Scoping study on metals used in specialist alloys in the aerospace industry

Decarbonisation and Resource Management Programme

Open Report OR/23/016

BRITISH GEOLOGICAL SURVEY

DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME

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Scoping study on metals used in specialist alloys in the aerospace industry

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Foreword

Minerals will assume greater importance in contributing to the UK's economic growth and high standard of living over the coming decades. This will be driven by requirements for the UK to bring all greenhouse gas emissions to net zero by 2050, grow the advanced manufacturing sector, mitigate risks to national security, deliver economic prosperity and create opportunities for UK businesses in critical mineral supply chains domestically and internationally. This report has been produced by the British Geological Survey (BGS) under the auspices of the Department for Business & Trade-funded UK Critical Minerals Intelligence Centre (CMIC). The CMIC aims to provide up to date, accurate, high-resolution data and dynamic analysis on primary and secondary minerals resources, supply, stocks and flows of critical minerals, in the UK and globally. Its work supports delivery of the UK Critical Minerals Strategy that aims to improve the security of supply of critical minerals by accelerating the UK's domestic capabilities, collaborating with international partners, and enhancing international markets.

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Summary

This scoping study assesses the use of specialist alloys in the UK aerospace and defence industries. It considers their applications and importance; material production and supply chains, and the availability and quality of associated data and information; the market characteristics of the alloying metals; and UK import reliance and key dependencies. It also explores supply chain risks and the concerns of material suppliers and consumers. The research is based on a combination of literature review, analysis of trade statistics and stakeholder consultation.

The aerospace and defence industries are almost unique in terms of their essential requirements for a range of minor metals, used to produce specialist alloys, sometimes referred to as high-performance or superalloys. These must combine extreme temperature resistance with the highest levels of mechanical integrity and resistance to corrosion and oxidation. It is only by using superalloys that improvements in the performance, fuel efficiency and emissions of aircraft engines have been achieved.

Superalloys are typically nickel-, iron- or cobalt-based, with much smaller quantities of an array of additional alloying elements that are used as additives or coatings, owing to their highly specialist properties. Important additions include chromium, molybdenum, scandium, titanium, and sometimes ruthenium, tantalum, rhenium, hafnium, tungsten, niobium, and zirconium. Varying the composition allows the superalloys to meet and balance a wide range of performance requirements.

Demand for superalloys is forecast to increase as the global aviation sector continues to recover from the COVID-19 pandemic, orders for new commercial aircraft grow and suppliers tackle major production backlogs. There is also growing demand for superalloys and alloying metals from other established end-use sectors, most notably the nuclear power industry and industrial gas turbines for the power generation industry. Furthermore, there is increasing or emerging demand from other sectors, including automotive, and for space exploration.

Secure and sustainable supply of superalloys and alloying metals, at acceptable prices are vital to support the international competitiveness of the UK aerospace and defence industries. These industries make a significant contribution to value added and export earnings.

Substitution of the elements used in superalloys is generally extremely difficult, as each addition yields specific performance benefits and aerospace components are subject to strict certification processes. Recycling is used throughout the manufacturing process and product life cycle of aircraft engines to maximise recovery of metals from superalloys. This helps to reduce demand for virgin materials, thereby helping to mitigate supply chain risk and has significant environmental and sustainability benefits.

The UK is almost entirely dependent on imports for its primary supply of alloying metals. Despite a lack of UK trade data for certain metals, the available data highlights the importance of trade relationships with specific countries. The most important suppliers of alloying metals to the UK are the USA, China, Japan, South Africa and several European Countries.

Stakeholders in the UK aerospace supply chain that participated in this study were willing to provide high-level, technical information on the UK market for superalloys and alloying metals, and an overview of international supply chains. They were not forthcoming with detailed information on supply chains and volumes of material traded, and supply and purchasing relationships, as it is commercially sensitive.

Concentration of production of the alloying metals and dependence on imports exposes the UK to several supply risks. Increasing demand for alloying metals globally, including in major producing countries that will prioritise the domestic market; growing intersectoral competition; limited market transparency, owing to long-term supply agreements and certain metals not being traded on exchanges; markets imbalances and price volatility; and the ongoing recovery

from the COVID-19 pandemic and Russia’s invasion of Ukraine present challenges for UK aerospace material supply chains.

Some of the alloying elements are entirely or partially by-products of the extraction of another metal. This introduces an additional level of complexity to their markets and means supply is not always responsive to increased demand. Several UK companies highlighted concerns about the current market availability of hafnium and escalating prices. This is because of increasing demand, it being a by-product and not commercially viable to recycle, most material being tied into long-term supply agreements and developments in the Chinese market.

UK businesses operating in the aerospace supply chain place significant emphasis on responsible sourcing and ensuring compliance with environmental, social and governance standards. It is typically covered in material supply contracts and adds to the cost of procurement. Data quality, reporting standards and illegal practices in the international market are of concern to companies.

Geopolitical developments during the last year contribute to greater supply risk or likelihood of supply disruption for several alloying metals. To mitigate the risk, it was suggested that the UK Government should focus on resource diplomacy with key metal producing countries to develop more secure trade flows. This may include supporting domestic suppliers and consumers in negotiating material supply agreements with businesses in partner countries.

1 Introduction

1.1 CONTEXT

The UK aerospace and defence industries are highly interconnected. The UK aerospace industry is the second largest in the world and has a reputation as a global leader in developing new technologies, and for the design and manufacture of engines, helicopters, aircraft structures and systems. This is complemented by a strong maintenance and repair sector. In 2021 the UK aerospace and defence industries had a combined turnover of approximately £46 billion, £24 billion of which was exported, contributing about £18 billion in value added, and directly employing more than 250 000 people. Importantly, the majority of these jobs are located outside London and the South East, and pay about 40 per cent above the national average (ADS, 2022; BEIS, 2018) (Figure 1). Civil aerospace is considered a high growth sector over the next 20 years and represents a huge opportunity for the UK, given its established reputation and the competitive advantage arising from its mature supply chain, comprising suppliers of all sizes (BEIS, 2018).

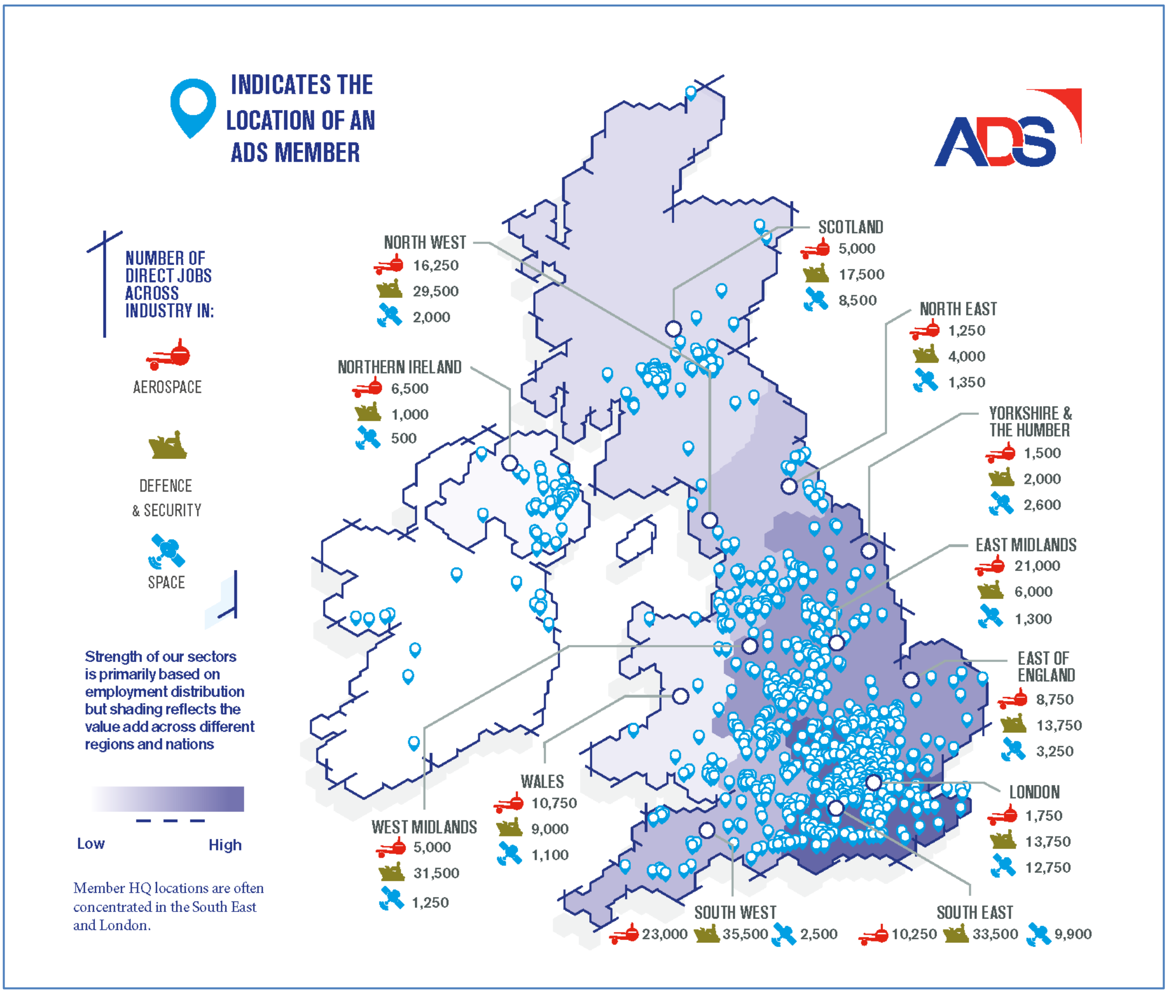


Figure 1. Locations of ADS members involved in the UK's aerospace, defence, security and space organisations (ADS, 2022). (ADS = aerospace, defence, security & space sectors). Source: ADS (2022) Industry facts and figures. All rights reserved; as modified by the British Geological Survey.

Rising demand for air travel during 2022 led to economic recovery for the aerospace industry. The aerospace and defence industry is expected to continue growing in 2023 as passenger air travel returns to pre-COVID-19 pandemic levels, and orders for new aircraft and defence platforms increase (Deloitte, 2022). Airbus reports that its deliveries of commercial aircraft rose by 8 per cent in 2022 but it has a major order backlog (7239 aircrafts), as it continues to receive a high number (820 net) of new orders (Airbus, 2022).

The aerospace and defence industries are dependent on a wide range of minerals and metals for the production of materials and the manufacture of the specialist, custom-made components and structures required to meet the rigorous specifications and withstand extreme environments. Some of the most important materials are alloys. Demand for alloys and alloying metals, such as titanium, chromium, hafnium, molybdenum, rhenium and tantalum are expected to grow as the aerospace industry recovers and returns to pre-COVID-19 pandemic levels (Argus, 2023). This scoping study aims to assess the use and importance of superalloys and unwrought alloying metals in the UK aerospace and defence sectors, their associated supply chains and potential vulnerabilities.

1.2 ALLOYS AND SUPERALLOYS

Alloys are created by mixing metal with another component, either another metal or a nonmetal substance. Metal alloys are generally created by melting the components, mixing them together and letting them cool to create a solid material. Alloys often have many benefits over pure metals, as the process of combining them can enhance their mechanical strength, chemical properties, hardness, machinability and corrosion resistance. Alloying has permitted the creation of a myriad of bespoke materials, with properties appropriate for an ever-increasing range of applications across many industrial sectors. For example, alloys are important in the transport sector, where they are used for weight reduction whilst retaining high strength in aerospace and power plants for efficient turbines that can operate at very high temperatures, in the nuclear industry, including for waste management, for creating infrastructure that can resist hydrogen embrittlement, and for biomedical implants when longevity of corrosion resistance is vital (Raabe et al., 2019). Steel is an alloy of iron and a small amount of carbon, and represents the most common alloy, which is produced in the largest quantities. Alloy steels are made by combining carbon steel with one or several alloying elements, such as silicon, nickel, chromium, titanium, manganese and vanadium. The objective is to increase hardenability (the potential the steel has to be hardened by thermal treatment), corrosion resistance whilst retaining hardness and strength. Accordingly, a wide range of characteristics are achievable depending on the specific elements that are added to change material performance, resulting in an equally wide range of applications (Leonghuat, 2023; MetalSupermarkets, 2015). Modern alloys typically comprise a base metal (a non-ferrous industrial metal e.g. nickel, copper, aluminium) and two or more minor alloying elements that are added to achieve the desired performance (DebRoy et al., 2018). A range of modern alloys can be broadly categorised based upon their performance characteristics and metals composition (Table 1). Within each of these categories, hundreds of variants with different metal compositions exist (Table 2).

