University of Sheffield | Materials - a SUBJECT that MATTERs

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Aerospace Metallurgy

How can we make flight more sustainable?

What is Materials Science and Engineering (MSE)?

MSE is defined as an 'interdisciplinary subject, bridging the physics and chemistry of matter towards engineering applications and industrial manufacturing processes.' The programme content spans from foundations in physics and chemistry to the mechanical, electrical, magnetic, and optical properties of materials, and the design, manufacture and applications of metals, alloys, ceramics, polymers, composites, and biomaterials.

MSE continues to establish itself amongst engineering disciplines and is offered as a degree course across the UK at the Universities of Birmingham, Cambridge, Imperial College London, Leeds, Loughborough, Manchester, Oxford, Queen Mary, Sheffield and Swansea, as well as Materials Chemistry being offered at St Andrews and Glasgow.

Key Learning outcomes

- **Flight is currently not sustainable…**
  The airline industry has a goal of becoming 30 percent more energy efficient by 2050. To achieve this target the work to make jet engines more efficient is critical, even improving efficiency by just 1% would translate into avoiding 500 to 1000 tonnes of carbon dioxide for each plane every year. That's the equivalent of taking 100 to 200 cars off the roads for each plane that's designed with a better, more energy efficient engine.

- **How is materials science important to making the aerospace industry more sustainable…**
  Aerospace industry is looking into the transition to using more carbon neutral fuels and looking into the concept of fully electric or hybrid electric planes, both solutions to making the industry more sustainable. However, it is hard to make these solutions a reality with the current materials we have available to us and lots of materials we already use in service are currently unsustainable themselves!

Key Learning outcomes

What are three of the current research areas?

1. **Designing new materials** (specifically new alloys) which are able to operate in these new fuel environments and be compatible with the new fuels (such as hydrogen and SAF). It is important to design new materials to operate in these environments as the new environments will influence the materials behaviour. In particular, the mechanical properties of the alloys, as well as their resistance to corrosion and oxidation.
2. **Designing materials that are sustainable to be used from the offset.** This requires us to use elements which are not unsustainable through being scarce or sourced from areas of conflict. As well as challenging us to understand how to eliminate these problematic elements from the alloys we already use.
3. **Making the materials that we currently use last longer.** This involves looking at how we can take a material that has degraded in service, repair it and extend the lifetime of the material as a result so that it doesn't need to be replaced, scrapped or recycled. For example, we may use additive manufacturing to repair a component in service.

GCSE Chemistry topics this episode could be taught alongside…

Bonds, structure, and properties of matter (bonding and substance properties- properties of metals and alloys)	**Chemistry of the atmosphere** (causes of atmospheric pollutants- atmospheric pollutants from fuels)	**Using resources** (alloys as useful materials)

How does this episode go beyond the curriculum?

Alloys are taught and students learn about important materials properties so combine the two and they can understand why superalloys are important in the aerospace industry…

A **superalloy** (or high-performance alloy) is an alloy with the ability to operate for prolonged periods at a **high fraction of its melting point** without compromise to mechanical properties.

Superalloys are commonly classified into three major categories: nickel, iron–nickel and cobalt based alloys, all of which can be found in jet engines as well as a variety of different applications where structural integrity and **resistance to oxidising and corrosive environments** is critical.

The most important type of superalloy is the nickel-based material that contains a high concentration of chromium, aluminium, titanium, cobalt, and other alloying elements. Superalloys are used in engine components such as the high-pressure turbine blades, discs, components within the combustion chamber, afterburners and thrust reversers. **Nickel superalloys** can operate for long periods of time at temperatures of 800–1200 °C, which makes them suitable for the hottest sections of gas turbine engines.[2]

Several **key characteristics of a superalloy** are excellent mechanical strength, resistance to thermal creep deformation, good surface stability, and resistance to corrosion or oxidation.

These metals also have excellent **heat resistant properties**, which means that they can retain their stiffness, strength, toughness, and dimensional stability at temperatures much higher than other aerospace structural materials and are therefore used in the most critical components within jet engines.

