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RESOURCES FOR SCHOOL TEACHERS

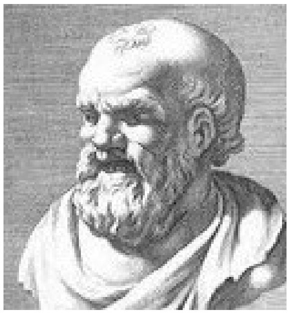
METALS, ALLOYS & METALLURGY

The *Atlas of Human Imagination* and its many pioneers have played a huge role in our understanding of materials and chemistry. One class of material, in particular, that has shaped much of human history is "the metals" – giving us the copper-based Chalcolithic Age, Bronze Age, Iron Age, as well as incredibly important modern-day developments like structural steels, silicon-based semiconductor chips, lithium batteries, nuclear materials, superconductors and rare-earth magnets.

Metallurgy, the study of metals, alloys and their processing, is one of the most fascinating, diverse and cross-disciplinary fields of research – often relying upon physics, chemistry, geology, mining, mathematics, computing, design, metrology, testing, engineering, manufacturing and art, all at the same time.

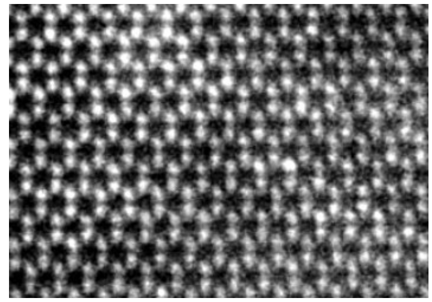
This document gives 20 examples of key pioneers selected from the *Atlas* poster; highlighting their bold discoveries and concepts; and how they link to our understanding of modern metallurgy today.

1. Democritus (400 BC)



Research Discovery

Theoretical concept of "atoms" in all materials, including metals



Democritus, also known as the "Laughing Philosopher", was an Ancient Greek thinker who was the first person to conceive that materials, like metals and alloys, were comprised of particles that could not be broken down any further. He called these indivisible particles "*atomos*", giving rise to *atomic theory*. In the modern era, we are now able to visualise individual atoms in metals using special TEM microscopes – see the author's image, right, of a magnesium-yttrium (Mg-Y) alloy with a hexagonal arrangement of atoms (white dots) on a black background.

Key breakthroughs related to:

- Concept of atoms and birth of atomic theory

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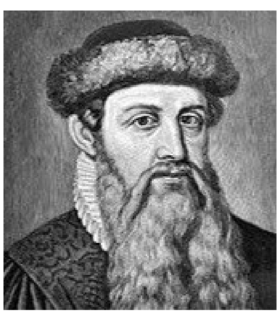
2. Johannes Gutenberg (1440)



Research Discovery

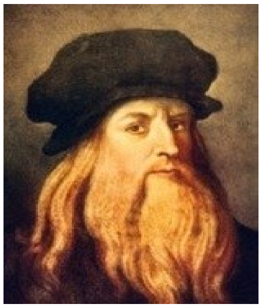
Applied metallurgy - alloy development for making harder alloys for his printing press

Gutenberg was a German engineer who is most renowned for inventing the scalable printing press. However, he was also a skilful metallurgist and carried out many experiments to find the ideal alloy for his movable type (see photo, right). Crucially, he discovered that adding the semi-metal antimony (Sb) into a mixture of lead-tin (Pb-Sn) made the alloy very hard, sharp-edged, wear-resistant and durable – exactly what he wanted for his press. *Functional alloy design*, almost 600 years ago!

Key breakthroughs related to:

- Lead–tin–antimony (Pb-Sn-Sb) alloys for movable type
- Precision casting, hardness control, melt behaviour (all relevant to solders today)

3. Leonardo Da Vinci (1510)



Research Discovery

Engineering metallurgy, for both military and artistic purposes

Leonardo Da Vinci was an Italian polymath who had many engineering projects in his lifetime. Many of those projects involved large-scale metallic structures, such as cannons and weapons, but also beautiful *bronze* (copper-tin) statues, like the cast horse statue shown right. In his notebooks, Da Vinci also showed awareness of how materials fail due to wear and metal fatigue.