A ‘superalloy’ sometimes referred to as a high-performance or specialist alloy, is defined by its ability to operate at a high fraction of its melting point without compromising its properties, such as high mechanical strength, creep resistance (the tendency of an alloy to slowly deform over a long period of exposure to high levels of stress), significant surface stability, corrosion and oxidation resistance at high temperature (Blakey-Milner et al., 2021). Accordingly, ‘superalloys’ can maintain their mechanical properties after sustained exposure to high temperatures. These materials were originally developed for demanding, specialist applications such as the blades in gas turbine jet engines, rocket engines and turbo-superchargers. Overtime their use has expanded to many industrial applications and sectors such as chemical and hydrocarbon processing, industrial gas turbines, nuclear reactors, marine engineering, pumps, heat exchangers and a range of defence systems (Kishawy and Hosseini, 2019) (Table 3).

Table 1. Modern alloys and their metal composition (modified from Graedel et al. (2022)

Alloys	Metals composition
Stainless steels	Fe, Ni, Cr, Mn, Mo,
High-strength low alloy steels	Fe, V, Cr, Mn, Nb, Mo
Nickel-based superalloys	Ni, Al, Cr, Co, Mo, Ti, Hf, W, Re, Ru, Zr, Ta, Nb, V
Bulk metallic glasses (for research purposes only)	Zr, Hf, V, Ti, Be
High-entropy alloys (for research purposes only)	Al, Ni, Cr, Co, Cu, Fe, Sc, Mn
Advanced thermoelectric alloys	Pb, Te, Se, Sb, Ge
Shape-memory alloys (mainly used in sensors, actuators, and springs)	Cu, Al, Ti, Ni
Self-healing alloys (for research purposes only)	Ti, Al, Cu, Fe, Mg

Table 2. Composition of common alloys used in discs, blades, and other parts of aeroengines (in wt%) (modified from Grilli et al., 2021).

Alloy	Ni	Fe	Co	Cr	Mo	Al	Ti	Ru	Mn	Ta	Re	Hf	C	B	W	Nb	Y	Zr	Other
Wrought alloys																			
Inconel 600	76.6	7.2	-	15.8	-	-	-	-	0.2	-	-	-	0.04	-	-	-	-	-	0.2 Si
Inconel 718	52.8	18.5	-	19	3	0.5	0.9	-	-	-	-	-	-	0.2	-	5.1	-	-	-
ATI-718 Plus	51.3	9	9	19	2.8	1.45	0.75	-	-	-	-	-	0.025	0.0055	1.1	5.6	-	-	-
Rene 41	55.3	-	11	19	10	1.5	3.1	-	-	-	-	-	0.09	0.005	-	-	-	-	-
Nimonic 80A	76.6	-	-	19.5	-	1.4	2.4	-	-	-	-	-	0.06	0.003	-	-	-	0.06	-
Nimonic 105	54.6	4.5	20	14.5	5	-	1.2	-	-	-	-	-	-	0.2	-	-	-	-	-
Waspaloy	58.6	-	13.5	19.5	-	1.3	3	-	-	-	-	-	0.08	0.006	4	-	-	0.03	-
Hastelloy X	35.9	6	1.5	22	9	18.5	-	-	0.5	-	-	-	0.1	-	6	-	-	-	0.5 Si
Hastelloy S	68.8	-	-	15.5	14.5	1	0.2	-	-	-	-	-	0.02	0.009	-	-	-	-	0.02 La
Udimet 500	52.6	-	18.5	18	4	2.9	3.9	-	-	-	-	-	0.08	0.006	-	-	-	0.05	-
Udimet 700	53.4	-	18.5	15	5.2	4.3	3.5	-	-	-	-	-	0.08	0.03	-	-	-	-	-
Powder-processed alloys																			
Rene 95	65.9	-	8	13	-	3.5	2.5	-	-	-	-	-	0.065	0.013	3.5	3.5	-	0.05	-
Rene 88DT	60.5	-	13	16	-	2.1	3.7	-	-	-	-	-	0.03	0.015	4	0.7	-	-	-
Inconel 100	59.8	-	18.4	12.4	-	4.9	4.3	-	-	-	-	-	0.07	0.02	-	-	-	0.07	-
N18	63.8	-	15.6	11.2	-	4.4	4.4	-	-	-	-	0.5	0.02	0.015	-	-	-	0.03	-
Astroloy	55.2	-	17.2	14.9	5.1	4	3.5	-	-	-	0.04	-	0.025	-	-	-	-	0.04	-
Conventionally cast alloys																			
Rene 80	60.3	-	9.5	14	4	3	5	-	-	-	-	-	0.17	0.02	4	-	-	0.03	-
MAR-M200	60.8	-	10	9		5	2	-	-	-	-	-	0.15	0.015	12	1	-	0.05	-

MAR-M246	59.8	-	10	8.3	0.7	5.5	1	-	-	3	-	1.5	0.14	0.02	10	-	-	0.05	-
Inconel 713LC	74.8	-	-	12	4.5	5.9	0.6	-	-	-	-	-	0.05	0.01	-	2	-	0.1	-
Directionally cast alloys																			
Rene 80DS	59.8	-	9.6	12.9	4	3.02	4.48	-	-	-	-	0.074	0.07	0.015	6	-	-	0.02	-
CM247 LC DS	69.8	-	9.2	0.07	0.5	5.6	1	-	-	3	-	1.5	0.07	0.015	9.2	-	-	0.015	-
First-generation single-crystal alloys																			
Rene N4	61.5	-	7.5	9.8	2	4.2	3.5	-	-	4.8	-	0.15	0.05	-	6	0.5	-	-	-
PWA 1480	62.5	-	5	10	-	5	1.5	-	-	12	-	-	-	-	4	-	-	-	-
CMSX-2	65.8	-	5	8	0.6	5.6	1	-	-	6	-	-	-	-	8	-	-	-	-
CMSX-3	65.7	-	5	8	0.6	5.6	1	-	-	6	-	0.1	-	-	8	-	-	-	-
RR2000	61.5	-	15	10	3	5.5	4	-	-	-	-	-	-	-	-	-	-	-	1 V
SRR99	66.3	-	5	8	-	5.5	2.2	-	-	3	-	-	-	-	10	-	-	-	-
Second-generation single-crystal alloys																			
Rene N5	63.1	-	7.5	7	1.5	6.2	-	-	-	6.5	3	0.15	0.05	-	5	-	0.01	-	-
PWA 1484	59.3	-	10	5	2	5.6	-	-	-	9	3	0.1	-	-	6	-	-	-	-
CMSX-4	61.7	-	9	6.5	0.6	5.6	1	-	-	6.5	3	0.1	-	-	6	-	-	-	-
CMSX-6	70.6	-	5	9.8	3	4.8	4.7	-	-	2.1	-	-	-	-	-	-	-	-	-
SC180	59.7	-	10	5	2	5.2	1	-	-	9	3	0.1	-	-	5	-	-	-	-
Third-generation single-crystal alloys																			
Rene N6	56.8	-	12.5	4.2	1.4	5.8	-	-	-	7.2	5.4	0.15	0.5	-	6	-	0.01	-	-
CMSX-10	69.4	-	3	2	0.4	5.7	0.2	-	-	8	6	0.2	-	-	5	0.1	-	-	-
TMS-75	59.9	-	12	3	2	6	-	-	-	6	5	0.1	-	-	6	-	-	-	-
TMS-113	58.5	-	11.9	2.9	2	6.6	-	-	-	6	6	0.1	-	-	6	-	-	-	-
TMS-121	64.9	-	6	3	3	6	-	-	-	6	5	0.1	-	-	6	-	-	-	-

Fourth-generation single-crystal alloys																			
MC-NG	70.4	-	-	4	1	6	0.5	4	-	5	4	0.1	-	-	5	-	-	-	-
PWA 1497	50.5	-	16.5	2	2	5.6	-	3	-	8.3	6	0.15	-	-	6	-	-	-	-
TMS 138	63.7	-	5.8	3.2	2.8	5.9	-	2	-	5.6	5	0.1	-	-	5.9	-	-	-	-
TMS 138A	61.8	-	5.8	3.2	2.8	5.7	-	3.6	-	5.6	5.8	0.1	-	-	5.6	-	-	-	-
Fifth-generation single-crystal alloys																			
TMS-162	59.1	-	5.8	3	3.9	5.8	-	6	-	5.6	4.9	0.1	-	-	5.8	-	-	-	-
TMS-173	59.8	-	5.6	3	2.8	5.6	-	5	-	5.6	6.9	0.1	-	-	5.6	-	-	-	-
TMS-196	59.1	-	5.6	4.6	2.4	5.6	-	5	-	5.6	6.4	0.1	-	-	5.6	-	-	-	-
Sixth-generation single-crystal alloys																			
TMS-238	58.8	-	6.5	4.6	1.1	5.9	-	5	-	7.6	6.4	0.1	-	-	4	-	-	-	-
Iron-based alloys																			
A-286	26	18.9	15	--	1.25	0.2	2.15	-	-	-	-	-	0.05	-	-	-	-	-	0.2 V
N-155	20	47.5	21	20	3	-	-	-	-	-	-	-	-	-	2.5	1	-	-	-
CG-27	38	23.2	13	--	5.5	1.5	2.5	-	-	-	-	-	0.05	0.01	-	0.6	-	-	-
Cobalt-based alloys																			
HS-188	22	3	39	22	-	-	-	-	-	-	-	-	0.1	-	14	-	-	-	-
X-40	10		56	25	-	-	-	-	-	-	-	-	0.5	-	7.5	-	-	-	-

Table 3. Common alloys and their application in different sectors.

Alloys /applications	Aluminium	Maraging steel	Stainless steel	Titanium	Copper alloys	Cobalt superalloys	Nickel superalloys
Aerospace	X		X	X	X	X	X
Medical			X	X	X	X	
Power generation industry			X			X	X
Automotive	X		X	X		X	X
Navy			X	X		X	X
Mechanical tools		X	X				
Consumer products	X		X		X		

2 Superalloys in aircraft engines

Commercial aircraft engines typically weigh between 2000–8500 kg, with metallic materials comprising 85–95 per cent of the total weight of the engine. Since their development, the performance of aircraft gas turbines (a rotary engine that extracts energy from a flow of combustion gases) has been dependent on the materials employed in the high-temperature sections of the engine (Figure 2). This is because the peak temperature and pressure attainable and hence the thermo-dynamic efficiency of the cycle is limited by the operating temperatures of the materials used. Gas turbine jet engines comprise several sections that require different materials, primarily related to their operating temperatures (Figure 2). The air intake and compression sections are relatively cool, with temperatures rising significantly in the combustion section before reaching the turbine and exhaust. During compression, the gas-stream temperature increases through the compressor, reaching up to about 700 ºC. This section is primarily comprised of titanium alloys used in the fan and low pressure stages up to the high pressure compressor and then largely shifts to nickel superalloys. Temperature peaks (up to 1560 ºC) in the combustor and decreases through the turbine where nickel- and cobalt-based alloys are the principal construction materials used, including for the turbine blades (Figure 3) (Reed, 2008; Rolls-Royce, 2013). The high pressure turbine blades are cast as single crystals to eliminate imperfections in the grain structure to help with high temperature strength and creep resistance. Temperature resistance is further enhanced with cooling channels and use of platinum and ceramic coatings to help dissipate heat. Improvements in performance, fuel efficiency and emissions are only possible using superalloys (Beddington, 2021).

