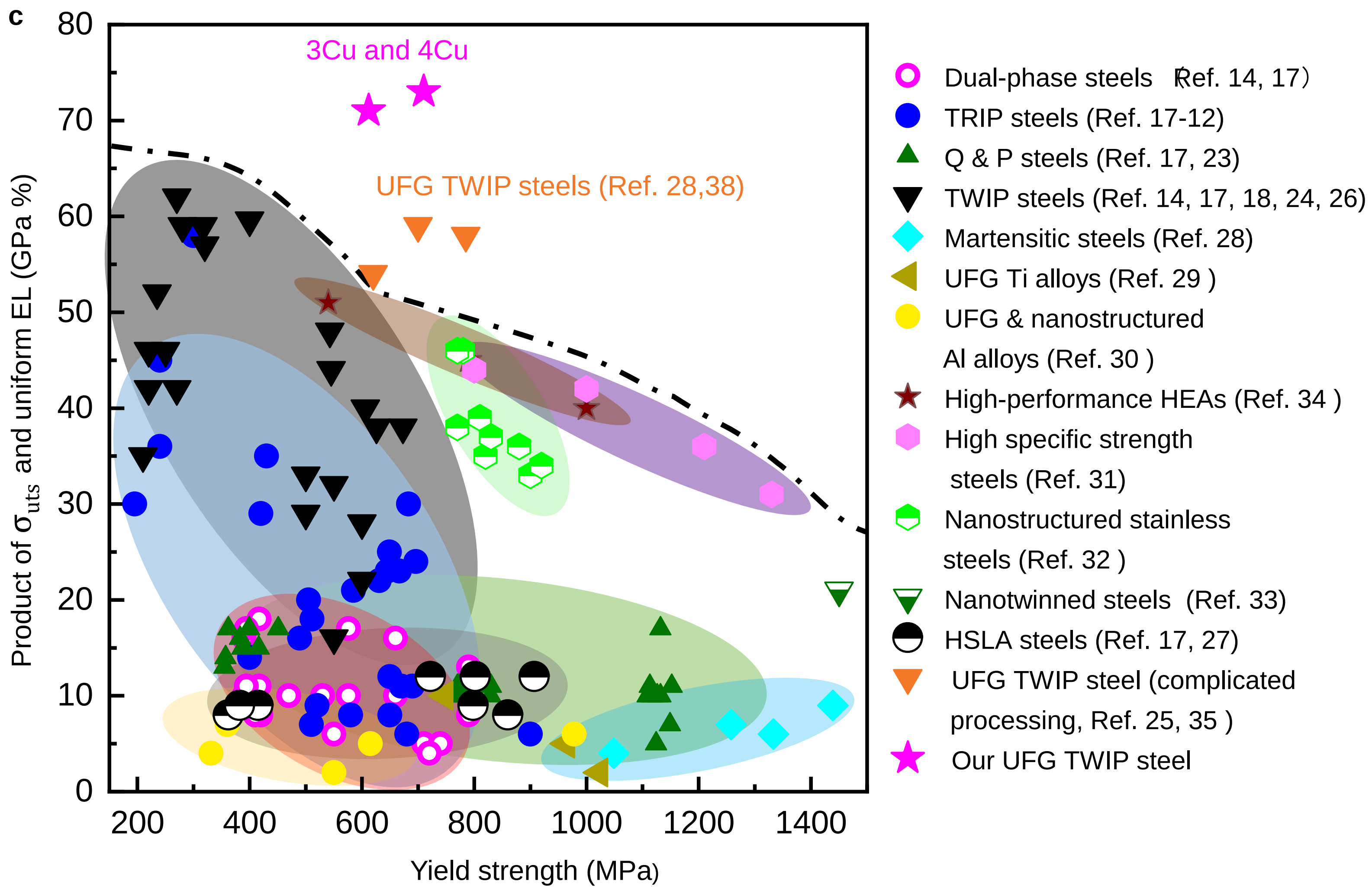


University of Sheffield

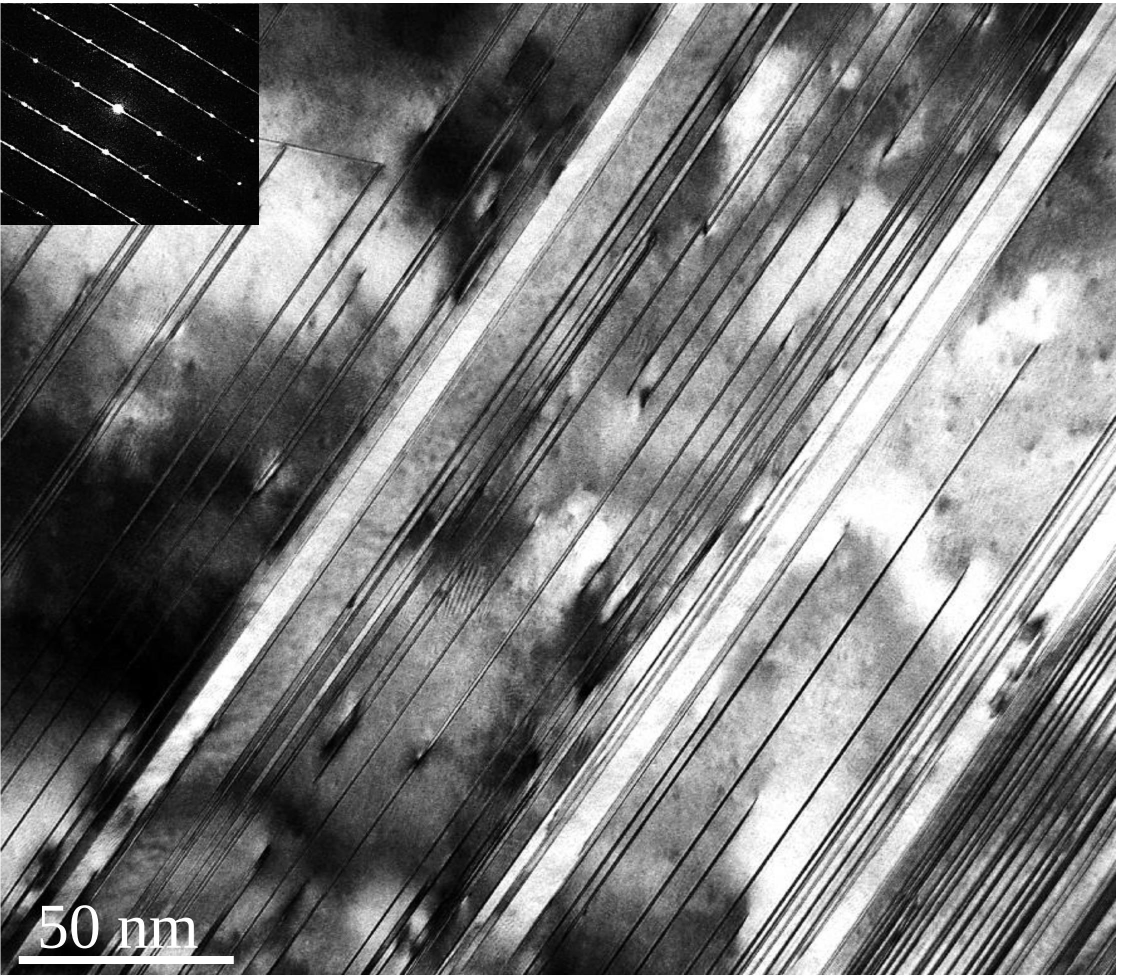
SUSTAIN Future Steel Manufacturing Research Hub