Key breakthroughs related to:

- Casting and forging of alloys for armour, weapons, statues and jewellery
- Empirical understanding of metal fatigue, wear and material strengths

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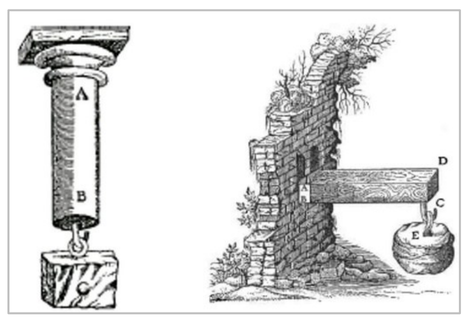
4. Galileo Galilei (1609)

Research Discovery

Physical metallurgy and mechanical properties, such as strength and stiffness



While Galileo is best known for his work on telescopes, astronomy and gravity, he was also very interested in the properties of materials. He devised several thought experiments and practical quantitative tests (see image, right) to better understand the strength and stiffness of different materials. These groundbreaking insights led to the birth of strength-of-materials science, inspiring others like Robert Hooke who further studied elasticity of materials (i.e. *Hooke's law*).

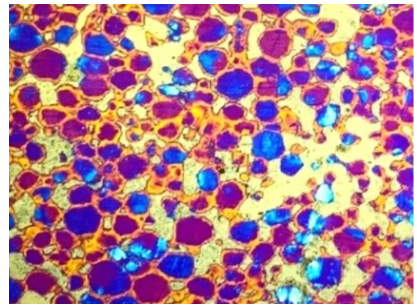
Key breakthroughs related to:

- Strength of metal wires and rods
- Founder of strength-of-materials science

5. Antonie van Leeuwenhoek (1674)

Research Discovery

Practical development of high-mag microscopes to visualise underlying structure in materials



The Dutchman Antonie van Leeuwenhoek invented the single-lens microscope capable of magnification up to x300 – an impressive performance due to his skilful preparation and polishing of the glass lenses. These optical microscopes were then used by him and others (notably Hooke) to reveal structures at the microscopic level. Today, amazing microstructures in metal alloys can be visualised, such as the author's colour image (see right) of a titanium-zirconium alloy (Ti-Zr).

Key breakthroughs related to:

- Invention and development of high-magnification microscopes (x300 mag)
- Use of microscopes to open up and visualise the microscopic world

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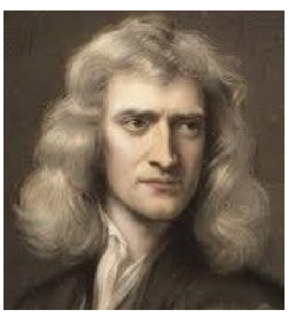
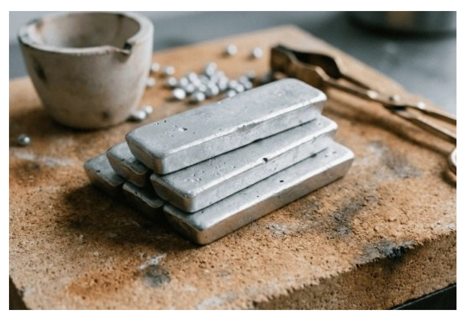
6. Sir Isaac Newton (1686)



Research Discovery

Engineering metallurgy, alloy design and eutectics



Sir Isaac Newton worked extensively on optics for many years, and for this research he needed low-melting-point alloys for jigs, holders and sealing. He researched and invented his own alloys, which are still called *Newton's Metal* today (see photo, right). Sadly, he also worked with mercury amalgams, which were highly toxic and caused him serious health problems during his career.

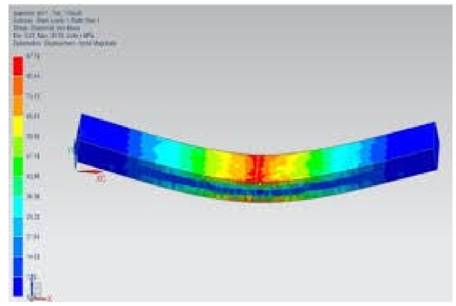
Key breakthroughs related to:

- Low melting point alloy called *Newton's Metal* (50% Bi, 31% Pb, 19% Sn, melting at 97°C)
- Early eutectic behaviour for optical applications

7. Leonhard Euler (1745)

<u>Research Discovery</u>

The mathematics of stresses, buckling and deformation of metals



Leonhard Euler was a Swiss mathematician, who worked on the mathematics of metal deformation. While not a metallurgist in the strict sense, he had phenomenal insight and discovered how metals *deform and fail under stress*, like column buckling and bending (see image, right). Similar to Galileo above, Euler's contribution is still felt today whenever engineers use finite element analysis (FEA) to simulate metal rolling, bending, extrusion, wire drawing or forging.