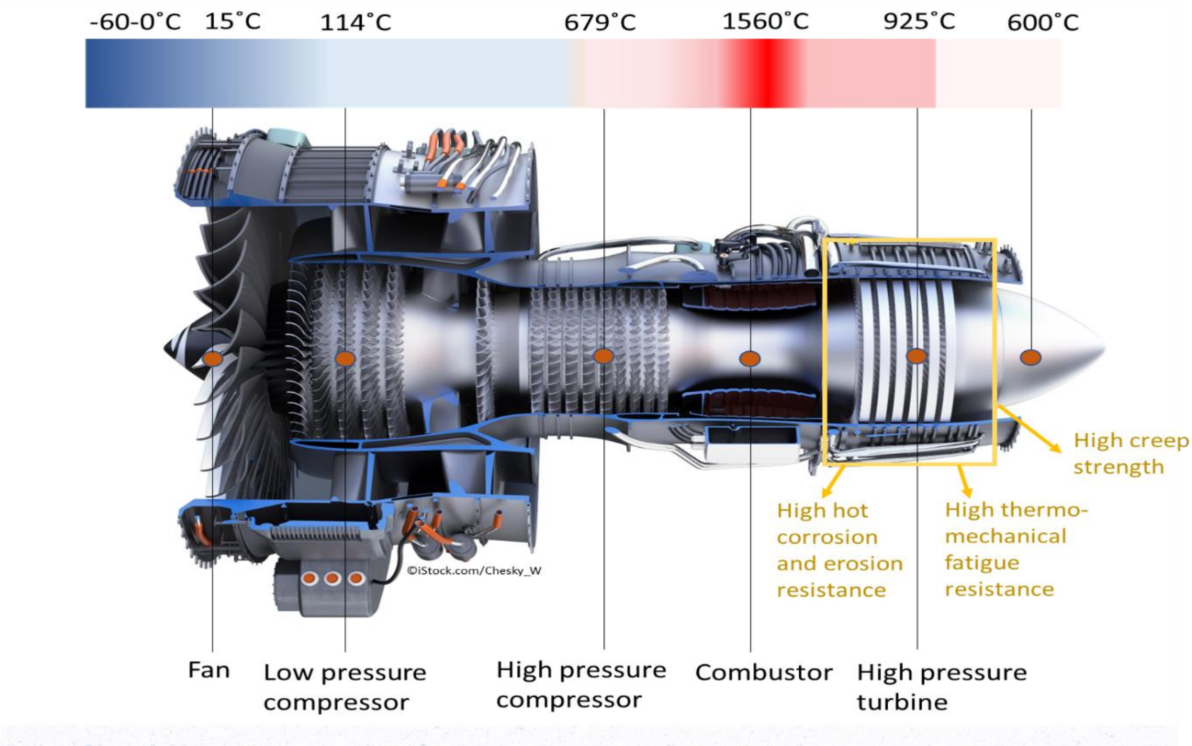


Figure 2. Cross section of a gas turbine engine representing different sections and their thermos-mechanical properties (information based on Read, 2008 and EASA, 2018). *Image: ©iStock.com/Chesky_W*

Figure 3. An end-of-life single-crystal turbine blade. The holes in the surface of the blade permit airflow along cooling channels to keep the blade within its specified operating temperature range.

3 Types of aerospace alloys and their key properties

Alloys are frequently referred to by their primary base metal, for example aluminium alloys, titanium alloys, cobalt alloys, nickel alloys and copper alloys. The most important alloys used in the aerospace industry are described below.

3.1 ALUMINIUM ALLOYS

Aluminium alloys have been an essential material for the aerospace industry since they entered mainstream use during and after World War II. They are the preferred choice for the aerospace industry because of their relatively low cost, relatively low density (ranging between 2,640kg/m^3 and 2,810kg/m^3;(Thyssenkrupp Materials, 2022), high strength-to-weight ratio, and ease of manufacturing characteristics (The Aluminium Association, 2023). This means aluminium is the most widely used material for components where low weight is a vital design criterion, such as aerospace, automotive and satellite components (Harrison, 2022). However, the poor resistance of aluminium alloys to elevated temperature and corrosion have limited their applications in modern aircraft and aluminium alloys are being progressively replaced by composite materials (Rambabu et al., 2017).

3.2 STAINLESS STEELS

Stainless steels are used in several aircraft components due to their high strength-to-weight ratio, excellent durability, hardness, and good mechanical properties at elevated temperatures. Various classes of stainless steels are often used in additive manufacturing, including austenitic, precipitation hardened, and maraging (Haghdadi et al., 2021). Austenitic refers to an alloy consisting mainly of 'austenite' which is a crystalline structure that prevents steels from being hardenable by heat treatment and makes them essentially non-magnetic (Kong et al., 2021). Precipitation hardening is a heat treatment technique used to increase the yield strength of malleable materials, particularly for structural alloys (Zai et al., 2020). Maraging refers to the heat treatment of steel, which results in superior strength and toughness without losing ductility (Tian et al., 2017). These forms of stainless steel are used in a range of components in engine and exhaust systems, hydraulic components, heat exchangers, landing gear systems, and structural joints (Zhang et al., 2018).

3.3 TITANIUM ALLOYS

Titanium is a hard, lightweight, lustrous, silvery metal (MMTA, 2016a). Titanium alloys are widely used in aerospace applications due to their high specific strength, excellent corrosion resistance and high-temperature stability (Uhlmann et al., 2015). In addition, titanium alloys are electrochemically compatible with polymer matrix-carbon fibre composites that are extensively used in modern aircraft (Williams and Boyer, 2020). Titanium alloys exhibit no ductile to brittle transition at low temperatures, which is important for cryogenic applications in rocket propellant tanks (Zang et al., 2022).

3.4 COPPER ALLOYS

Copper-alloys are commonly used in heat exchangers, such as the combustion chambers for liquid rocket engines, which require a high-strength and -conductivity alloy to effectively cool the walls of the thrust chamber containing a high-pressure propellant or oxidiser (de Groh et al., 2008). In addition, copper-based alloys are widely used in aircraft engineering where key components require materials with high strength, good ductility and resistance to corrosion. Examples of copper alloys used in the aircraft and aerospace industry include

C51000 (aircraft bushings and bearings), AMS 4634-C64200 (aircraft parts, landing gear parts), and C86300 (high load gear, bearing applications) (Bendall, 1955; CONCAST, 2023).

3.5 COBALT-BASED ALLOYS

Cobalt is a hard, shiny, and greyish metal that has a diverse range of important metallurgical and chemical uses, varying from aircraft engines to rechargeable batteries (MMTA, 2016_b). Since 1917, cobalt has been used in alloys that are applicable in a range of applications such as wind turbines, hard disk drives, motors, sensors, actuators, or magnetic resonance imaging (Cobalt Institute, 2023). Cobalt-based superalloys combine cobalt as the dominant metal, with other elements, including nickel, chromium and molybdenum. This combination of elements provides greater strength, corrosion resistance, excellent thermal stability, fatigue resistance, and malleability; meaning cobalt-based superalloys have applications in extreme temperature environments, including jet engines, gas turbines, and chemical processing equipment (Piping Mart, 2022). Cobalt-based alloys can also be processed to have the same two-phase equilibrium microstructure, consisting of gamma (γ) and gamma-prime (γ') as the more widely used nickel-based superalloys. These advanced cobalt superalloys have been shown to have solidus temperatures 100–150ºC higher than optimised nickel-based superalloys. These high temperatures of operation could potentially have an enormous impact on the optimum thermodynamic efficiency parameters of an engine, where efficiency is directly proportional to increased operating temperatures. Furthermore, cobalt-based superalloys can be processed into large single crystals (a form needed to achieve good high temperature creep resistance) without forming solidification defects on their surface (so-called freckles) that plague nickel-based superalloys (UNAND, 2023).

3.6 NICKEL-BASED ALLOYS

The excellent mechanical properties of nickel-based alloys under high temperatures (up to 1150ºC), high pressures and in corrosive environments are essential for improving the efficiency of modern aircraft engines (Figure 4) (Perrut et al., 2018). Nickel-based alloys are broadly used for the manufacturing of disks and blades in high-pressure gas turbine jet engines (Minet et al., 2019). They are also used in many high-temperature and cryogenic applications, such as valves, turbomachinery, injectors, igniters, and manifolds (Gradl et al., 2018). Currently, more than 50 per cent of the quantity of an advanced aircraft engine is comprised of nickel-based superalloys (Akca and Gürsel, 2015).

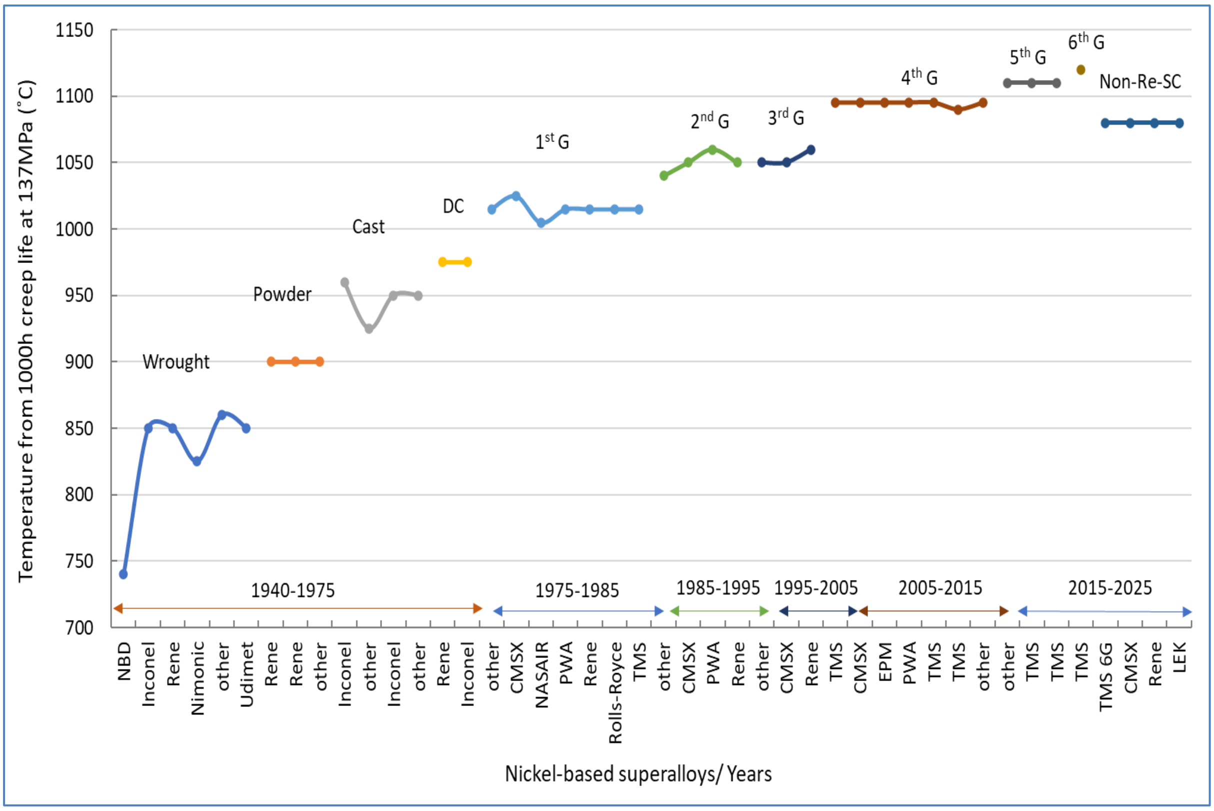


Figure 4. The improvement in creep rupture temperature capability of nickel-based superalloys over time. DC = directionally solidified; G = generation; SC = single crystal; Re = rhenium (Long et al., 2018; NIMS, 2022; Rolls-Royce, 2013). (Note: the temperature exposure on the y axis is based on 1000h creep life at 137MPa).

3.7 REFRACTORY ALLOYS

Incorporating refractory materials (those resistant to alteration or decomposition by heat, pressure, or chemical attack) in superalloys is common in applications where they are exposed to extreme temperatures or experience high levels of friction. For example, refractory alloys are commonly used in radiatively-cooled thrusters and rocket nozzles (Snead et al., 2019). These superalloys typically incorporate elements such as niobium, tantalum, hafnium, molybdenum, zirconium, titanium and tungsten. Examples, of customised superalloys produced for aerospace and related applications, include C-103 (Nb-Hf-Ti-Zr) and stellite (Co-Cr) alloys, that are used in applications where the materials are exposed to high levels of abrasion and high-temperatures, respectively (Philips et al., 2020).

4 Selected minor metals vital for high performance superalloys

The metals used in the alloying come in a variety of forms such as pellet or sponge depending on the extraction route. For example, powder alloys produced through gas atomisation and consolidation followed by forging are used for the highest performance disc alloys, but most are not derived from this route. Wire alloys, principally used for welding, are mostly cast to ingot, then produced through conversion to billet and forging (Dunkley, 2019). Examples of selected alloy families include Hastelloy, Inconel, Waspaloy, Rene alloys, Incoloy, MP98T, TMS alloys, and CMSX single crystal alloys (Table 3). The source, properties, applications and market characteristics of selected important minor metals required for high performance superalloys are described below.