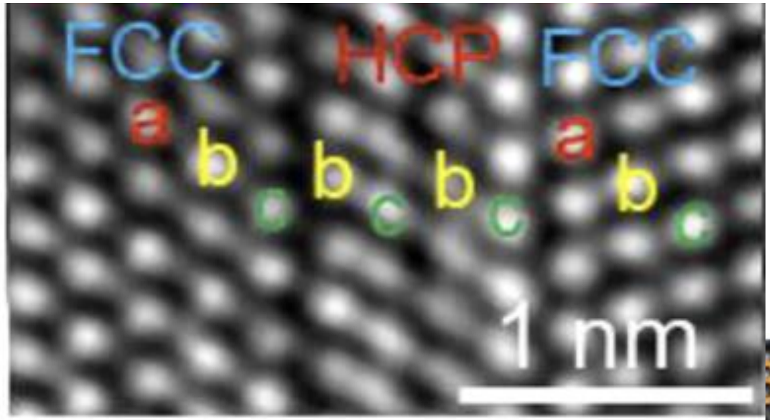
DARE

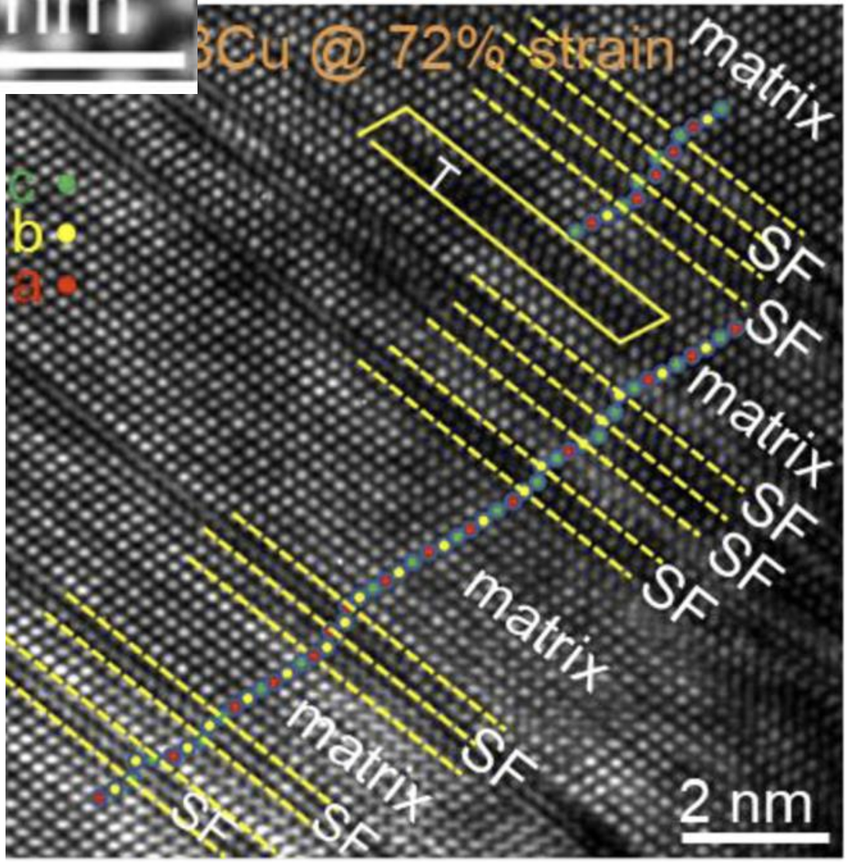
Comparison of these new steels to the current high strength metals



Deformation is by twinning (i.e. TWIP- twinning induced plasticity) and the formation of martensite (i.e. TRIP-transformation induced plasticity)