Key breakthroughs related to:

- Mathematical equations for buckling, stress and elasticity, still applicable today
- Foundational maths for finite element analysis (FEA), widely used in industry

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8. Antoine-Laurent Lavoisier (1774)

<u>Research Discovery</u>

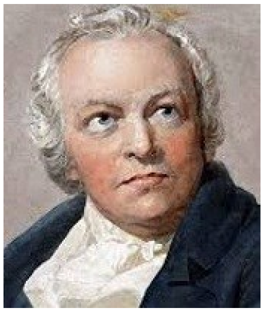
Chemical reactions of metals and extractive metallurgy with high precision

Antoine-Laurent Lavoisier was an excellent French chemist who, with the help of his wife Marie-Anne Pierrette Paulze, laid the foundation for quantitative smelting processes – or in other words – *extractive metallurgy*. These processes (see photo, right) were able to turn mineral ore into useful metals, by reduction-oxidation reactions, or *redox* in modern chemical terminology.

Key breakthroughs related to:

- Explained metal oxidation and reduction correctly; quantitative basis of smelting
- Conservation of mass in metal reactions

9. William Blake (1794)



Research Discovery

Copper forming as part of his copperplate printing technique

William Blake was a poet and artist, and although he was not formally trained as a metallurgist or scientist, he nonetheless played a major role in the application of metals in the art world. From the age of 12, he was trained as a copperplate printer – a profession that demanded great skill, manual dexterity, patience and a good understanding of the copperplate itself*. Over his lifetime, he perfected his metal forming techniques and used them to illustrate all of his major poems. The image, right, is an example of his copperplate used to print the famous poem *London* in 1794.

* An interesting video of the process can be seen here: www.youtube.com/watch?v=96LUAaaPqRc

Key breakthroughs related to:

- Skilful copperplate forming to shape ‘negative’ images of an art piece
- Cross-disciplinary approach, merging metallurgy with the arts

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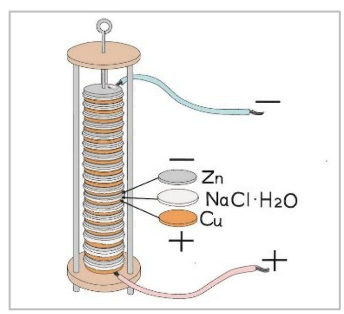
10. Alessandro Volta (1800)

Research Discovery

Electrochemistry of metals, used for making the first-ever batteries, or voltaic piles



Alessandro Volta was an Italian chemist who discovered, for the first time, that two dissimilar metals with different *electrode potentials* (e.g. copper and zinc) could create a stable voltage when separated by a layer of liquid electrolyte such as salt water (see image, right). This led to the first ever *battery* that could generate electricity with a reliable, constant flow of electrons.

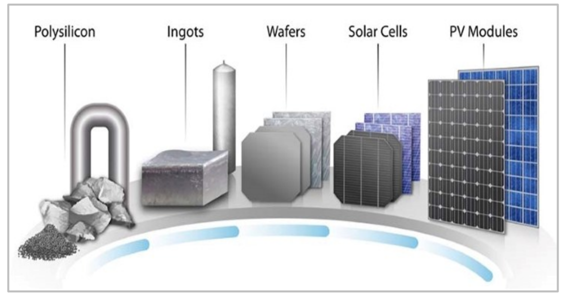
Key breakthroughs related to:

- Dissimilar metal electrodes creating stable voltage and electricity
- Foundations of electrometallurgy and corrosion science

11. Jöns Jakob Berzelius (1820)

Research Discovery

Mineralogy and metal chemistry; key concepts like atomic weights and chemical symbols

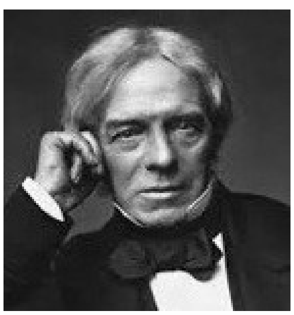


Jöns Jakob Berzelius was a Swedish chemist and metallurgist who dedicated his whole career to discovering new elements, minerals, compounds and alloys. He is credited with the discovery and isolation of several *metallic and semi-metallic elements* (Si, Se, Ce, Th), as well as a whole host of discoveries in the field of 'rare earth metals'. These are now key materials for the green transition, for example: silicon solar cells (see image, right) and rare-earth magnets for wind turbines.