4.1 HAFNIUM

Hafnium is a silvery metal that is hard and extremely ductile. It is not produced anywhere independently, as it is solely a by-product of purifying zirconium for the nuclear industry where the lowest possible level of hafnium is essential (MMTA, 2016c). The principal sources of zirconium are deposits of heavy mineral sands, containing ilmenite, rutile and zircon ($ZrSiO_4$) where hafnium occurs at a ratio of 1:50 with zirconium (Callaghan, 2008). Hafnium is chemically very similar to zirconium, and it is virtually impossible to produce either element without having traces of the other present (MMTA, 2016c). It is estimated that about 70–80 tonnes of hafnium is produced annually, mostly by France and the United States of America (USA), as a by-product of their nuclear industries (Dareen, 2023). Owing to the strategic nature of nuclear facilities, very few producers of hafnium exist globally. Hafnium is classed as a 'dual use' metal under the Treaty on the Non-Proliferation of Nuclear Weapons, meaning import/export licences and end user statements are required when it is being traded and transported. The two most significant producers are Wah Chang in the USA (about 40 tonnes annually) and Cezus in France (about 30 tonnes annually), owned by Areva. Reports suggest that the Ukraine did produce hafnium under the Soviet system, but this is thought to have ceased. Production from Russia continues. China also produces hafnium (MMTA, 2016c). The USA is the largest consumer of hafnium, followed by Europe and China (Mordor Intelligence, 2023a).

Hafnium is highly resistant to corrosion because when it is exposed to air, it produces a tough, impenetrable oxide layer on its surface. It is unaffected by acids and alkalis, except hydrofluoric acid (MMTA, 2016b). Hafnium carbide and hafnium nitride have melting points of 3890°C and 3310°C, respectively (Mordor Intelligence, 2023a). Hafnium is primarily used in its purest form (99.9%) in superalloys, providing high strength and stability when operating at very high temperatures. This means it is used in applications such as turbine blades, vanes, and industrial gas turbines (CRM Alliance, 2023). The leading hafnium-bearing alloys, MAR-M-246 and CM247 LC DS, contain 1.5 per cent hafnium (Table 2, Figure 5). Hafnium has also a vital role in the nuclear sector, where it is used as a neutron absorber in nuclear control rods. Other uses of hafnium (Figure 6a) include refractory ceramic materials, semiconductors, integrated circuits, nozzles for plasma arc cutting, and it is used as a catalyst in certain polymerisation reactions.

Hafnium is essential in many of these applications and an absence of potential substitutes is a concern for end-users. Competing nuclear and non-nuclear drivers support the hafnium market, and it is suggested that if shortages were to emerge the nuclear industry would likely be prioritised over other industrial consumers (MMTA, 2016c). It is reported that the global hafnium market experienced a deficit of five to ten tonnes in 2022, owing to increasing demand and an absence of supply from Russia. Growing demand is primarily attributed to a global resurgence in aircraft manufacturing, and the electronics and semi-conductor industries. Levels of demand from the latter have approximately doubled over a 5-year period. Although Russia only accounts for about 3 per cent of world hafnium production a lack of export licences means this material is not available to the global market, contributing to the overall deficit. It is suggested that Chinese production could help to alleviate the market shortfall, but exports have slowed down. This is likely to be the result of increased domestic demand (Dareen, 2023). China consumes a significant amount of hafnium in its nuclear reactors and plans to build many more nuclear plants, which will continue to drive Chinese demand. In parallel, it is expected that the Chinese aerospace industry will expand significantly, further increasing domestic demand for hafnium superalloys. Between 2023–2028 the global hafnium market is forecast to grow at annual compound growth rate of more than 7 per cent (Mordor Intelligence, 2023a).

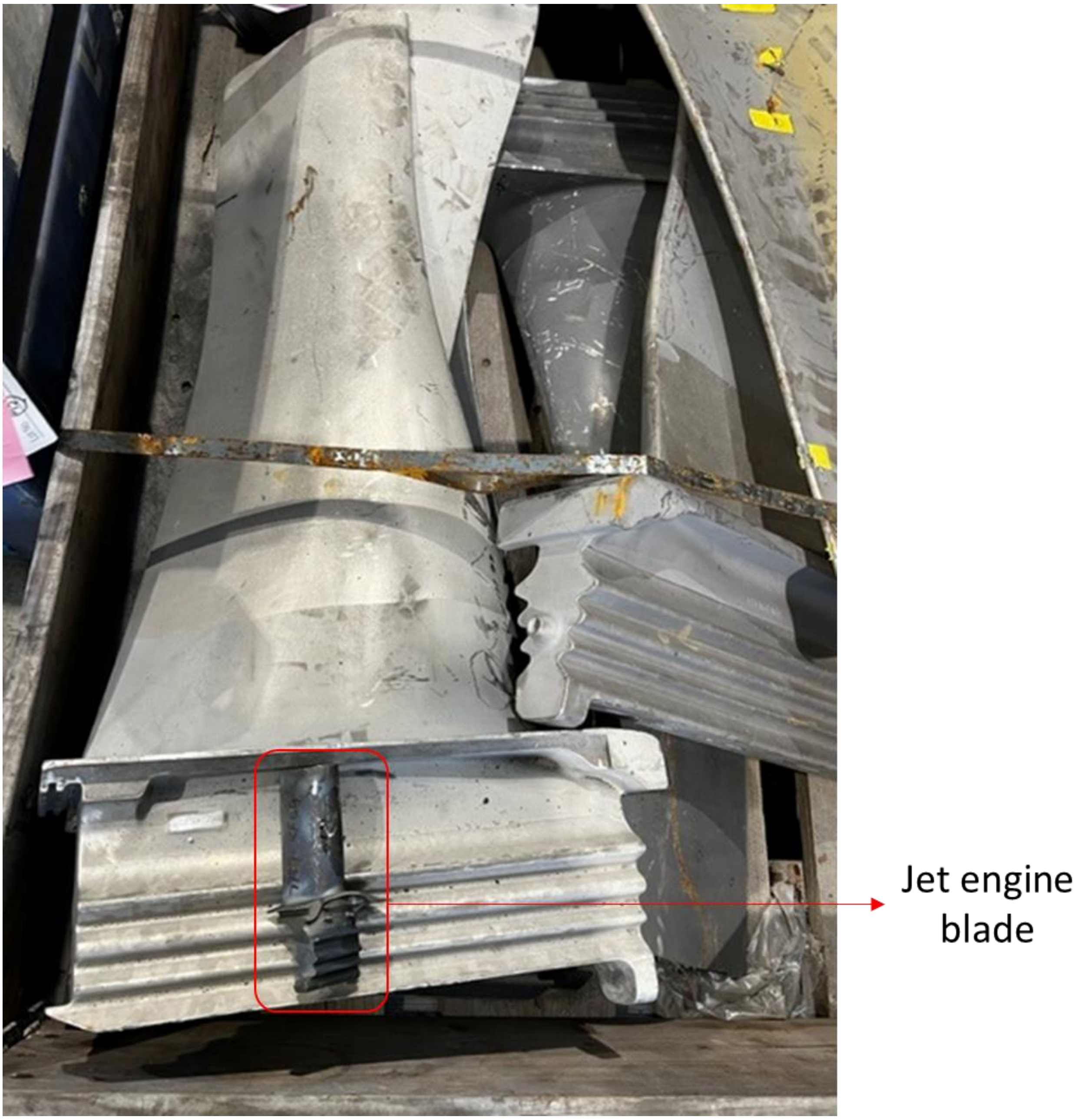


Figure 5. A blade from an aerospace jet engine on top of one from an industrial gas turbine for power generation. The industrial gas turbine blade is MarM247 containing 1.5% Hf. © Advanced Alloy Services Ltd, reproduced with permission.

4.2 ZIRCONIUM

Zirconium is a silvery, hard, strong and durable metal. Zirconium metal is very reactive with oxygen, forming a tough oxide layer on its surface, which protects it from further reaction and makes it very resistant to corrosion. In common with hafnium, zirconium does not dissolve in acids (except hydrofluoric acid) or alkalis (MMTA, 2016d). Zirconium and hafnium are naturally contained in the mineral zircon at a ratio of about 36 to 1 (USGS, 2023a). To produce zirconium metal, zircon-rich sand is reduced via a solvent extraction process to form a low hafnium sponge (the basic form before it is processed and machined) for the nuclear sector (MMTA, 2016d). In common with hafnium, owing to their co-product dependency, zirconium production is tied to countries with established nuclear sectors, notably France

(Cezus-Areva), the USA (Wah Chang) and Russia (Chepetsky Mechanical Works). The growth of the Chinese nuclear industry means it also produces nuclear grade zirconium sponge (MMTA, 201dc). Zirconium is an important constituent of thermal barrier coatings and in nickel-based superalloys where it segregates at grain boundaries and contributes to greater creep resistance (Després et al., 2021) (Figure 6b). Zirconium sponge is required in titanium alloy for aerospace parts. It is also used in some aluminium alloys for aerospace, as well as automotive engine blocks. It is reported that industrial consumers outside the nuclear sector are generally reliant on supply arising from off-cuts and scrap, which are recycled and priced based on size, form and purity (MMTA, 2016d). China dominates global consumption of zirconium and expansion of its nuclear power industry is expected to drive zirconium demand (Mordor Intelligence, 2023b).

Figure 6. A various forms of material and alloy used in aerospace and defence industries. (a) Hafnium crystal bar, (b) High Pressure Turbine blade with thermal barrier coating, (c) Rhenium pellets and (d) Tantalum ingot. © Advanced Alloy Services Ltd, reproduced with permission

4.3 RHENIUM

Rhenium is a silvery metal and one of the rarest elements in the Earth's crust. Rhenium has a very high melting point and density and resists corrosion (MMTA, 2016e) (Figure 6c). Rhenium is primarily used in nickel-based superalloys or in combination with molybdenum and tungsten in rocket and aircraft engines or stationary gas turbines. It is also used as a catalyst in the chemical and petrochemical industries, and to produce spray-on powders that act as corrosion-resistant coatings. The turbine blades in gas turbine jet engines are produced from nickel-based alloys containing about 3–6 per cent rhenium (Table 3). Rhenium increases the creep strength of superalloys, allowing engines to maintain a higher temperature, which is important for engine efficiency and reducing fuel consumption. The biggest producer of rhenium in Europe is Hermann C. Starck (Germany), which in 2015 had an annual production capacity of 3.3 tonnes of rhenium powder (Argimbaev et al. 2021).

Rhenium is a by-product of molybdenum, which is itself primarily a by-product of the extraction of copper (MMTA, 2016e). Accordingly, it is found and produced where copper ores are mined and refined, with the leading global producers being Chile, the USA, Poland, China, Russia, Kazakhstan, Uzbekistan and Armenia (Statista, 2022b). Global mine production has decreased in recent years and was about 37 tonnes in 2020 (Statista, 2022b). It is estimated that 25 tonnes of rhenium were produced from secondary sources in 2021. The leading producers of secondary material were the USA and Germany, with production also taking place in Canada, Estonia, France, Japan, Poland, and Russia (USGS, 2022a).

Aerospace is the dominant end use sector, and the global market for rhenium is forecast to grow at a compound annual growth rate of more than 5 per cent. North America, is expected to continue to dominate demand, owing to the needs of its aerospace and defence industries (Mordor Intelligence, 2023c). Rhenium is typically purchased on long-term multi-year supply agreements between producers and consumers, but a spot market does exist (Lipman Walton & Co Ltd., 2021a). Rhenium prices have fluctuated significantly over the past 40 years, falling from US$3000 per kilogram in 1980 to about US$300 per kilogram in 1996 caused by an influx of new material to the market. Prices recovered, reaching US$12 000 per kilogram in 2008 due to the combined demand from aerospace and industrial gas turbines (Lipman Walton & Co Ltd., 2021a; Strategic Metals Invest, 2023). These high prices stimulated the recovery of rhenium from end-of-life nickel superalloys and the cleaning of used alloys for addition to new alloy melts (Lipman Walton & Co Ltd., 2021a). This substantial new source of supply led to a gradual decline in rhenium prices, which at the time of writing are currently about US$1200 per kilogram.

4.4 TANTALUM

Tantalum is a shiny metal that is soft in its pure form and ductile. It is very resistant to corrosion by most acids because it develops a protective surface layer when it oxidises (MMTA, 2016f) (Figure 6d). About 50 per cent of the tantalum produced annually is consumed by the electronics sector, mainly to produce capacitors. The remaining demand comes from other electronics applications, including semi-conductors, aerospace alloys, defence end-uses, industrial gas turbines, and additive manufacturing of components for a range of industries, including aerospace, automotive, medical, defence, and chemical processing equipment. The high melting point and corrosion resistance of tantalum means it is an important addition to nickel-based superalloys (Global Advanced Metals, 2022). The global tantalum market is forecast to grow at a compound annual growth rate of more than 5 per cent between 2023–2028, reaching about 2200 tonnes by the end of 2023 (Mordor Intelligence, 2023d).

The Democratic Republic of Congo accounts for more than half of the world's total mine production of tantalum, which is about 1500 tonnes. Other major producers are Rwanda, Nigeria, Mozambique, Australia, China and Brazil (BGS, 2022). Tantalum is recycled, principally from new scrap that is generated by the electronics industry and from cemented carbide and superalloy scrap (USGS, 2023b).