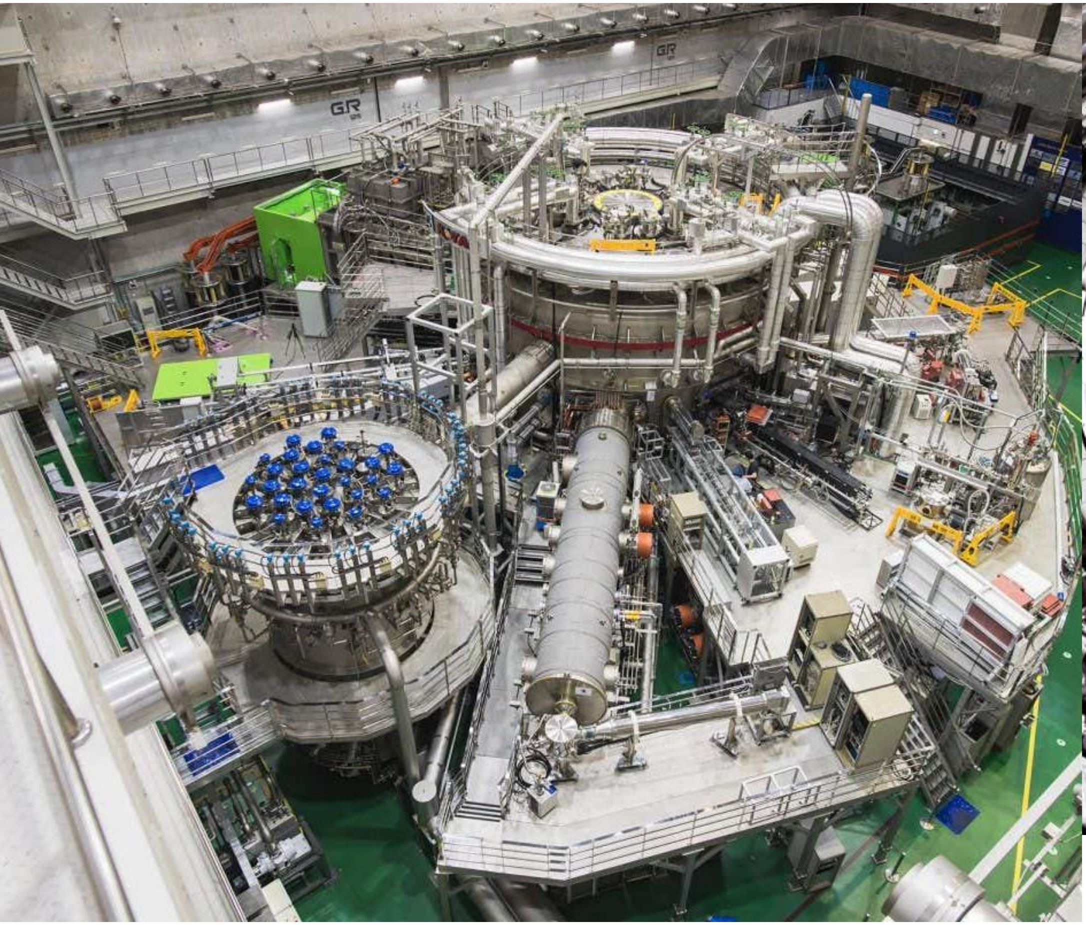


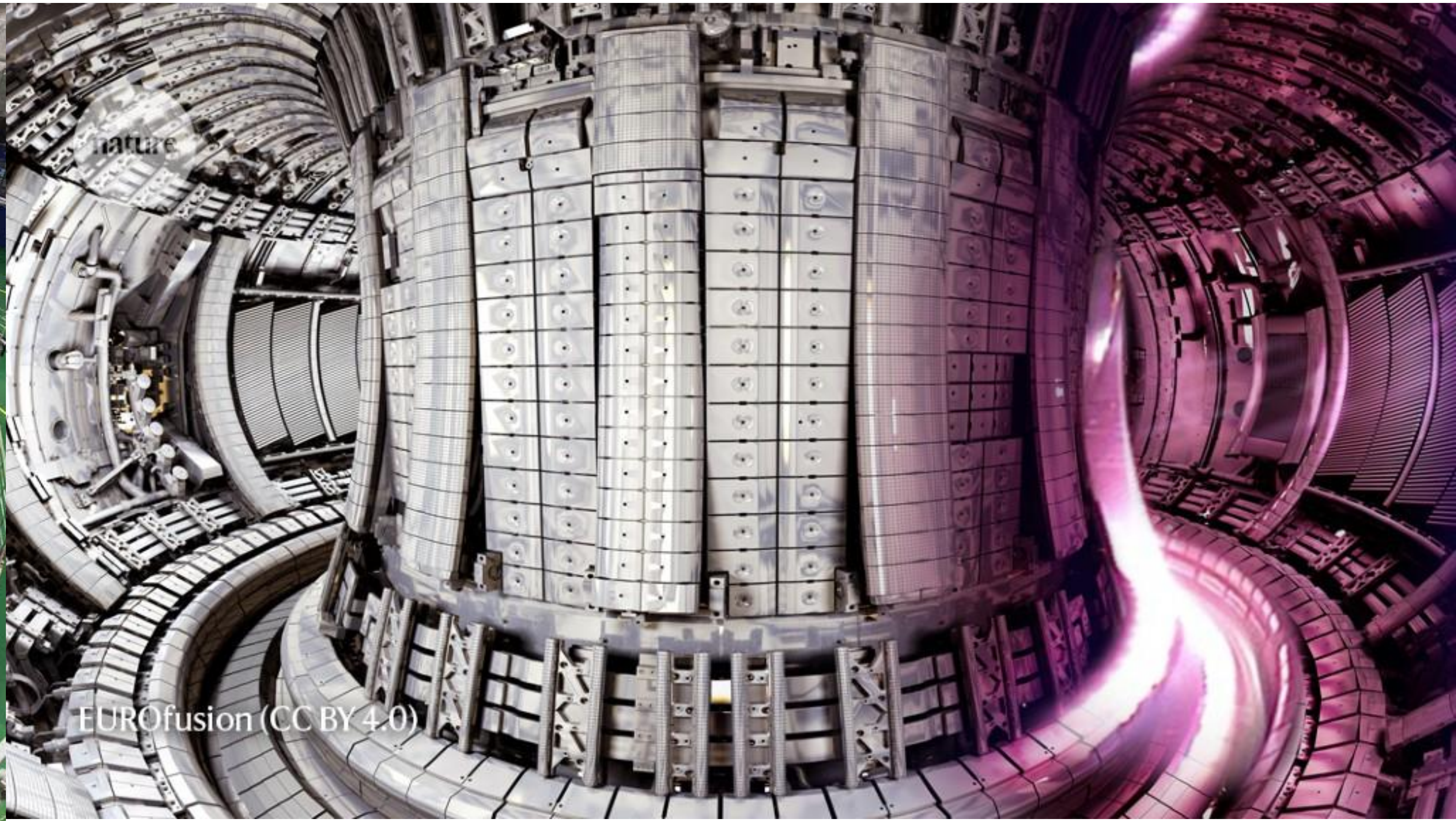




Energy supply

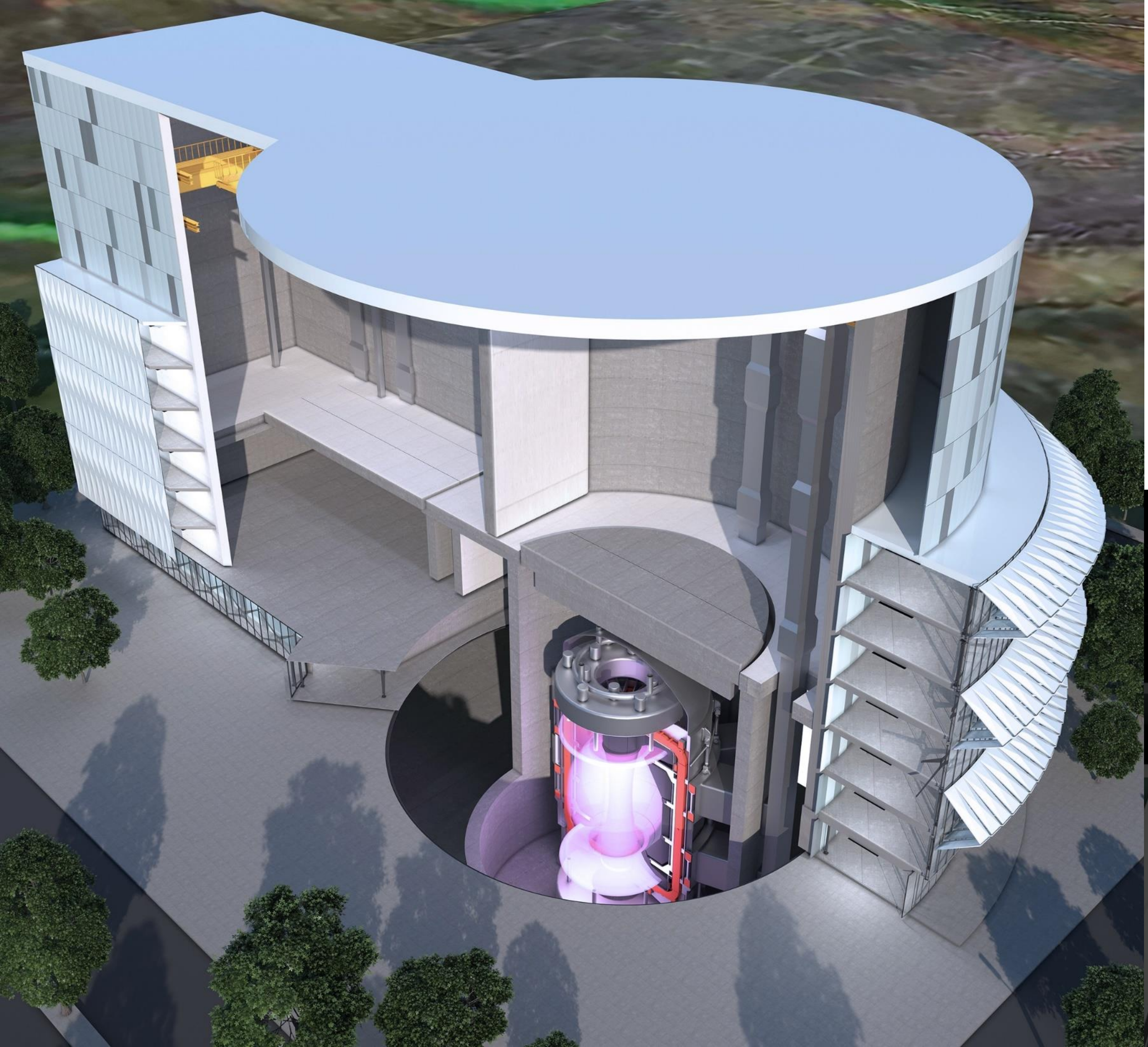
Next generation reduced activation ferrite/martensite steels for the blanket wall of fusion reactors





University of Sheffield

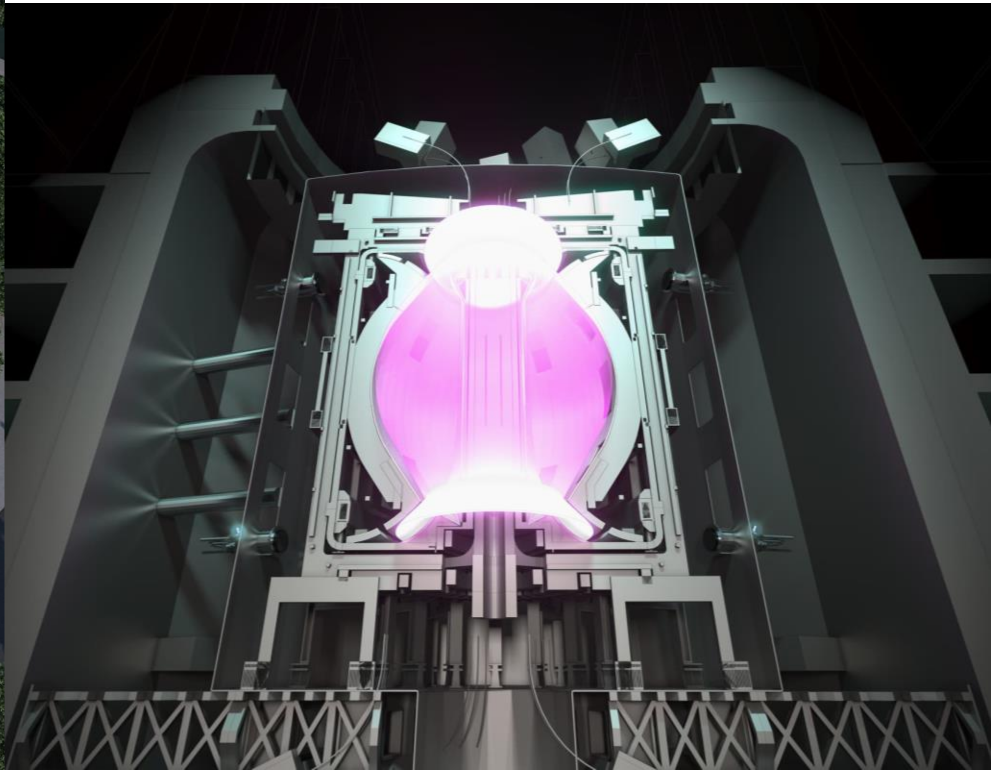
UK Atomic Energy Authority



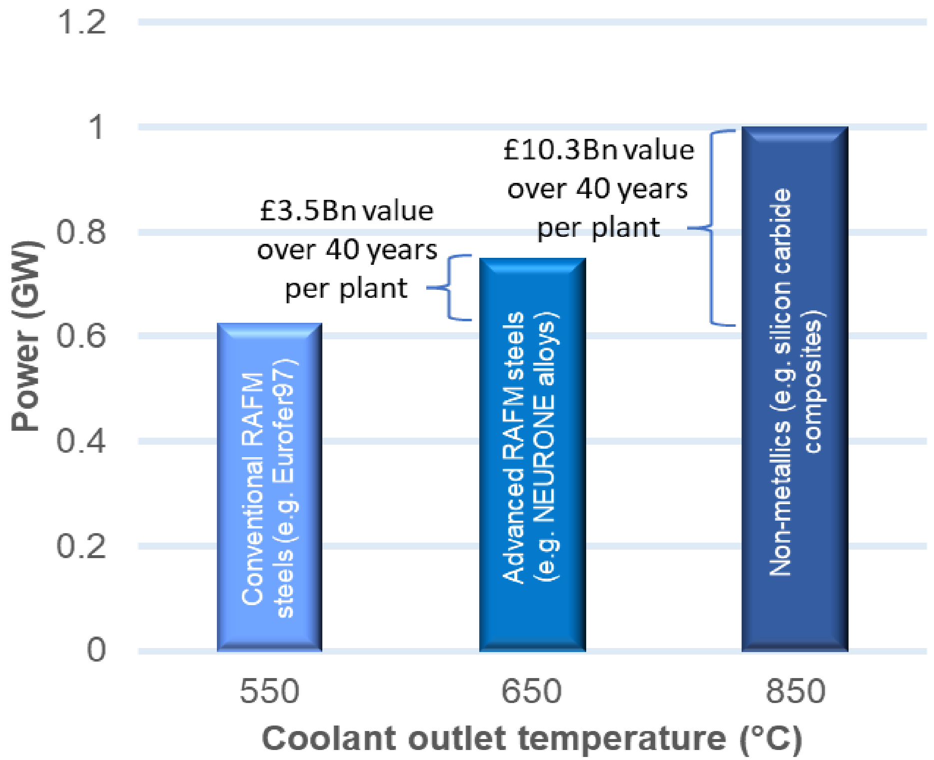
Spherical Tokomak for Energy Production (STEP)