Key breakthroughs related to:

- Isolation and characterisation of metallic elements, from mineral ores
- Key chemical concepts and notation essential to metals, compounds and reactions

12. Michael Faraday (1831)



Research Discovery

Electro-metallurgy, physical metallurgy and magnetism

Michael Faraday was a British scientist who devoted his long career to physics and chemistry. Trained by Humphry Davy, Faraday was exposed to many new elements, including the alkali and alkaline metals. He also studied steel and bronze alloys (see photo, right), as well as their metal purity. After his discovery of electromagnetic induction, Faraday extensively investigated *magnetism* in iron and the *electrical conductivity* of copper, laying the basis for physical metallurgy. His work on *electrolysis* and electro-metallurgy remains foundational to this day.

Key breakthroughs related to:

- Electrical conductivity and magnetic properties of metals
- Electrolysis, electroplating, steel and bronze alloys, metal purity

13. James Prescott Joule (1843)

Research Discovery

Thermal and electrical behaviour of metals, Joule heating

James Prescott Joule was a British scientist who had a ‘red-hot’ impact on metallurgy because of his studies of *heat transfer*. Joule accurately quantified heat generation in metal conductors carrying electrical current (see photo, right) which then had a direct influence on technology like resistive heating elements and industrial furnaces. He also discovered *magnetostriction* in iron, whereby a piece of iron changes length as it is magnetised.

Key breakthroughs related to:

- Joule heating in metal conductors; thermal effects central to metal processing
- Magnetostriction in iron, as used in sensors and actuators

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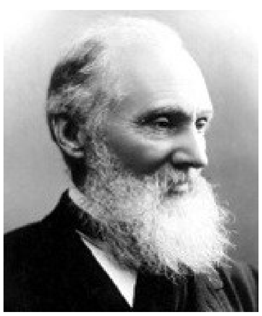
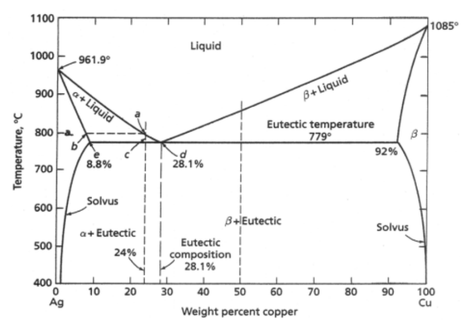
14. Lord Kelvin (1848)



Research Discovery

Thermodynamics, thermometry and phase changes

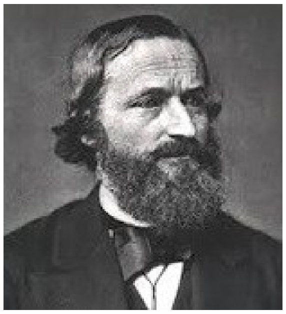


Lord Kelvin is most famous for his development of the Kelvin temperature scale, starting at 0 K or absolute zero. He also established fundamental *laws of thermodynamics* which govern heat flow and phase changes, like freezing and melting. These principles were later used by other scientists like Josiah Willard Gibbs to create phase diagrams of metal alloys (see image, right).

Key breakthroughs related to:

- Thermometry and thermodynamics in metallurgy
- Phase changes, leading to equilibrium phase diagrams of metallic alloys

15. Gustav Kirchhoff (1859)



Research Discovery

Spectroscopy as a method to measure chemical composition of materials

Gustav Kirchhoff was a German physicist who developed *spectroscopy* as a method for identifying elemental emissions, including metals. This has become one of the main non-contact methods of measuring the chemical composition of materials from afar – underpinning modern spectroscopic methods like LIBS and XRF (see photo, right), both widely used in the metallurgy and recycling industries. Kirchhoff also worked on laws for thermal radiation and electrical circuits, all essential for analytical metallurgy and temperature control.