Tantalum is considered a ‘conflict mineral’, because of its association with production from minerals mined in conditions of armed conflict and human rights abuses, and which are sold or traded by armed groups. The European Union’s Conflict Minerals Regulation did not become active until 1 January 2021 and therefore does not form part of the UK’s retained EU law. Whilst the regulations do not apply to importers outside Northern Ireland, the UK Government suggests UK-based importers follow OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (Achilles, 2023). However, since 2010 ethically aware UK-based companies have only purchased tantalum from ethically approved sources (University of Birmingham, 2021).

5 Structure of the UK aerospace industry

The UK is home to some of the largest players in the international aerospace industry, notably BAE Systems, Cobham, GKN, Meggitt, QinetiQ, Rolls-Royce, and Ultra Electronics, while major non-domestic companies with a presence in the UK include Boeing, Airbus Group, Leonardo (including its AgustaWestland and Selex ES subsidiaries), General Electric (including its GE Aviation Systems subsidiary), Lockheed Martin, MBDA, Safran, and Thales Group.

5.1 SUPPLY CHAIN CONNECTIONS WITH OTHER INDUSTRIES

The aerospace industry is notable relative to other industrial sectors for the extent of its value chain network, owing to it primarily being based on innovation and knowledge sharing, with each industrial tier contributing value to components and assembly of parts and services. The UK aerospace supply chain is mature and it has a reputation as a global centre of excellence for the design and production of engines, and other essential aircraft parts (Menner, 2022). The Midlands Aerospace Alliance has about 300 members and represents an industrial cluster making engines, fuselages, wings, cockpits, propellers, tail assemblies and landing gear. These manufactures of flying parts are supported by a variety of companies providing research, parts and services such as design and training. Many aerospace parts manufacturers and support companies also supply other industries, which use similar materials and components, for example automotive, power generation, electronic and telecommunications (Figure 7) (Mair, 2020).

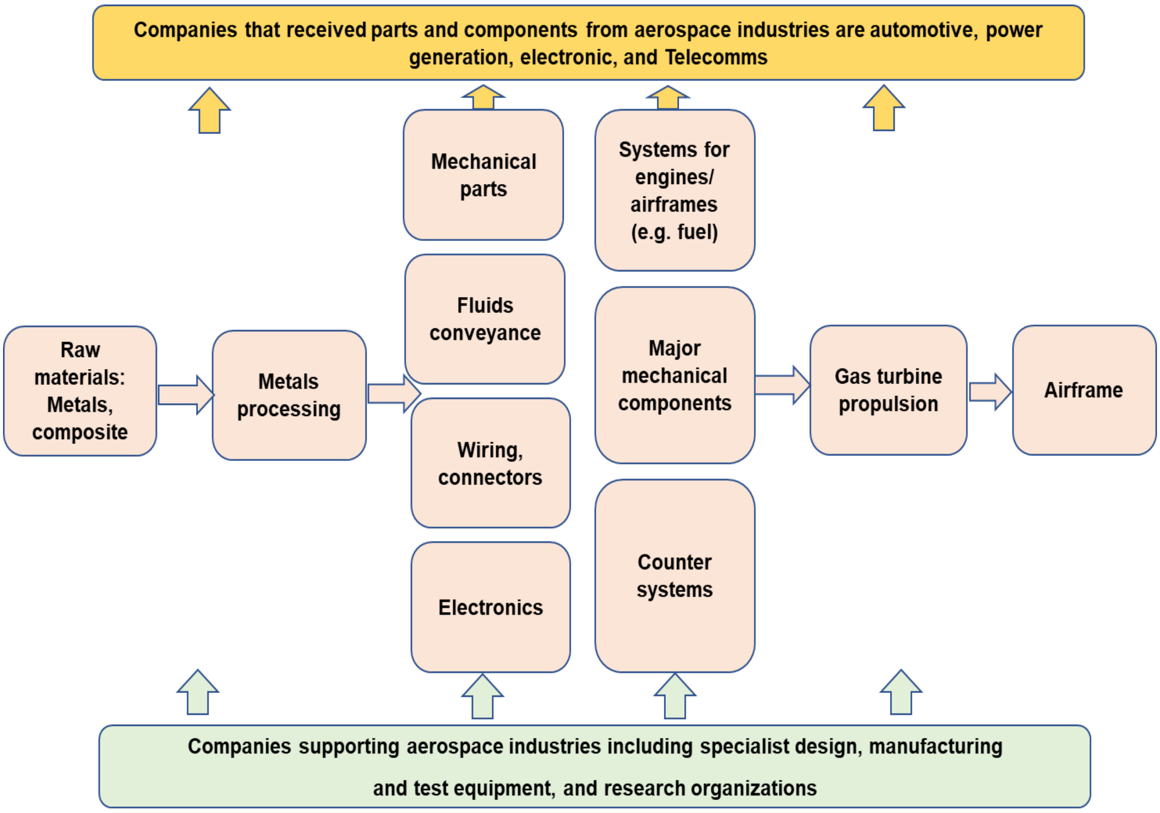


Figure 7 Overview of aerospace component manufacturing stages that take place in the UK (Modified from Mair, 2020).

5.2 THE IMPORTANCE OF RECYCLING AND REVERT

Recycling of superalloys has become prevalent in the aerospace industry to reduce demand for virgin materials that can be affected by supply shortages and significant price volatility, whilst resulting in significant environmental and sustainability benefits. Therefore, recycling offers the aerospace industry the potential to secure the resources it needs. However, the extent of functional recycling in the sector remains limited, due to extensive non-functional recycling or downcycling practices (recycling after which the alloying elements are present in the new material as “tramp elements” that serve no useful purpose and may in some cases be detrimental) (Graedel, et al., 2022).

Rolls-Royce, the British multinational civil aerospace and defence company, report that they consume more than 20 000 tonnes of alloys annually. They have partnered with companies that specialise in waste metal handling and processing. In collaboration they have developed new processes to remove coatings, separate alloys and clean up end-of-life metals. Unserviceable engine parts and waste metal from machining and castings are recovered and returned to their material suppliers for re-melting and reuse, enabling them to be returned to aerospace grade alloys and reused to make new engines (Rolls-Royce, 2017). This process or programme, known as ‘revert’ is considered distinctive from conventional recycling, as it involves the collection and cleaning of alloy for close-loop recycling to the same alloy grade, enabling full recovery of the value of all the alloying additions.

Almost 95 per cent of a used aero engine can now be recycled and around half of the recovered material can be recycled to a standard where the quality of the recovered material is high enough that it can be reused to make new engine components as part of a fully closed loop (when a product is reprocessed and the recyclate generated is used to manufacture a similar product, without significant degradation or waste) recycling system.

The remainder is reused as a lower grade alloy. Rolls-Royce report that through their closed loop recycling programme they annually save 300 000 megawatt hours of energy and reduce their carbon dioxide production by 80 000 tonnes (Rolls-Royce, 2017).

In common with Rolls-Royce, Airbus, the European multinational aerospace corporation, also reports that 92 per cent of an aircraft's total weight and more than 99 percent of its engine parts can be recycled. This is undertaken by the French company Tarmac Aerosave, a specialised recycling company equally owned between Airbus, Safran and Suez SA (Airbus, 2022a). However, ENVISA, an international environmental research and Consultancy Company specialising in identifying innovative solutions to reduce the environmental footprint of the aviation industry, report that, in practice, the process of dismantling end-of-life aircraft is challenging as they contain various hazardous materials. For example, old military aircraft may contain asbestos, fire extinguishers contain Halon 1301, and smoke detectors and emergency exit signs found in commercial aircraft enclose radioactive elements. Additionally, hexavalent chromium can also be found in the aircraft paint primer. These issues not only pose economic challenges for the dismantling process, but often lead to downcycling of metals into ferroalloys or as oxidants in electric steelmaking (ENVISA, 2014).

6 Scope of the study

Secure and adequate supplies of mineral raw materials and components are a core requirement for companies in the aerospace and defence industries. The global aerospace materials market is projected to grow from about US$36 billion in 2021 to about US$67 billion in 2030, representing a compound annual growth rate (CAGR) of about 7 per cent (Precedence Research, 2022). Superalloys use was valued at US$6 billion in 2021 and is projected to reach about US$12 billion in 2030, a CAGR of 9 per cent (Straits, 2022). Increasing use of specialist alloys in the automotive and gas turbine industries, where these materials provide improved operating efficiency and reduced environmental emissions, will be a key driver for future demand. Given increasing demand for alloys, potential intersectoral and international competition for materials and global concerns about the security of supply of minerals, it is timely to consider UK demand for specialist alloys and unwrought alloying metals used in the aerospace industry, their markets, and potential supply chain vulnerabilities. Furthermore, in common with other industrial sectors, increasing importance is being placed on their sustainable and responsible sourcing, which needs to be considered when assessing supply risk.

The research aimed to undertake a high-level assessment of these topics, assesses data availability, and identify key issues and knowledge gaps that may require urgent interventions and/or inform future in-depth, sector-specific studies. The study used a combination of collation, review and analysis of public-domain data and information and consultation with stakeholders, spanning raw materials handling and trading, processing, recycling, and manufacturing.

7 Methodology overview

Three approaches were used to gain insights into this topic.

7.1 LITERATURE REVIEW

The first, comprised a literature review to provide background information on the topic. It examined research papers and reports and online databases containing data and information on superalloys, their characteristics, uses in the aerospace and defence applications, and their mineral raw material requirements.

7.2 TRADE DATA COMPILATION AND ANALYSIS

The second approach involved the compilation and assessment of trade data for a range of alloying metals, to quantify material flows and identify trading dependencies. The trade data was extracted from the UN Comtrade database, which provides open access to official international trade statistics (DESA/UNSD, 2022). UN Comtrade presents trade data based on the Harmonised System (HS). Accuracy of the data was validated by reconstructing the search inputs between the reporting and partner countries. UK and global import and export data for the years 2017 to 2021, inclusive, were downloaded by both quantity (kilogrammes) and value (US$), for the HS trade codes representing the raw materials essential for manufacturing specialist alloys (Table 4). This was used to produce graphs, showing annual UK and global quantity and value of imports and exports of nine alloying metals, plus selected platinum-group metals (PGM). This data was also used to produce graphs of UK imports for individual alloying metals by quantity, and to calculate an average, for a 5-year average period of the proportion of imports derived from supplying countries. The UK's top trading partners plus the share from the rest of world is shown on the graphs.

Table 4. Selected Harmonised System trade codes for alloying metals and their descriptions.

HS codes	Description
711041	Metals; iridium, osmium, ruthenium, unwrought or in powder form
750220	Nickel; unwrought, alloys
810194	Tungsten (wolfram); unwrought, including bars and rods obtained simply by sintering
810294	Molybdenum: unwrought, including bars and rods obtained simply by sintering
810320	Tantalum: unwrought, including bars and rods obtained simply by sintering, powders
810520	Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders
810820	Titanium; unwrought, powders
810920	Zirconium; unwrought, powders
811212	Beryllium and articles thereof; unwrought beryllium, powders
811221	Chromium and articles thereof; unwrought chromium, powders
811241	Rhenium and articles thereof; unwrought, powders, waste and scrap (no data available)
811231	Hafnium and articles thereof; unwrought, powders, waste and scrap (no data available)
811240	Vanadium; including waste and scrap (no data available)

The selected HS codes assessed, represent the primary material forms (unwrought, powders, bars and rods obtained simply by sintering and other intermediate products of metallurgy) that are used for producing alloys and superalloys.