Designing engines or aircraft with superalloys that have the best high temperature and **hot corrosion properties** available means that engine performance and sustainability is greatly improved.

‘Over the past 20 years, the thrust of jet engines has increased by more than 60% whereas the fuel consumption has fallen by 15–20%, and these improvements are, in part, the result of improvements in the high-temperature properties of superalloys.’ [3]

Considering the atmospheric pollutants that may come from fuel…

Sustainable aviation fuels (SAF) are an alternative to fossil fuels. SAFs are produced from sustainable sources, for example from cooking oil, forest waste, algae and many others.

SAFs are used in the same way as traditional fuels but are more sustainable as they only release the carbon they've already taken out of the atmosphere, essentially achieving a **net-zero** effect over their lifecycle. There are also synthetic SAFs, which can be truly zero emission if produced correctly.

SAFs are significantly more **expensive** due to them being a new, unfamiliar technology. Regulatory incentives, such as tax credits for SAF producers, financial support for airlines switching to SAFs, and national mandates to blend SAFs with traditional fuels will all help increase uptake.

Key definitions

Entropy	High Entropy Alloys	Sustainability	Creep Resistance	Additive Manufacturing
A thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system. Hence a gas would have a higher entropy value than a solid as it has a more disordered structure.	Alloys formed by mixing proportions of typically five or more elements. The entropy increase of mixing is substantially higher when there is a larger number of elements in the mix, and their proportions are more nearly equal. These alloys are a focus in materials science and engineering because they have potentially desirable properties.	Fulfilling the needs of current generations without compromising the needs of future generations. There should be a balance between economic growth, environmental care, and social well-being. If something is sustainable, we can sustain it for long periods of time without there being detrimental effects.	A term used in materials science that refers to a solid material's ability to resist "creep". Creep describes the material's tendency to slowly deform over a long period of exposure to high levels of stress.	Also referred to as 3D printing, is an industrial process which builds a 3D component from a computer-aided design (CAD) model by adding and depositing materials successively, one layer at a time. It is the opposite of subtractive manufacturing.

Questions to think about

Apart from better fuel sources are there any other ways we could make the aerospace industry more sustainable?

Electric Flight is being researched. The two main areas currently under consideration are electric flight, hybrid electric (where we use both electric motors as well as a derivation of a propeller/jet engine), and hydrogen powered engines.

There are a lot of initiatives out there - if you search the airbus, Boeing, Rolls-Royce websites they all have resources on net zero flight etc. See further resources for Rolls Royce Net Zero Reports!

Airbus for example have committed to hydrogen powered engines (although hydrogen sounds great, there are issues with it currently too - primarily that we can’t make “green” hydrogen)

Questions to think about

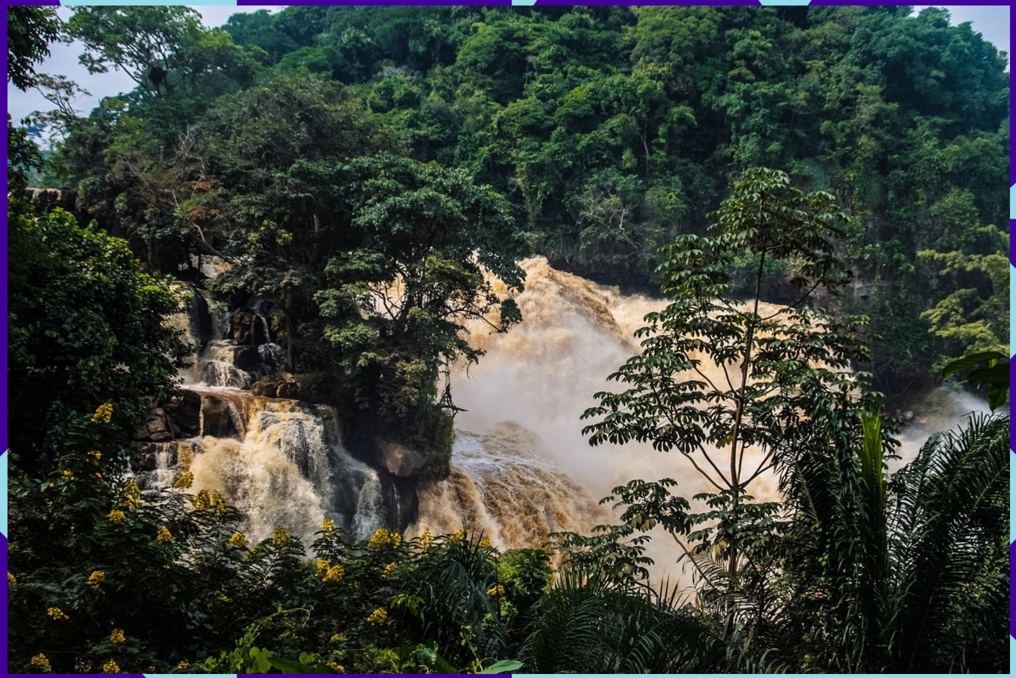
What are the 2 key considerations when looking at designing new elements for use in jet engines?