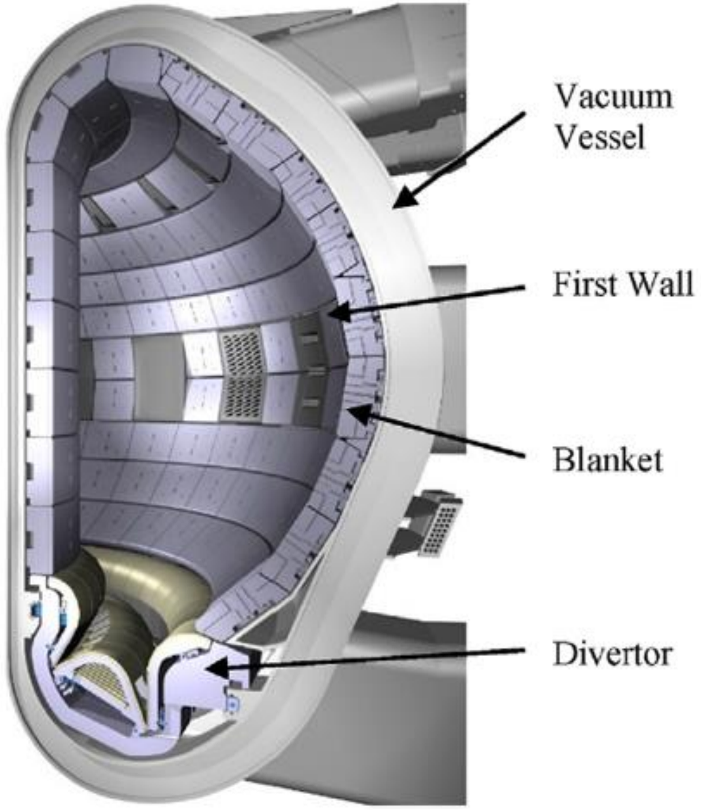
Concept design: **2028**

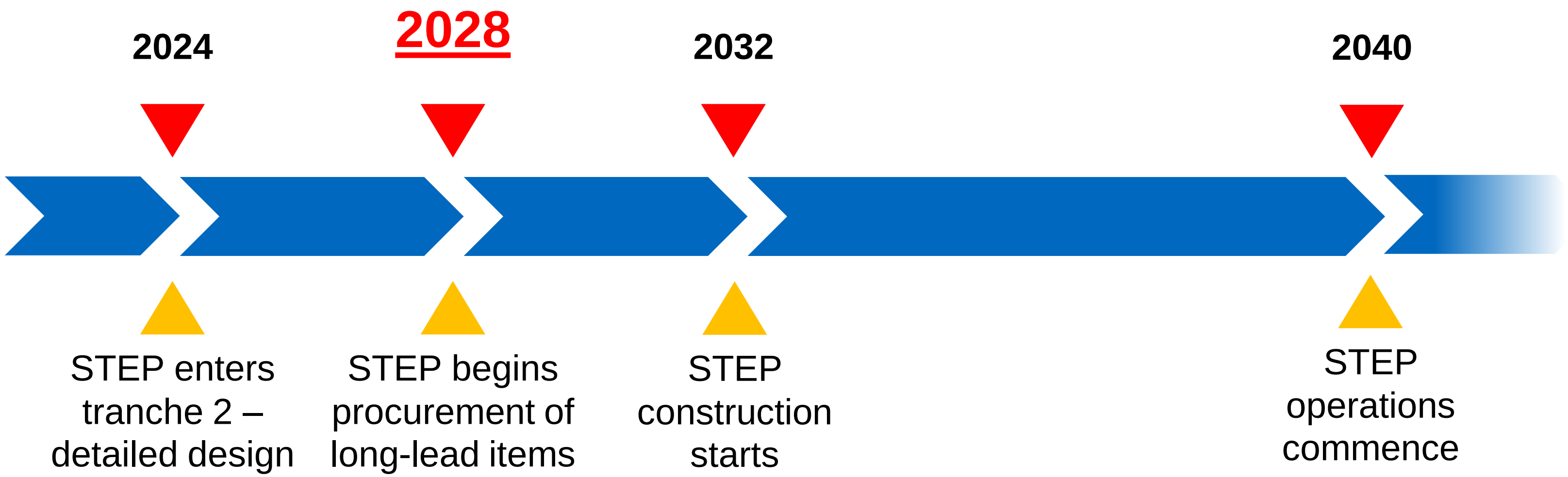
Prototype construction: **2040!**



STEP: The need for new steels



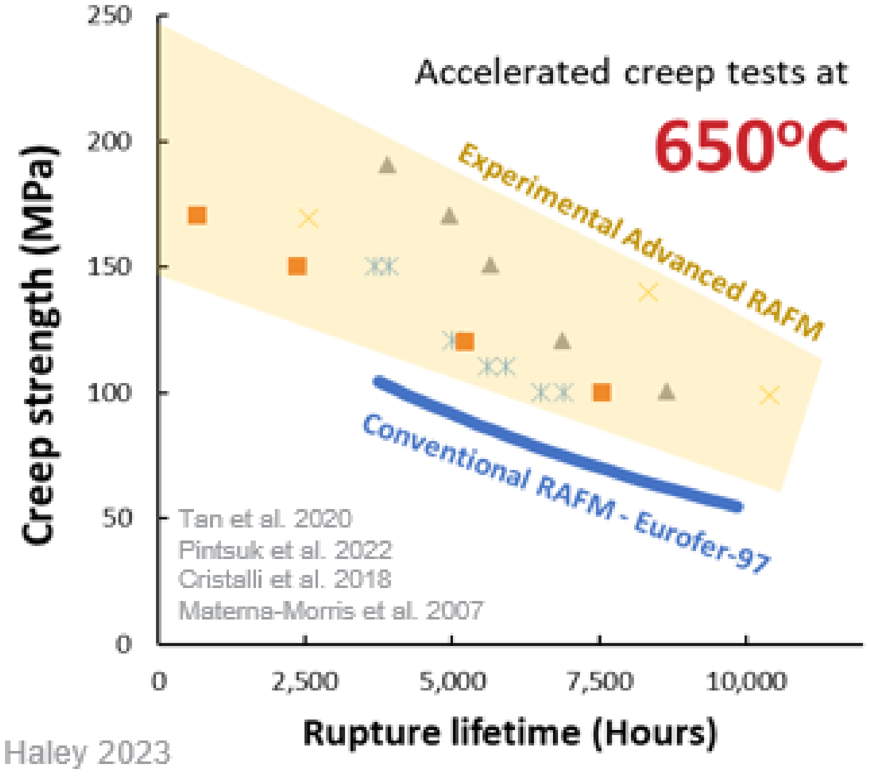




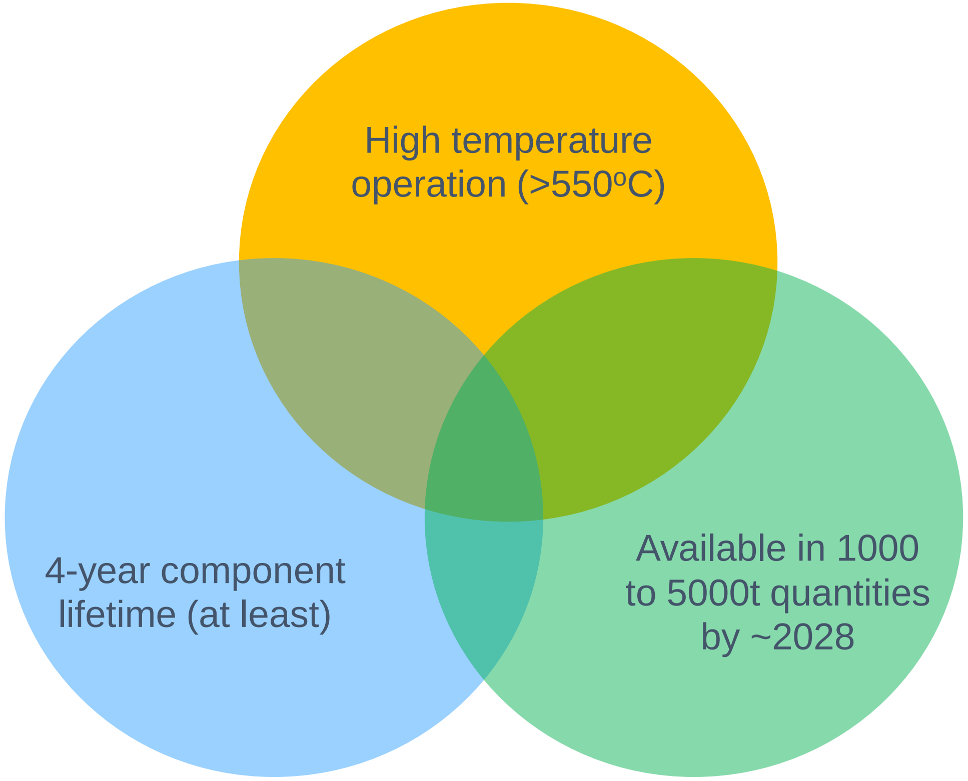
University of Sheffield

UK Atomic Energy Authority

STEP: The need for new steels



Haley 2023



University of Sheffield

UK Atomic Energy Authority

UK: The first Eurofer97 steel continuously cast at MPI, and cast and forged at Sheffield Forgemasters