7.3 STAKEHOLDER CONSULTATION

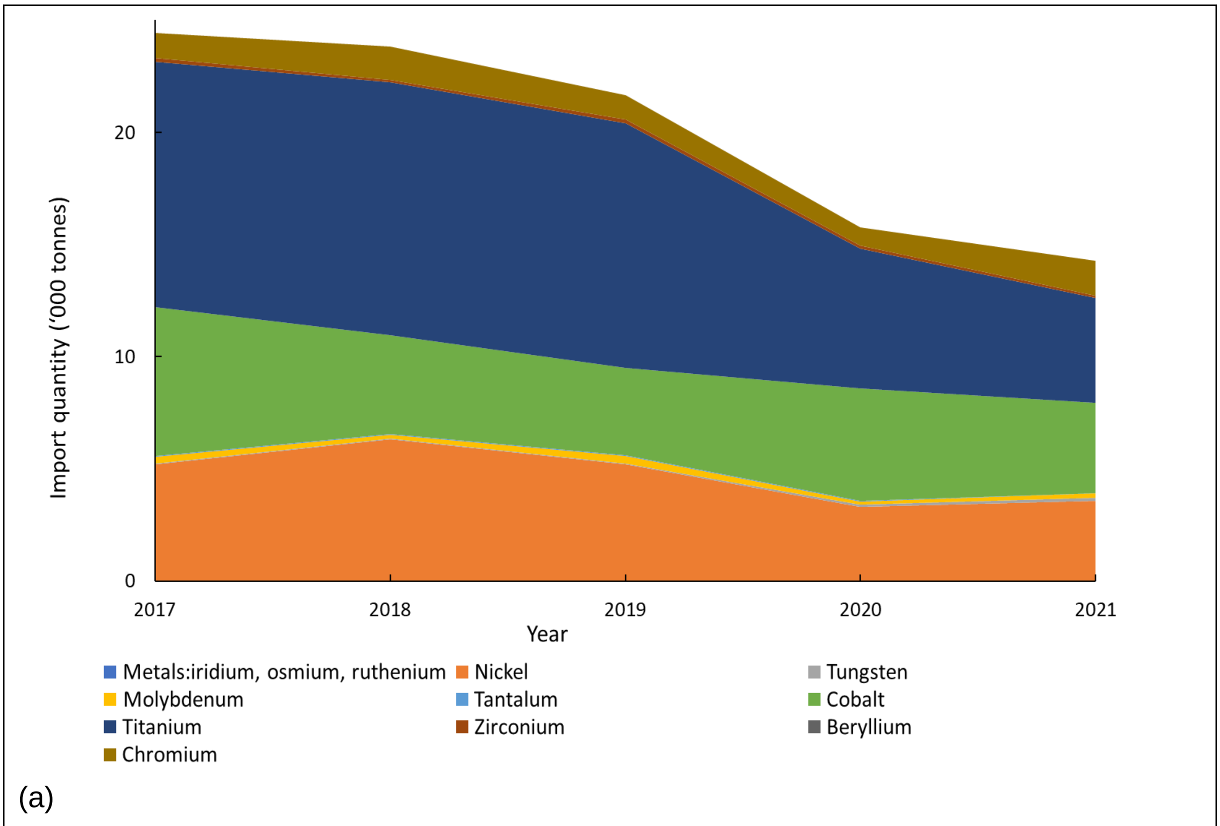
The third approach involved undertaking interviews with key stakeholders in the UK aerospace industry. The stakeholder list attempted to reflect the breadth and scale of companies operating in this sector and associated industry and research and development organisations. Thirty-two organisations were approached to participate in semi-structured interviews.

Those approached spanned original equipment manufacturers (OEMs – aircraft manufacture) e.g. Airbus SE, Boeing Co, Lockheed Martin Corp, and Tier 1 (system integrators) e.g. Rolls-Royce Holdings plc, GKN Aerospace Services Ltd., GE Aerospace to Tier 4 companies (materials supply or processing, including those involved in supplying pure metals, processing revert and trading metals) e.g. Advanced Alloy Services Ltd., Metalysis Ltd., Special Metal Alloys UK Ltd. Seven organisations responded positively to requests for interview/meetings, a response rate of 22 per cent. A combination of in person and virtual meetings were used. A list of questions (Appendix 1) was sent in advance to each stakeholder. The questions and discussion aimed to gather information on the importance of different metals used in specialist alloys, import and supplier dependencies, environmental, social, and governance (ESG) monitoring or compliance, the importance of recycling, and to gain insights into the key challenges and risks for their businesses. The information arising from the interviews and subsequent email correspondence has been aggregated and anonymised to protect confidentiality.

8 Analysis of trade data

8.1 UK BULK TRADE FLOWS

The UK's total imports, by quantity of selected alloying metals (nickel, tungsten, molybdenum, tantalum, cobalt, titanium, zirconium, beryllium, chromium and mixed selected PGM, including iridium, osmium, and ruthenium; refer to Table 4 for full descriptions) has steadily decreased since 2017 (Figure 8a). This is consistent with the value of total UK imports of these metals generally decreasing since 2018. In 2021 the value of imports of these metals increased slightly, despite a reduction in total quantity over the previous year, which reflects higher metal prices. Despite global imports by quantity remaining similar in 2021 to the previous two years, the value of global imports in 2021 increased significantly relative to the previous two years, also reflecting higher prices in the global market for these metals. The UK's total exports of alloying metals, by quantity have decreased substantially since 2019, a trend which is also apparent in the global export data. In common with UK imports of these alloying metals, despite a decline in the quantity of exports in 2021, the value of UK exports increased relative to the two previous years. The value of global exports of these alloying metals also increased in 2021, reflecting higher prices (Figure 8b).



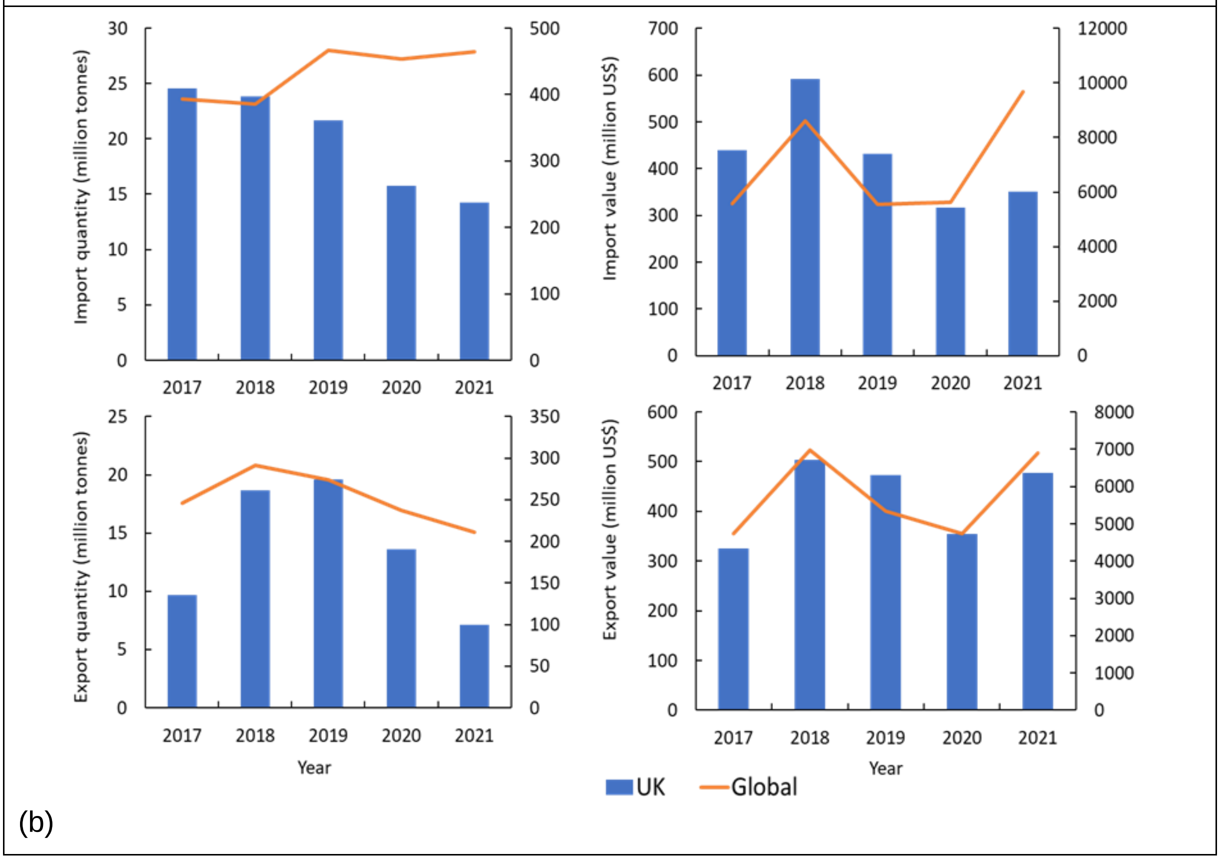


Figure 8. UK trade, from 2017 to 2021 for nine alloying metals, and mixed selected platinum-group metals required to produce specialist alloys. a) UK and global imports and exports of these metals by quantity; b) Imports of individual metals to the UK by quantity and value. Data source: DESA/UNSD (2022).

8.2 UK IMPORT DEPENDENCY

The trade data indicates that the USA is the dominant supplier of nickel; unwrought, alloys (24%), titanium; unwrought, powders (hereinafter referred to as titanium; 53%), and zirconium; unwrought, powders (hereinafter referred to as zirconium; 63) to the UK based on an average of UK imports over 5 years. This is consistent with the USA being a major producer of high-grade alloys, with leading domestic companies such as the PCC Group and ATI Inc supplying the UK market (Figures 9–11). UK imports of titanium from the USA have declined significantly since 2017. The importance titanium imports from Japan fluctuates annually, but Japan accounted for 33 per cent (based on average UK imports over 5 years) of total UK imports. UK imports of titanium from other countries, including China have remained broadly constant. There was a notable reduction of UK imports of zirconium from the USA in 2021. France and Germany are an important source of zirconium for the UK, accounting for 16 per cent and 15 per cent, respectively, based on an average of UK imports over 5 years.

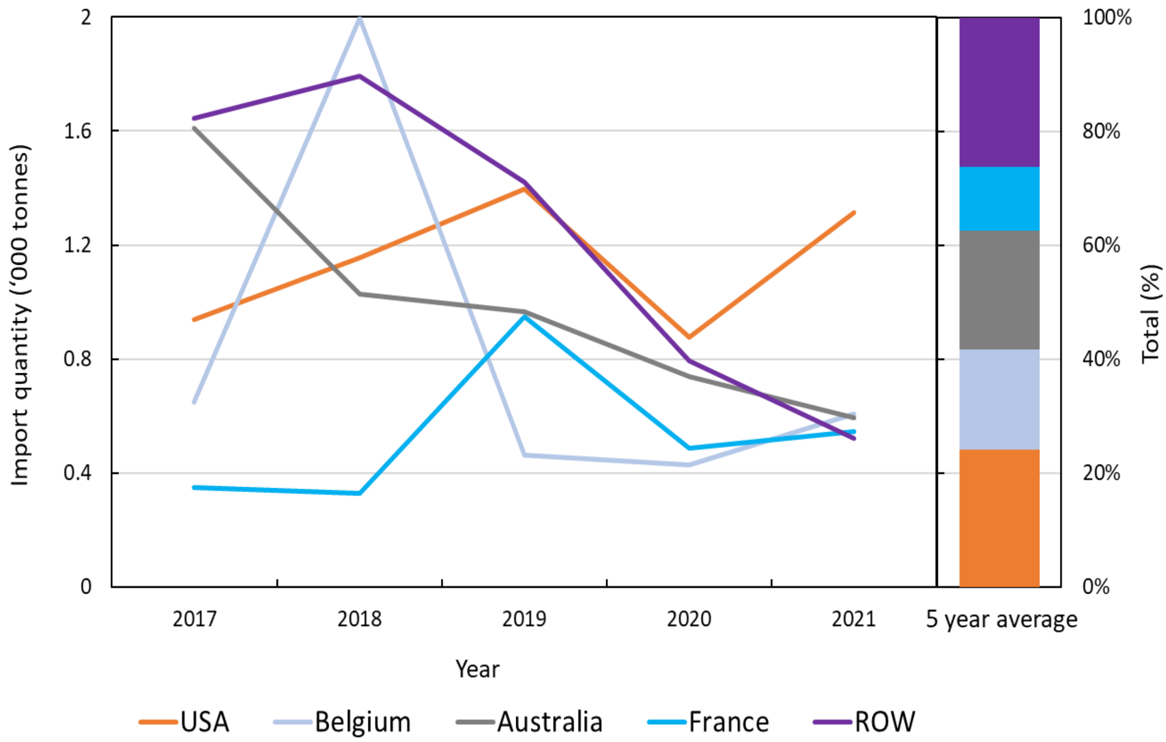


Figure 9 UK imports of nickel; unwrought, alloys between 2017¬2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 750220; USA = United States of America; ROW = Rest of World.