Key breakthroughs related to:

- Spectroscopic methods to measure chemical composition of metals
- Thermal radiation, emissivity and electrical circuits

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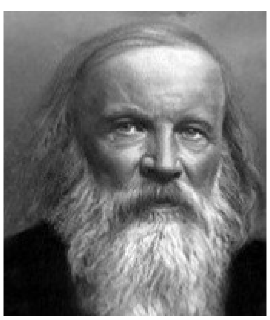
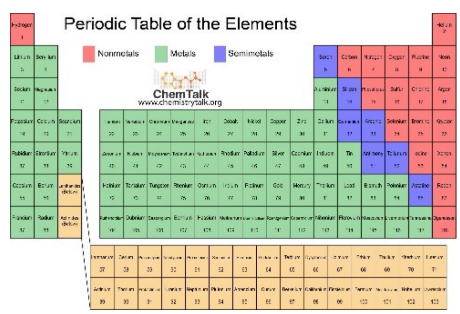
16. Dmitri Mendeleev (1869)



Research Discovery

Theoretical framework for metals and non-metals by arranging them in the Periodic Table



The Russian chemist, Dmitri Mendeleev was the first person to correctly arrange the known elements by their atomic properties and chemical behaviour, thus creating the famous *Periodic Table* in 1869 (see image, right). This framework enabled prediction of new metallic elements that were not known at that time (Ga, Sc, Ge), and also it led to a deeper understanding of alloy properties when they are mixed together. Metallurgy would be guesswork without it.

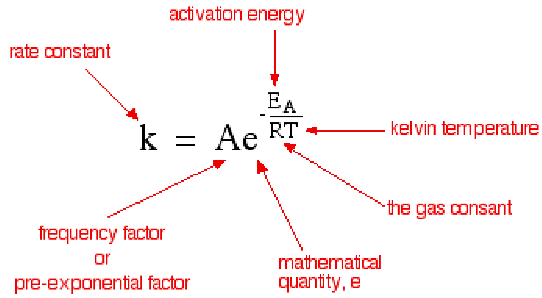
Key breakthroughs related to:

- Periodic organisation of the metallic elements, as well as non-metallic ones
- Prediction of metal properties and trends

17. Svante Arrhenius (1896)

Research Discovery

Kinetics of metal reactions, in the form of the Arrhenius equation



Svante Arrhenius was a Swedish physical scientist, best known for his work on kinetics. The famous *Arrhenius equation* (shown on the right) captures the key roles that temperature and activation energy plays in chemical reactions. This law describes many phenomena in metallurgy, including oxidation in air, corrosion in liquids, diffusion of atoms and vacancies, and creep deformation of hot materials. It is central to processes like heat treatment and material durability.

Key breakthroughs related to:

- Temperature dependence of oxidation, corrosion, diffusion, creep
- Ionic dissociation relevant to electroplating and corrosion

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18. Marie Curie (1898)

Research Discovery

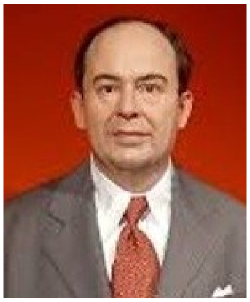
Metal isolation and the micro-scale, radio-chemical preparation of Ra and Po

Marie Curie was a French-Polish chemist who isolated metallic radium (Ra) using electrochemical techniques, for the first time. She also demonstrated the metallic character of polonium (Po), despite its extreme scarcity. These two *radioactive elements* were the first of their kind, allowing scientists to study radioactivity in more detail – and giving birth to *nuclear materials science*.

Key breakthroughs related to:

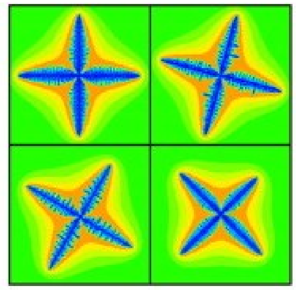
- First isolation of metallic radium
- Demonstrated metallic nature of polonium
- Electrochemical extraction methods for radioactive metals

19. John von Neumann (1945)



Research Discovery

Mathematical and computational foundations in materials modelling



John von Neumann was an exceptionally talented physicist and mathematician with great breadth. He worked in the US *Manhattan Project* and developed *computational methods* that are commonly used in metallurgy today. These methods include early forms of cellular automata and Monte Carlo models. These techniques are used to model phase transitions like dendrite growth in metals (see images, right), chemical reactions and high-strain-rate physics.