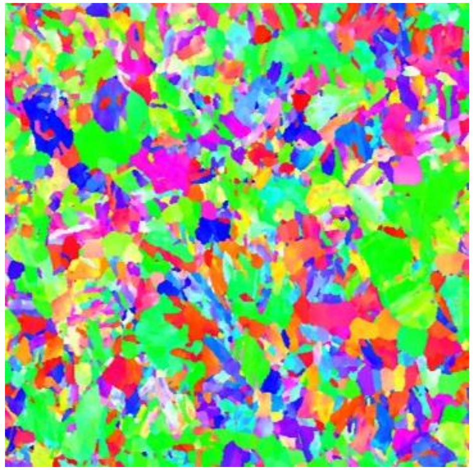
University of Sheffield

SHEFFIELD FORGEMASTERS

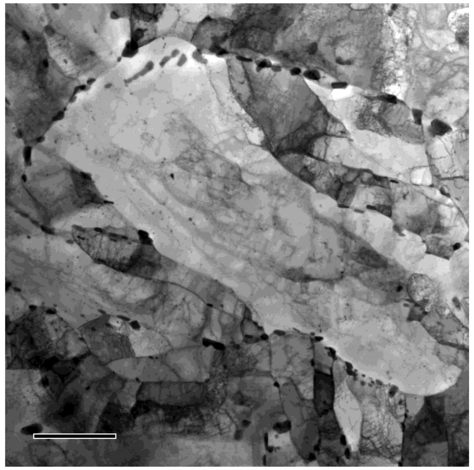
Materials Processing Institute

UK Atomic Energy Authority

How to achieve these improved properties at commercial scale?

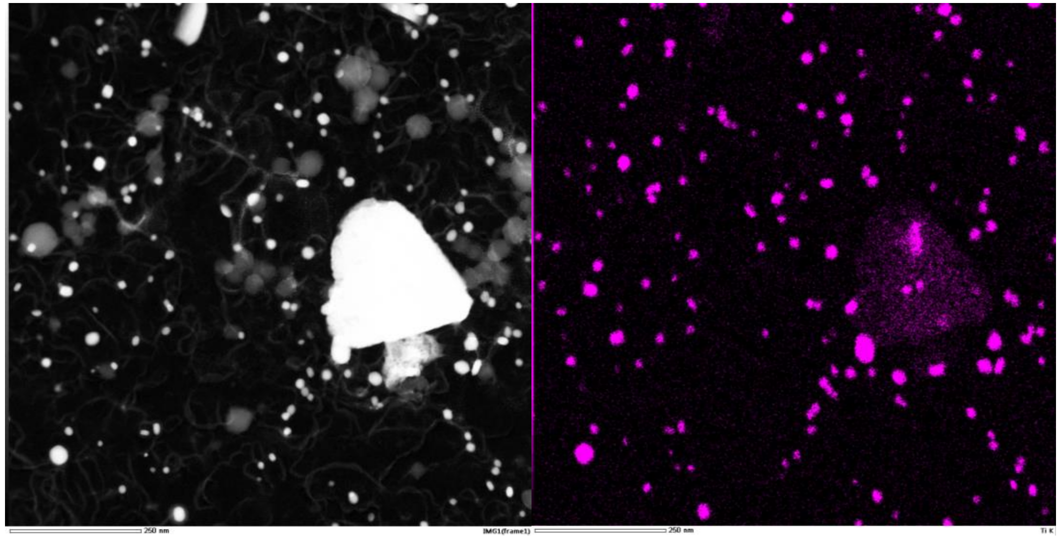


- Reduce grain size



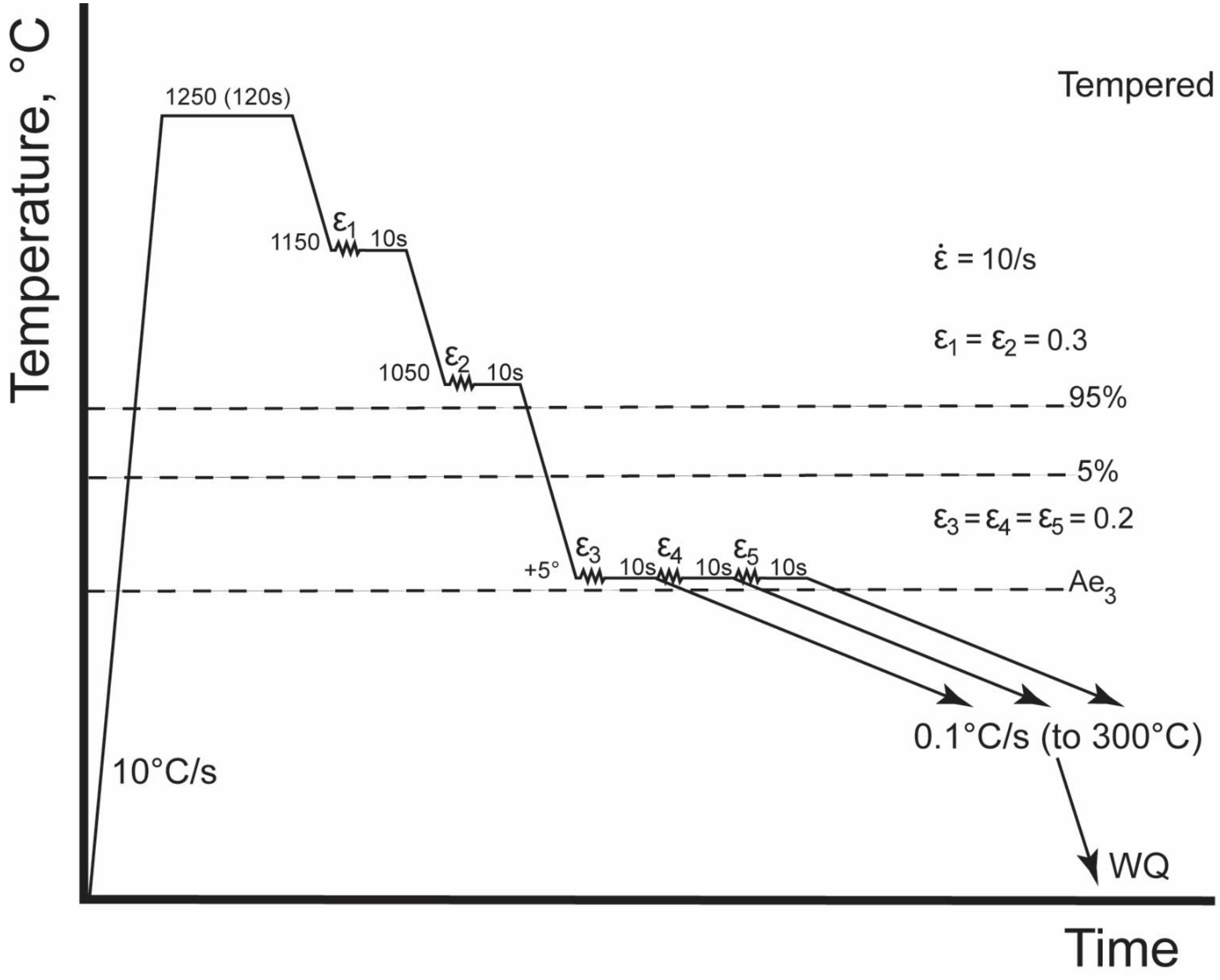
- Increase the temperature stability of carbides/carbonitrides

- Refine the size of the carbides/carbonitrides



University of Sheffield

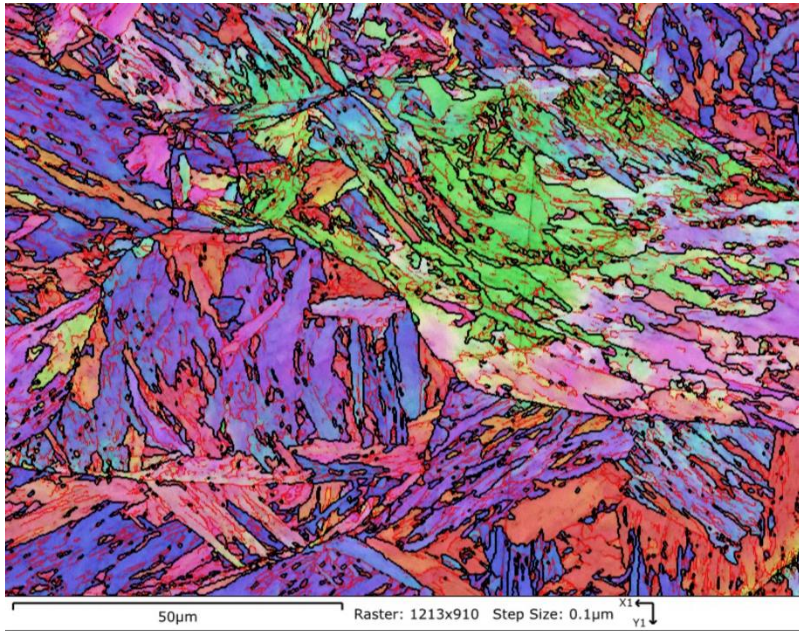
TMP Schedule to suppress recrystallisation of the austenite in the finishing deformations