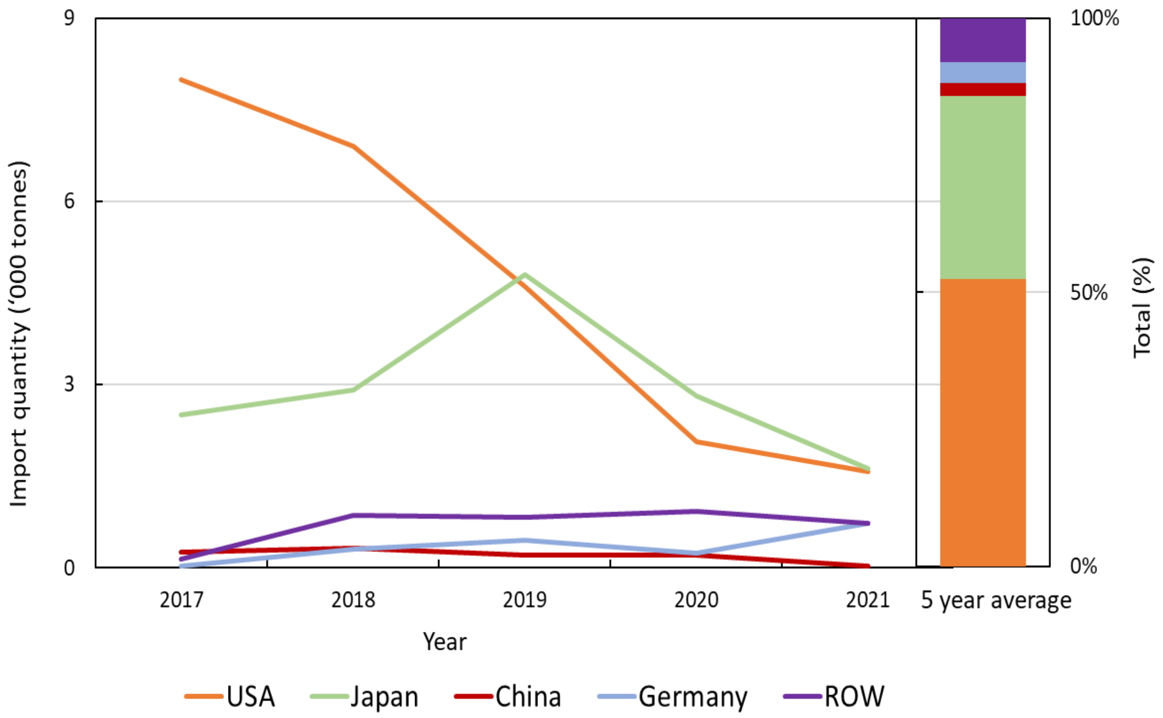


Figure 10 UK imports of titanium; unwrought, powders between 2017-2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 810820; USA = United States of America; ROW = Rest of World.

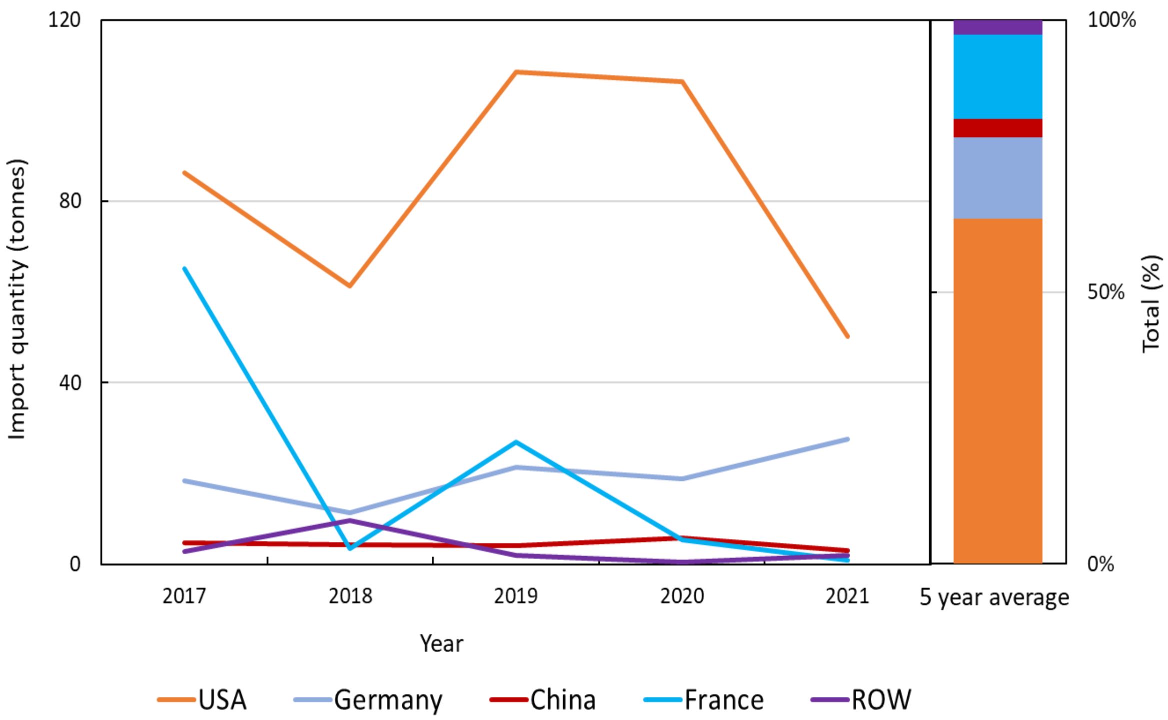


Figure 11 UK imports of zirconium; unwrought, powders between 2017-2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 810920; USA = United States of America; ROW = Rest of World.

Based on average UK imports over 5 years, China was the leading supplier of tungsten; unwrought, including bars and rods obtained simply by sintering (hereinafter referred to as tungsten) and molybdenum; including bars and rods obtained simply by sintering (hereinafter referred to as molybdenum), providing about 77 per cent and 39 per cent of UK imports, respectively (Figures 12 and 13). UK dependence on China for tungsten has been on an increasing trend since 2017, with significant growth from 2019 onwards. Following several years of declining importance, UK imports of molybdenum from China increased significantly in 2021, as imports from the Netherlands, Germany and the rest of the world continued to decline.

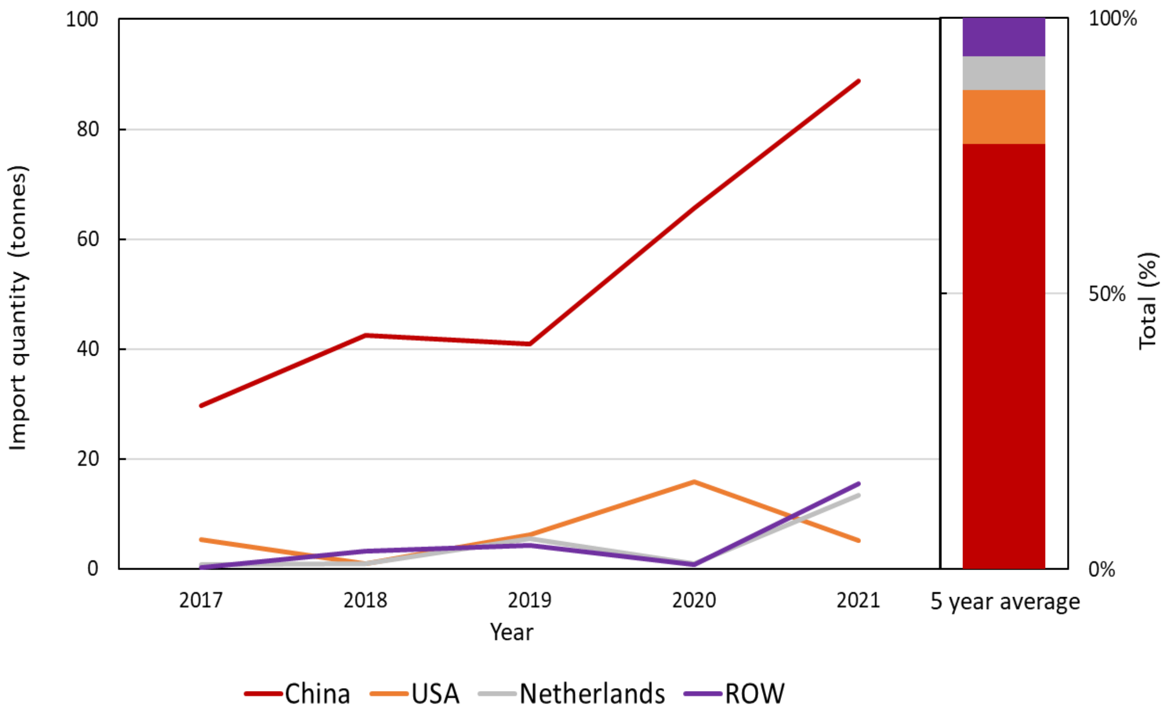


Figure 12 UK imports of tungsten; unwrought, including bars and rods obtained simply by sintering, between 2017-2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 810194; USA = United States of America; ROW = Rest of World.

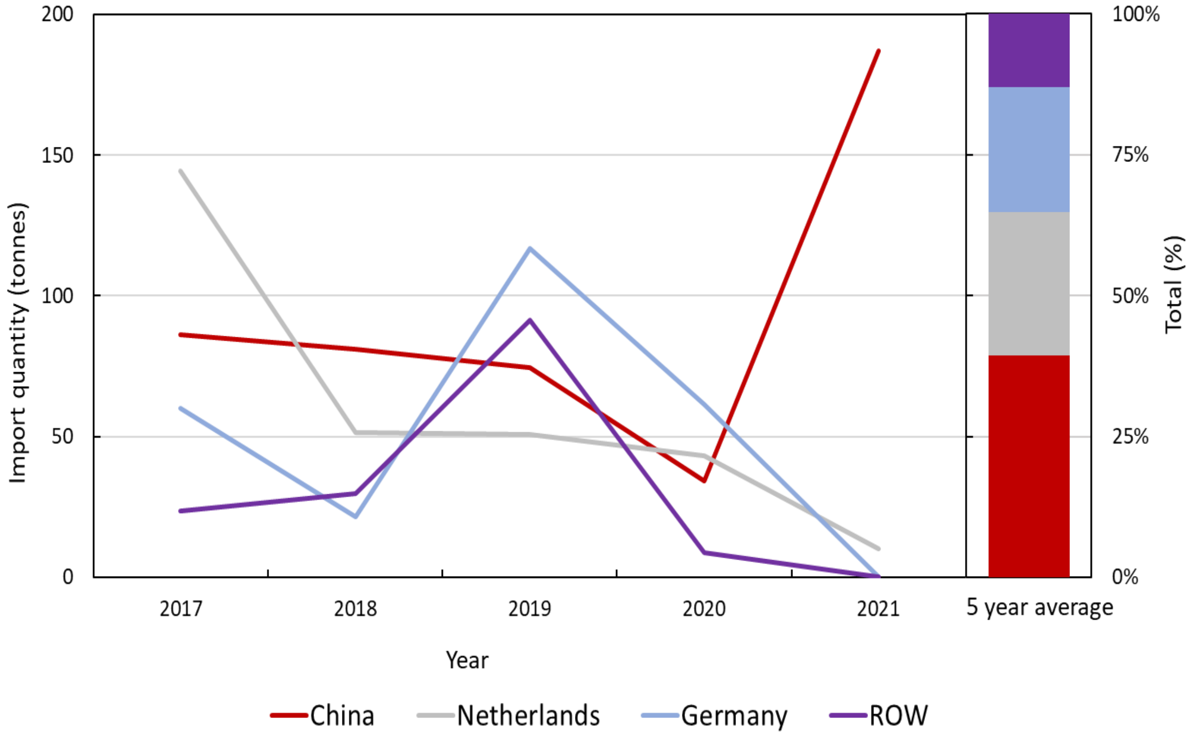


Figure 13 UK imports of molybdenum; unwrought, including bars and rods obtained simply by sintering between 2017-2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 810294; ROW = Rest of World.

Based on average UK imports over 5 years, China was the principal source (36%) of tantalum imports; unwrought, including bars and rods obtained simply by sintering, powders (hereinafter referred to as tantalum) to the UK. However, the importance of China as a tantalum supplier to the UK has fluctuated, reducing significantly since 2019, and primarily being replaced by increased imports from the rest of the world (Figure 14). Considering average UK imports over 5 years, the remaining supply of tantalum was relatively evenly distributed between Germany (23%) and the rest of the world (26%), with the remaining 14 per cent derived from the USA.