Key breakthroughs related to:

- Shock physics and equations of state for metals
- Computational methods and numerical modelling used in modern metallurgy

20. John Bardeen (1947)

Research Discovery

Semiconducting transistors and theory of superconductivity

The American John Bardeen was a solid-state physicist who developed the theoretical basis for much of the *semiconductor* industry. He co-invented the transistor, an electronic device that acts as a controlled switch inside electronic circuitry (see photo, right). These transistor devices have continued to shrink over the decades and are now at the length scale of nanometres in silicon chips. He also made theoretical advances by describing electron flow in *superconductors*.

Key breakthroughs related to:

- Semiconductors (germanium/silicon) for electrical transistors in computers
- Superconducting theory (BCS) to describe electron flow at cryogenic temperatures

Conclusion:

Together, these 20 pioneers from the *Atlas of Human Imagination* show that metallurgy is not just about metals, but about ideas – how humans learnt to measure, model, extract, shape and control matter. From early alloy design and casting in pre-history, through thermodynamics and electrochemistry, to modern computational modelling and semiconductors, progress in metals has always depended on advances across many disciplines. Today's challenges – sustainable materials, recycling, clean energy, CO_2 reduction and advanced manufacturing – continue this cross-disciplinary tradition, showing that the future of metallurgy will be shaped by *imagination* just as much as by metal itself.

David Jarvis

Some Honourable Mentions in the World of Metallurgy:

These additional 42 figures further highlight how metallurgy has been shaped by contributions from physics, chemistry, materials science and engineering across many centuries:

- Jabir ibn Hayyan (800) – father of metallurgical chemistry and smelting
- Ulfberht (900) – developer of high-carbon crucible steels for Viking swords
- Shen Kuo (1050) – documentation of iron, steelmaking and heat treatment in China
- Georgius Agricola (1555) – author of mining and metallurgy book *"De Re Metallica"*
- Robert Hooke (1670) – elasticity of materials and Hooke's law
- Humphry Davy (1810) – electrochemical isolation of reactive metals (Na, K, Ca, Mg)
- Auguste Bravais (1848) – established 14 crystal lattice types in 3D space
- Henry Bessemer (1856) – invented the Bessemer process for mass steel production
- Henry Clifton Sorby (1865) – developer of etched microstructures and metallography
- Josiah Willard Gibbs (1875) – phase rules and Gibbs free energy
- August Wöhler (1880) – metal fatigue under repeated loading, and S-N curves
- Robert Hadfield (1882) – invented high impact-toughness manganese steels
- Charles Martin Hall (1886) – inventor of electrolysis method for making pure aluminium
- Paul Héroult (1886) – inventor of electrolysis method for making pure aluminium
- Hans Goldschmidt (1895) – invented and industrialised thermite reactions
- Charles Édouard Guillaume (1896) – inventor of zero thermal expansion alloys, like invar
- Hendrik Roozeboom (1900) – systematic construction of equilibrium phase diagrams
- Alfred Wilm (1910) – inventor of precipitation-hardened aluminium alloys
- Elwood Haynes (1912) – inventor of corrosion-resistant nickel-based superalloys and stellites
- Harry Brearley (1912) – inventor of stainless steel via chromium alloying
- William Bragg (1912) – X-ray diffraction for analysing crystal phases in metals and alloys
- William Hume-Rothery (1926) – rules for explaining alloying behaviour
- Ernst Ruska (1931) – developer of first-ever practical electron microscope
- Egon Orowan (1934) – linkage between microstructure and properties, via dislocations
- Percy Bridgman (1935) – pioneered high-pressure studies of metals and alloys
- Linus Pauling (1939) – chemical bonding, crystal structure and metallic alloy bonding
- Cyril Stanley Smith (1940) – modern understanding of metal microstructure and texture
- Glenn Seaborg (1944) – actinides and nuclear metallurgy in the *Manhattan Project*
- William Kroll (1945) – invented methods for making titanium and zirconium commercially
- Alan Cottrell (1949) – discovered the interaction of dislocations with solute atoms
- Louis Néel (1950) – enabled design of magnetic alloys and permanent magnets
- David Turnbull (1952) – nucleation theory and solidification in metals
- Bernd Matthias (1960) – developed rules for finding new superconducting alloys
- John W. Cahn (1960) – modern phase transformations, like spinodal decomposition
- Paul Duwez (1960) – glass formation in amorphous, non-crystalline metals
- Peter Jost (1966) – wear, friction, lubrication and tribology of metals
- Julia Weertman (1975) – phase transformations, creep and diffusion in metals
- John Goodenough (1980) – inventor of lithium-ion batteries
- Michael Ashby (1981) – developer of material selection charts for engineering design
- Dan Schechtman (1982) – discoverer of non-repeating quasicrystals in metal alloys
- Sir Harry Bhadeshia (1990) – phase transformations and bainite/martensite in steels
- Brian Cantor (1999) – discoverer of multicomponent high-entropy alloys (HEAs)