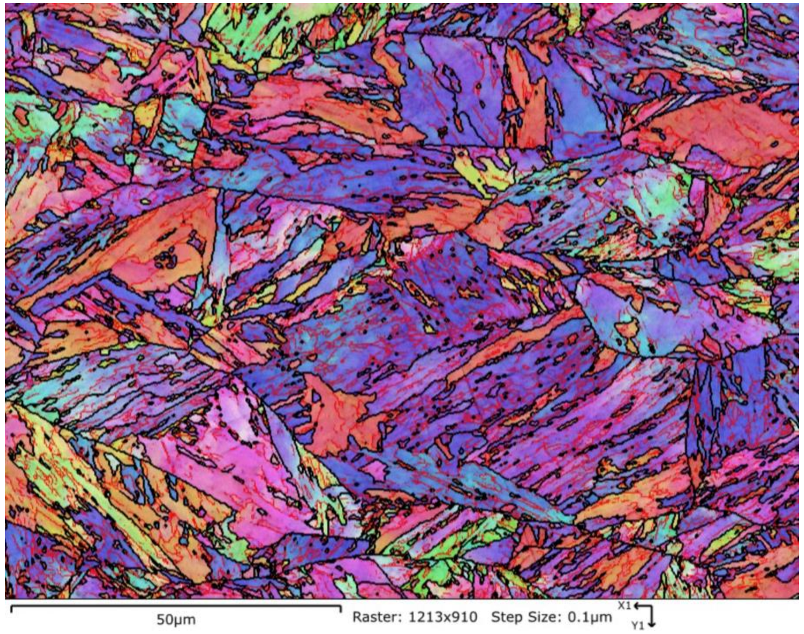
University of Sheffield

UK Atomic Energy Authority

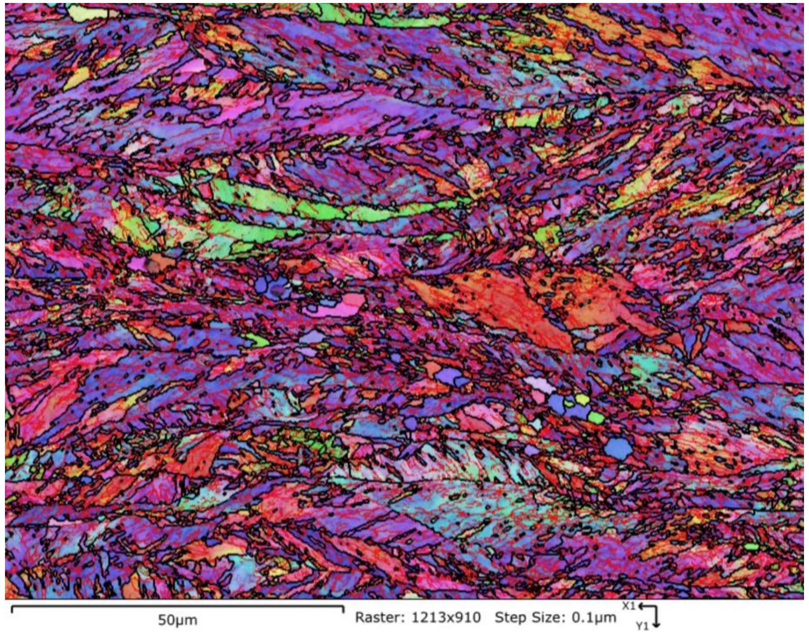
Generates a microstructure of elongated unrecrystallised austenite with some dynamic recrystallisation



Pass 1
ε = 0.2



Pass 2
ε = 0.4



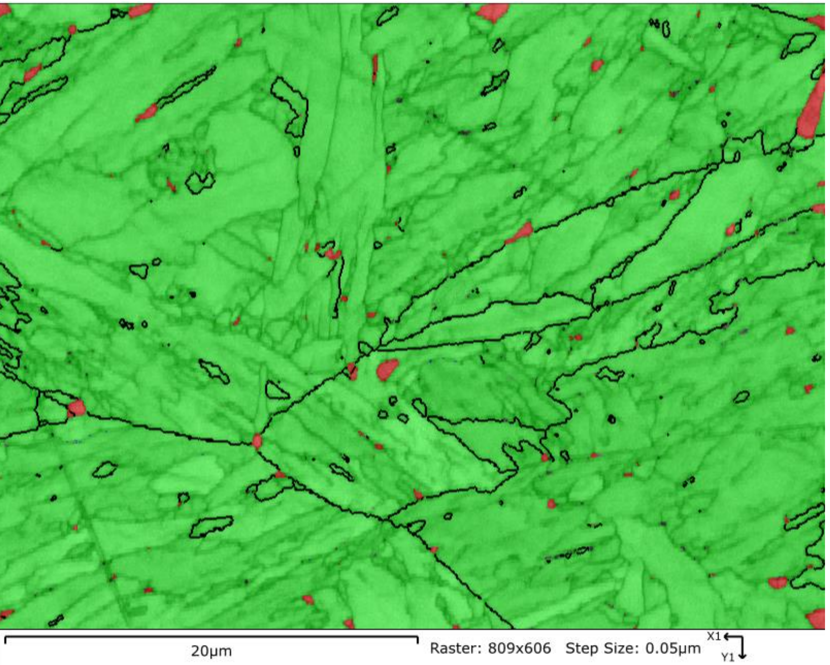
Pass 3
ε = 0.6

Deformation temperature = 877°C

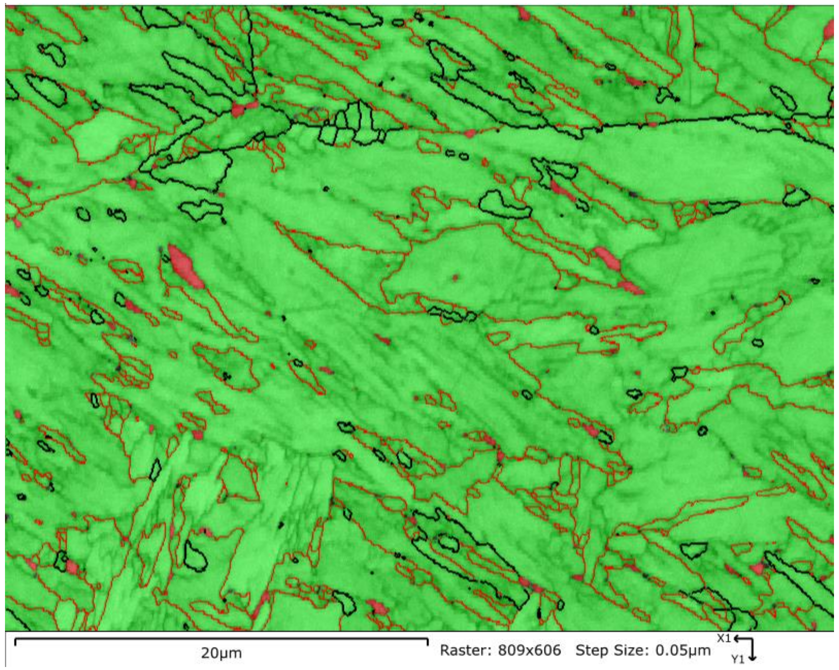
University of Sheffield

UK Atomic Energy Authority

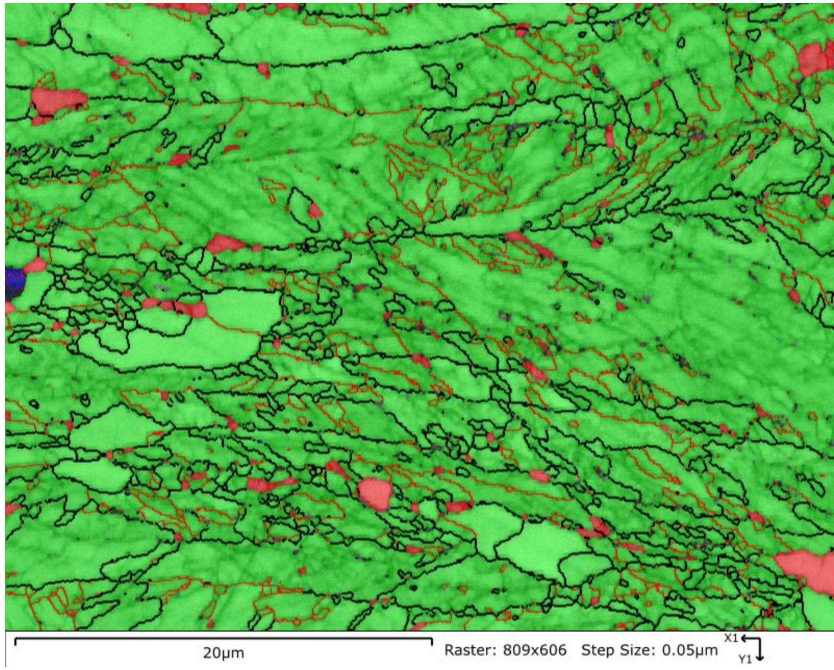
Reconstruction of the austenite structure