1. **The materials properties**, particularly the mechanical properties of the material and how these may degrade over time. The materials resistance to fatigue is particularly important when looking at the service lifetime of an aircraft. As well as mechanical properties, environmental considerations should be taken into account. At high temperature environments the materials are more likely to be susceptible to oxidation and corrosion.
2. **The carbon footprint of the material**. What elements are we using in the new material (or new alloy) and how are we manufacturing it? For the material to be sustainable and to be successfully used in a sustainable application we must consider the material through its entire life cycle.

Discussion Topics

Why are certain elements problematic, for example, why is cobalt considered a problematic element for use in these alloys?

Cobalt is sourced from the Democratic Republic of the Congo and so the ethics behind its mining are troublesome. If the way the element is sourced is unethical, then the element is unsustainable.



We can look at replacing problematic elements in the alloys that we currently use. For example, could we remove cobalt and replace it with an element like iron. Iron is cheaper than cobalt and has high relative abundance and so would be readily available for use.

Discussion Topics

Why would we develop SAFs when we are already looking at designing new, more sustainable engines?

SAFs are the only way to make a difference in the industry right now. Even if we have truly zero carbon concepts starting to emerge from the design of new engines and electric flight, the existing fleet of aircraft won't be scrapped for many years to come.

So, we need to really consider how can we quickly make a notable change to our fleet to reduce carbon. SAFs are the answer. As with any technology (and this is perhaps where Aviation has struggled) diversity of solutions is critical. We shouldn't be relying on a single energy source - starting with SAFs will give us a robust way to address the climate emergency immediately, and as we progress forward into different concepts, we should then be able to adapt more quickly as well.

Additional Resources

BBC Physics- The invention of the jet engine
https://www.bbc.co.uk/teach/class-clips-video/history-physics-ks4-gcse-the-invention-of-the-jet-engine/z4phf4j
Royal academy of engineering initiatives, eg aircraft design challenge
https://raeng.org.uk/education-and-skills/schools/stem-resources/aircraft-design
Mark Miodownik BBC Bitesize episode
https://www.bbc.co.uk/programmes/p011lf5t
Rolls-Royce Net Zero reports
https://www.rolls-royce.com/innovation/net-zero.aspx#section-creating-enabling-environment
You tube video- 'From atoms to turbine blades'.
https://www.youtube.com/watch?v=wYHch5QIWTQ
"Life Scientific" podcast with Baroness Brown of Cambridge - Julia King, addressing net zero
https://www.bbc.co.uk/programmes/m001jshz

REFERENCED FACTS

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[2] Mouritz, A.P. (2012) "1- Introduction to aerospace materials ," in Introduction to aerospace materials. Oxford: Woodhead Publishing, pp. 1–14.

[3] Mouritz, A.P. (2012) "12- superalloys for gas turbine engines," in Introduction to aerospace materials. Oxford: Woodhead Publishing, pp. 251–267.