FOR TEACHERS

Using the *Atlas of Human Imagination* in Lessons

Some Classroom Ideas about Metals and Alloys (14-18 Yrs):

1. Design Your Own Alloy (No Furnace Needed!)

Concepts: Alloying, hardness, trade-offs
Activity: Students "design" an alloy on paper by choosing base metal + different alloying elements (e.g. Fe + C + Cr). Each choice improves one property but worsens another (strength vs ductility vs corrosion)
Why it works: Feels like a game, teaches real alloy design thinking (Gutenberg → steels).

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2. The Paperclip Heat Treatment Challenge

Concepts: Work hardening, annealing, microstructure
Activity: Bend paperclips repeatedly to deliberately make them brittle, then gently heat in a flame (teacher demo) and cool to restore ductility.
Why it works: Dramatic, tactile and memorable — "the metal *heals* itself".

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3. Build a Volta Pile Battery

Concepts: Electrochemistry, dissimilar metals, voltage

Activity: Stack copper coins + zinc washers + salt-soaked paper to power an LED

Why it works: Students *see* electricity comes from metal chemistry (Volta).

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4. Corrosion Olympics

Concepts: Oxidation, galvanic corrosion

Activity: Place mild steel nails in water, salt water, vinegar, oil, and with copper wire attached

Outcome: Predict → observe → explain corrosion rates

Why it works: Rust never fails to fascinate.

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5. Crystal Formation (Salt Analogy)

Concepts: Dendrites, grain growth, microstructure
Activity: Make a salt solution (NaCl) with a small amount of starch powder, place it on a microscope slide and allow the water to evaporate. Get the students to observe the salt dendrites as they grow in real time
Link: Structural analogy to dendritic growth at the microscopic level (von Neumann)
Why it works: Visual, slow science at the micro-scale.

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6. Hooke's Law with Real Metal Wires

Concepts: Elasticity, stiffness, yield

Activity: Hang masses from thin wires (steel, copper) and measure extension

Link: Galileo → Hooke → Euler

Why it works: Turns abstract graphs into real metal behaviour.

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7. The Periodic Table Alloy Game

Concepts: Properties, trends, atomic size

Activity: Students pick elements from the Periodic Table to "build" an alloy with target properties for a certain application (e.g. magnets, or low-density electrical wire)

Constraint: Must justify choices using trends

Why it works: Makes the Periodic Table feel like a *tool*, not just a poster.

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8. Magnetism in Metals

Concepts: Ferromagnetism, domains

Activity: Compare steel, aluminium, copper with magnets; sprinkle iron filings to show field lines around a magnet

Link: Gilbert, Faraday, Joule

Why it works: Simple, visual, slightly 'magical'.

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9. Cast Without Melting: Chocolate or Wax Casting

Concepts: Casting, moulds, shrinkage
Activity: Pour melted chocolate or wax into moulds and put in the fridge; discuss defects, porosity, cooling rates.
Why it works: Safe, delicious, yet still metallurgical.

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10. Recycling Metallurgist for a Day

Concepts: Metal properties, separation, recycling
Activity: Make a mixture of paper clips, aluminium foil, copper wire strands and polystyrene balls, put them in a bucket. Get students to work out how to separate them on a conveyer belt.
Why it works: Shows students what metallurgists in the recycling industry actually *do* today.