Pass 1 ε = 0.2



Pass 2 ε = 0.4

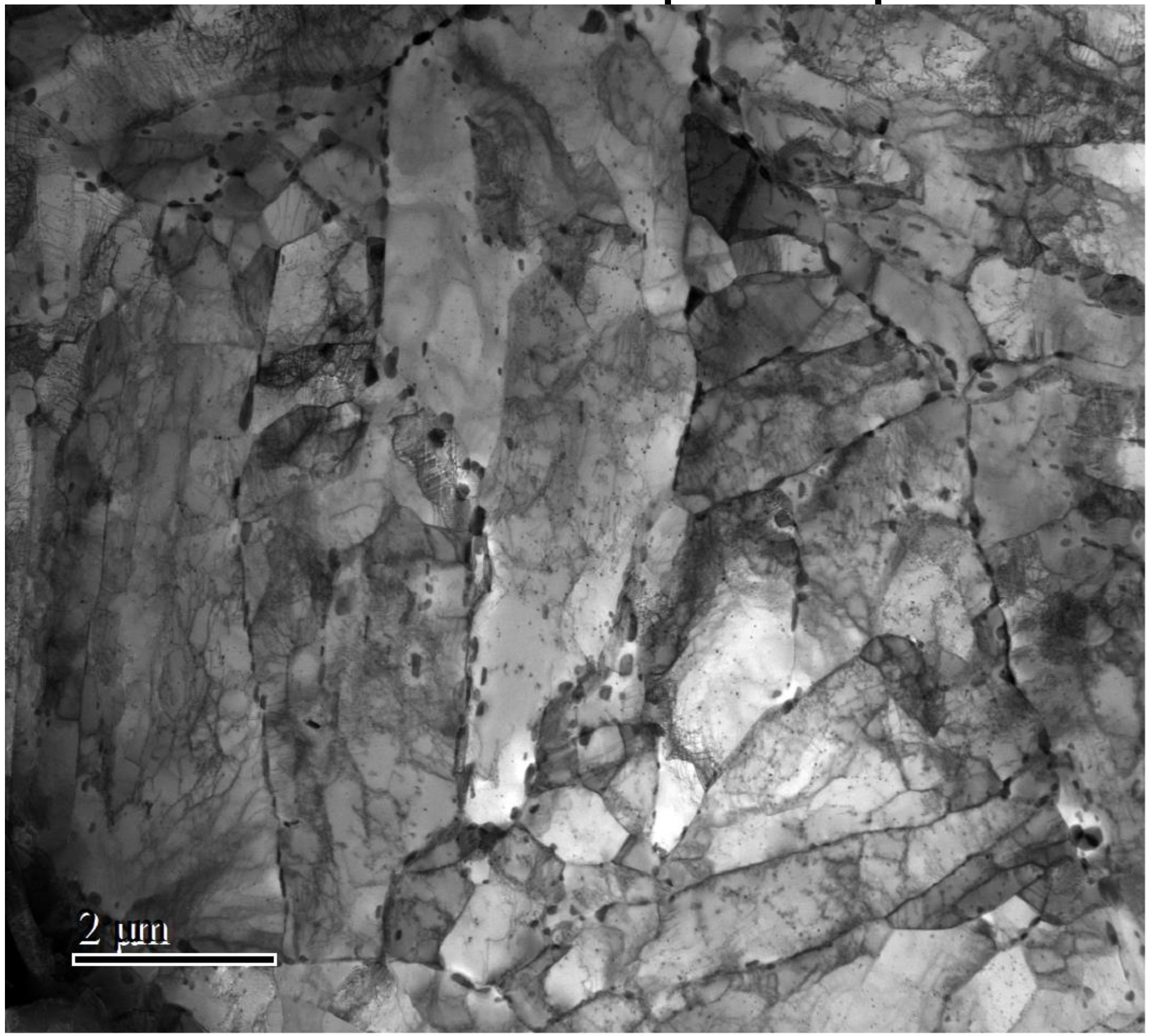


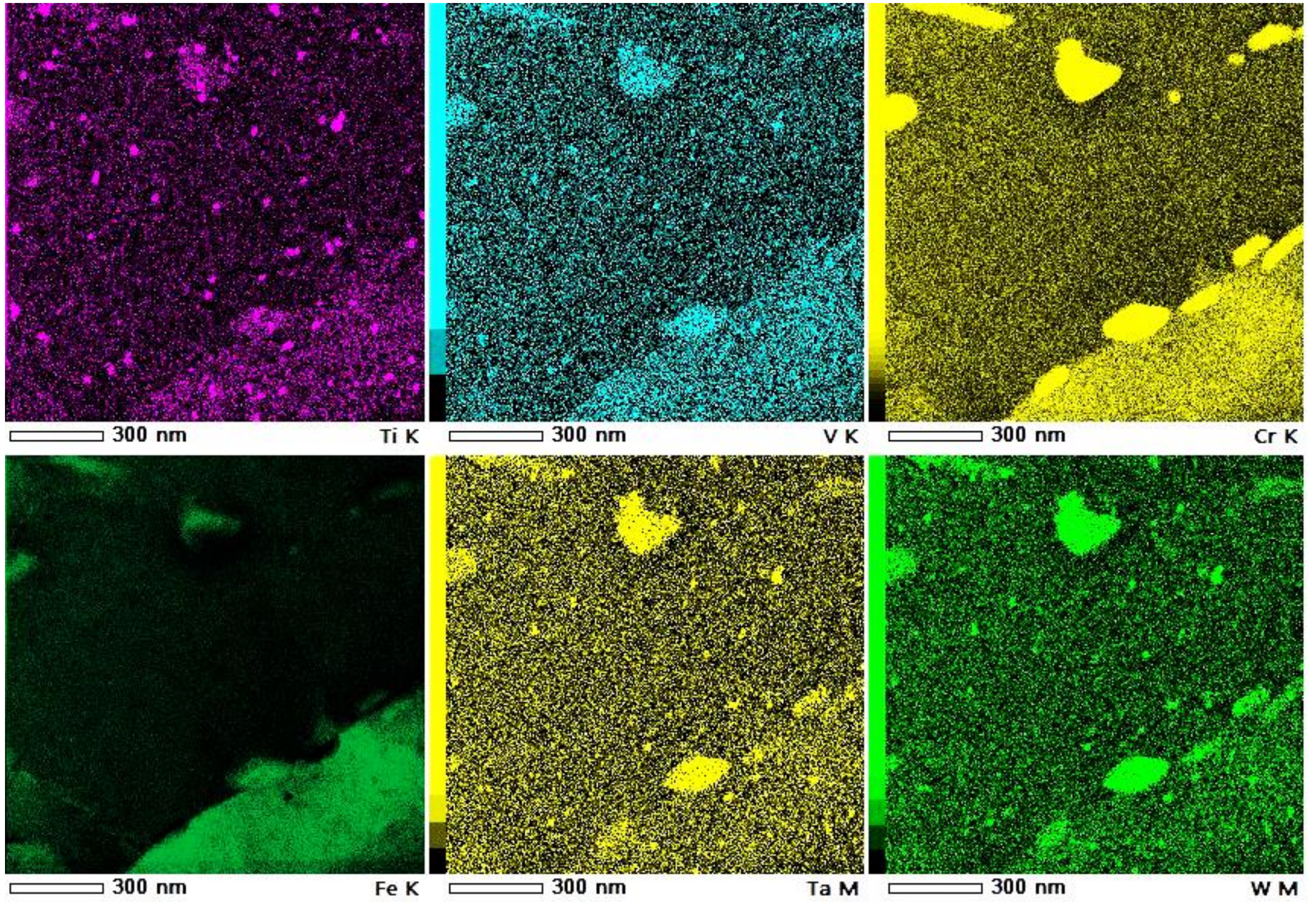
Pass 3 ε = 0.6

University of Sheffield

UK Atomic Energy Authority

Refined microstructure, with $M_{23}C_6$ clear along prior austenite and lath boundaries, but a higher fraction of MC precipitates

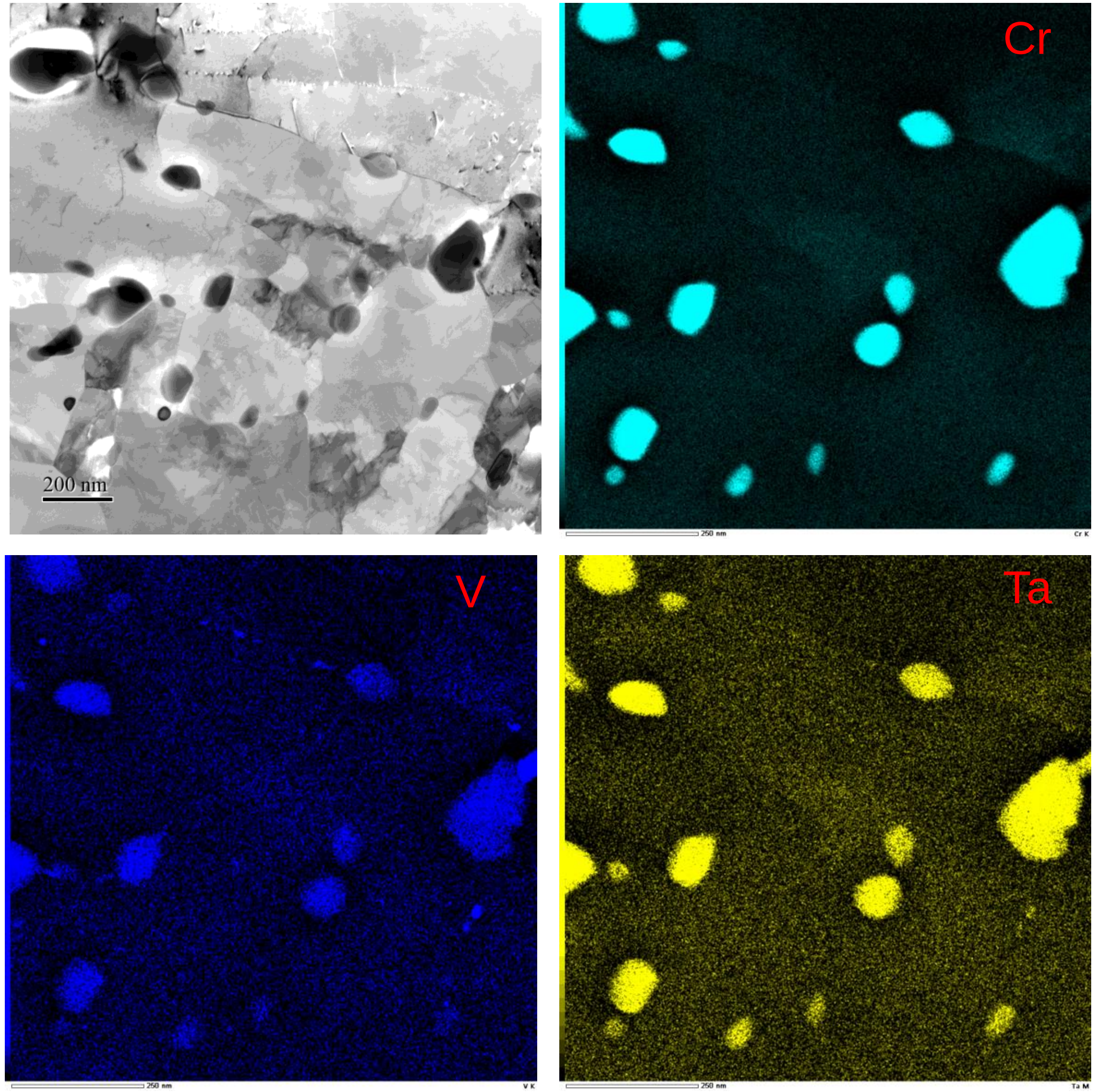




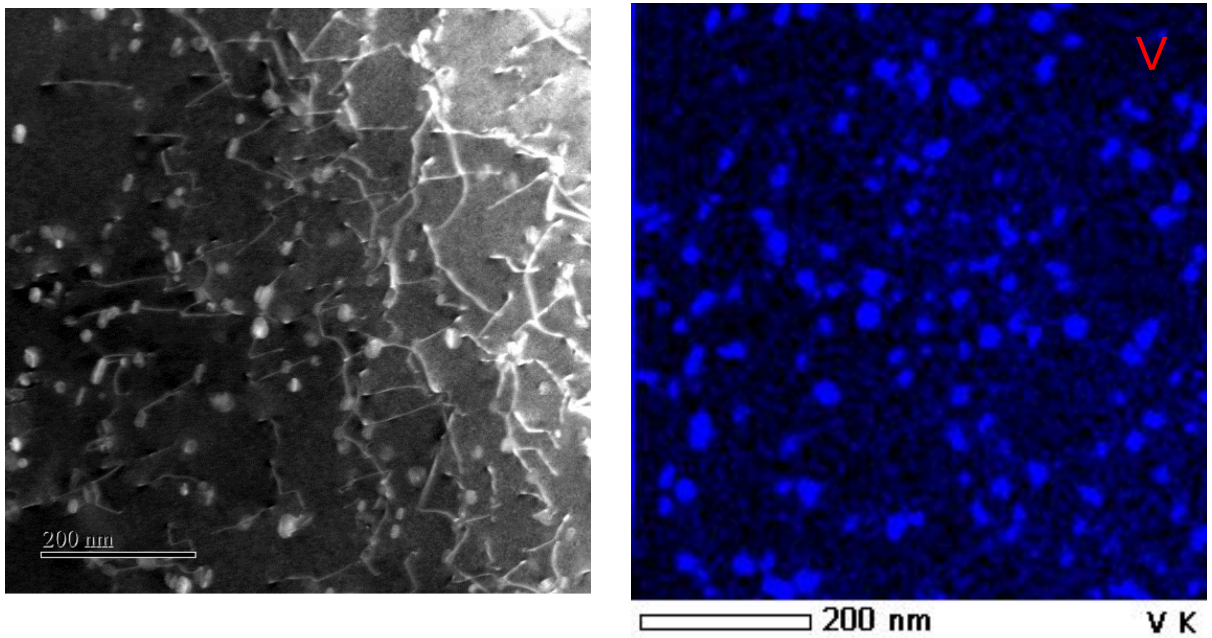
University of Sheffield

UK Atomic Energy Authority

Replacing $M_{23}C_6$ with MX and M_2X



$(Ta,Cr,V)_2C$

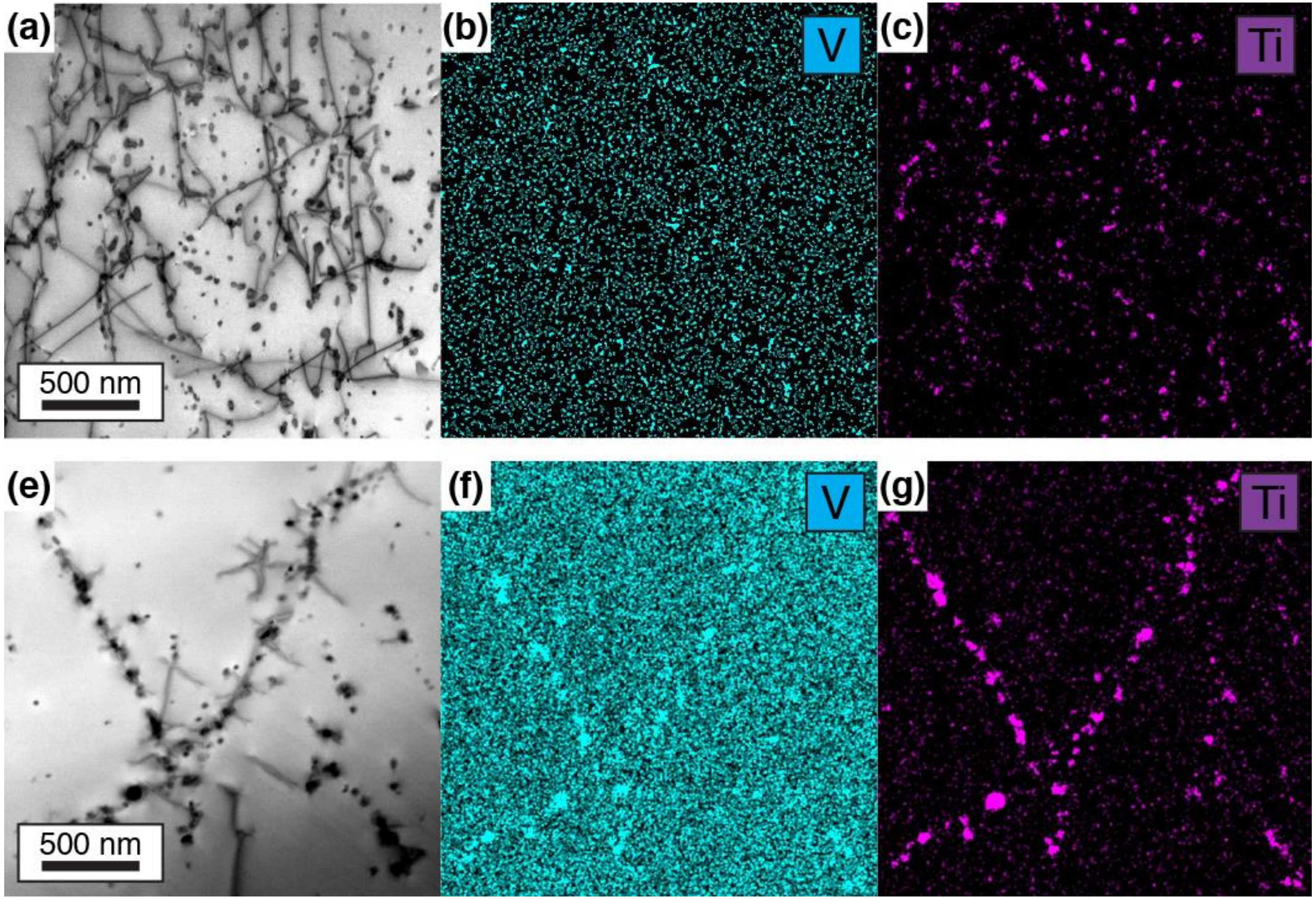


V(Ta)C,N

UK Atomic Energy Authority

University of Sheffield

The $M_{23}C_6$ is largely replaced with MX



University of Sheffield

Global conclusions

1) The inventions in steel have probably been the greatest seen in material science over the last 20 years
2) The drive towards ”green steel” is clear and attracting serious investment
3) The challenges are considerable, but the track record indicates that steel metallurgists can rise to the occasion