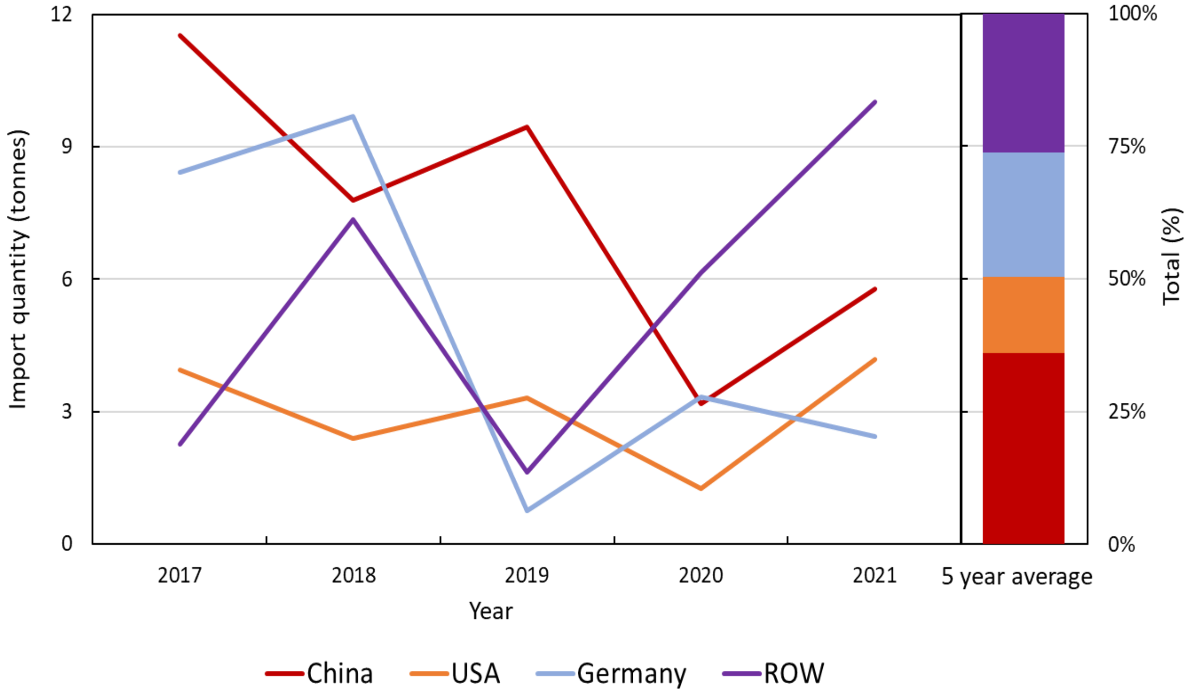


Figure 14 UK imports of tantalum; unwrought, including bars and rods obtained simply by sintering, powders between 2017-2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 810320; USA = United States of America; ROW = Rest of World.

Considering average UK imports over 5 years, France accounted for more than half of the UK's imports of chromium and articles thereof; unwrought chromium, powders (hereinafter referred to as chromium). Its contribution to UK imports has declined since 2018, with imports from other countries remaining broadly level, except for in 2021, when imports from the rest of the world exceeded those from France. Malta also supplies chromium to the UK, representing 8 per cent of average UK imports over 5 years (Figure 15). The UK imports of beryllium and articles thereof; unwrought beryllium, powders (hereinafter referred to as beryllium) have declined significantly from 232 kg in 2017 to 24 kg in 2019. Almost all this supply is from France, with a minor contribution from the USA (e.g., 3 kg in 2019) (Figure 16).

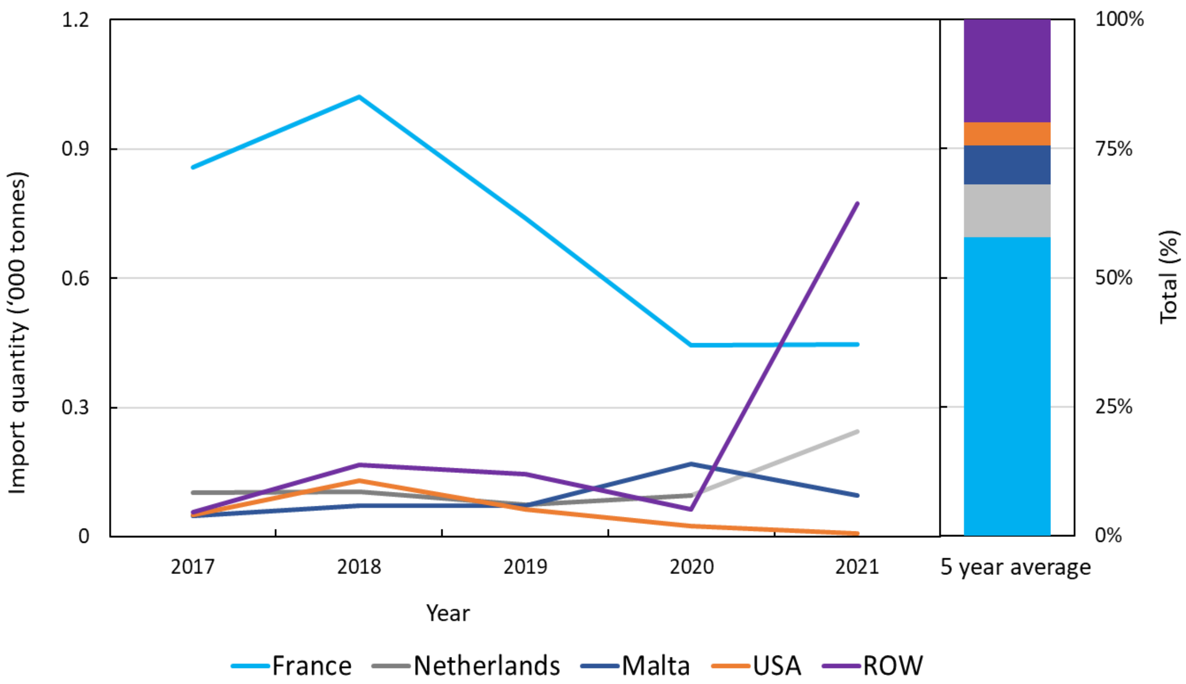


Figure 15 The UK import of chromium and articles thereof; unwrought chromium, powders between 2017-2019 by quantity. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 811221; USA = United States of America, ROW = Rest of World.

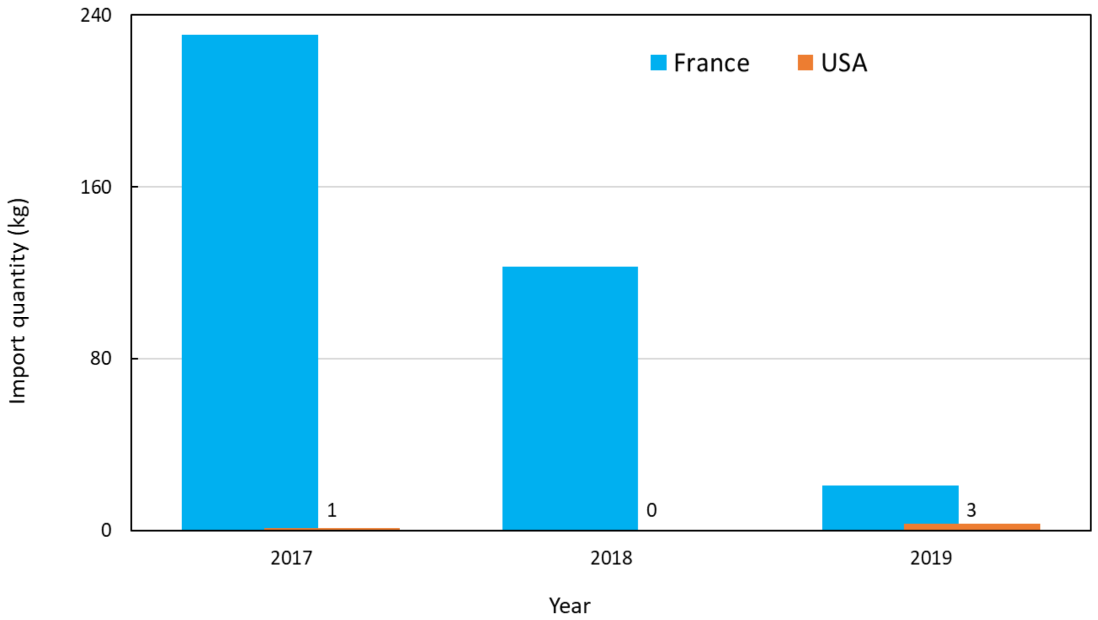


Figure 16 UK imports of beryllium and articles thereof; unwrought beryllium, powders between 2017-2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 811212; USA = United States of America.

Considering average UK imports over 5 years, the Netherlands accounted for almost half of UK supply of cobalt; mattes and other intermediate products of cobalt metallurgy (hereinafter referred to as cobalt) (Figure 17). The Netherlands has no cobalt production and refining capacity; therefore, this flow does not represent the primary source of this material. Large ports in the country act as major hubs for materials handling and distribution into the wider European market. Imports of cobalt to the Netherlands do reflect the locations of global cobalt refining activity, namely Canada, Morocco, Russia, Norway, Australia and the USA, in order of decreasing importance (BGS, 2022). Despite China being the world's largest producer of refined cobalt, a relatively small proportion of cobalt routed through the Netherlands originates in China. Another important European source of UK imports of cobalt is Belgium (10% of average UK imports over 5 years), which does have domestic recycling and refining capacity. Whilst Finland is Europe's largest producer of cobalt (14 287 tonnes in 2021), the proportion of UK cobalt imports from Finland has fallen year-on-year since 2017, with no reported imports from Finland in 2020 and 2021. Imports of cobalt to the UK from Russia have fluctuated since 2017, rising in importance in 2019 and 2020, before significantly declining in 2021.

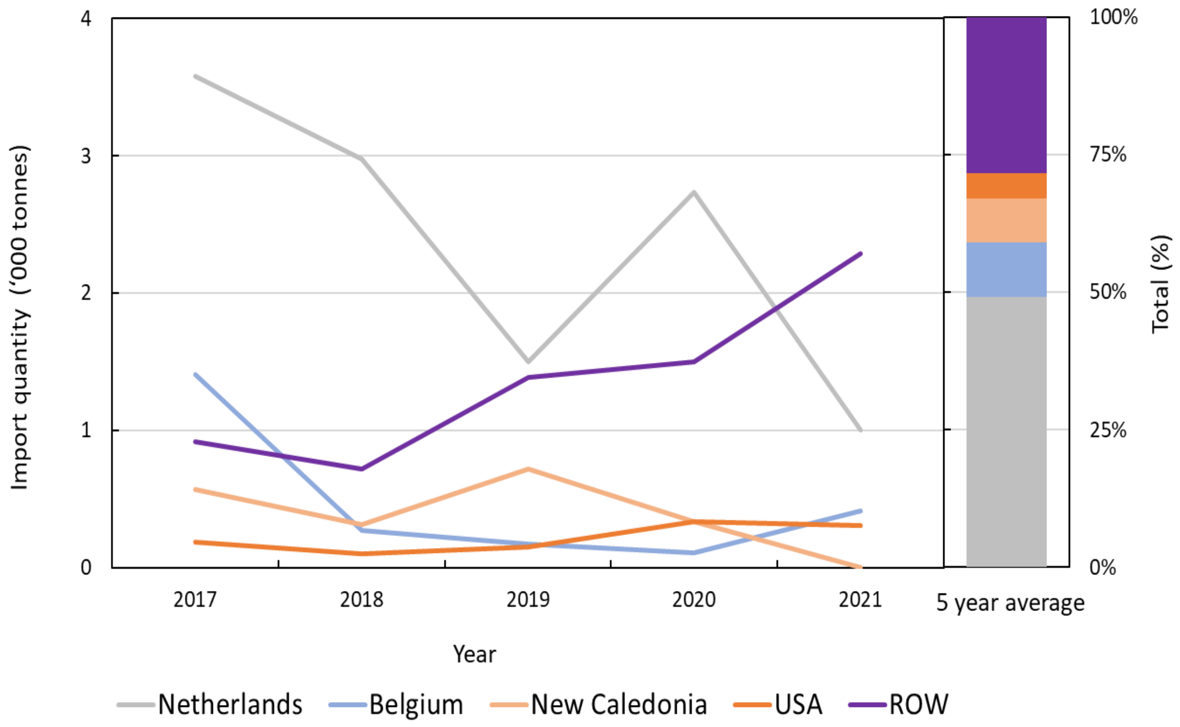


Figure 17 The UK's import of cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, between 2017-2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 810520; USA = United States of America; ROW = Rest of World.

Considering average UK imports over 5 years, South Africa supplied more than 50 per cent of the UK's metals iridium, osmium, ruthenium, unwrought or in powder form (hereinafter referred to as iridium, osmium and ruthenium). South African imports to the UK have declined since 2017, with a slight recovery in 2021. Based on average UK imports over 5 years, the UK received about 8 per cent of its imports of iridium, osmium and ruthenium from Russia, which is the world's second largest producer of PGM after South Africa. 6 per cent of UK imports were derived from the USA, which is the fifth largest producer of PGM globally. Despite Ireland not having any primary production of PGM, UK imports of iridium, osmium and ruthenium from this source were relatively constant between 2017-2020, but significantly decreased in 2021. Based on average UK imports over 5 years, 21 per cent of the UK imports of iridium, osmium and ruthenium form came from Ireland (Figure 18).

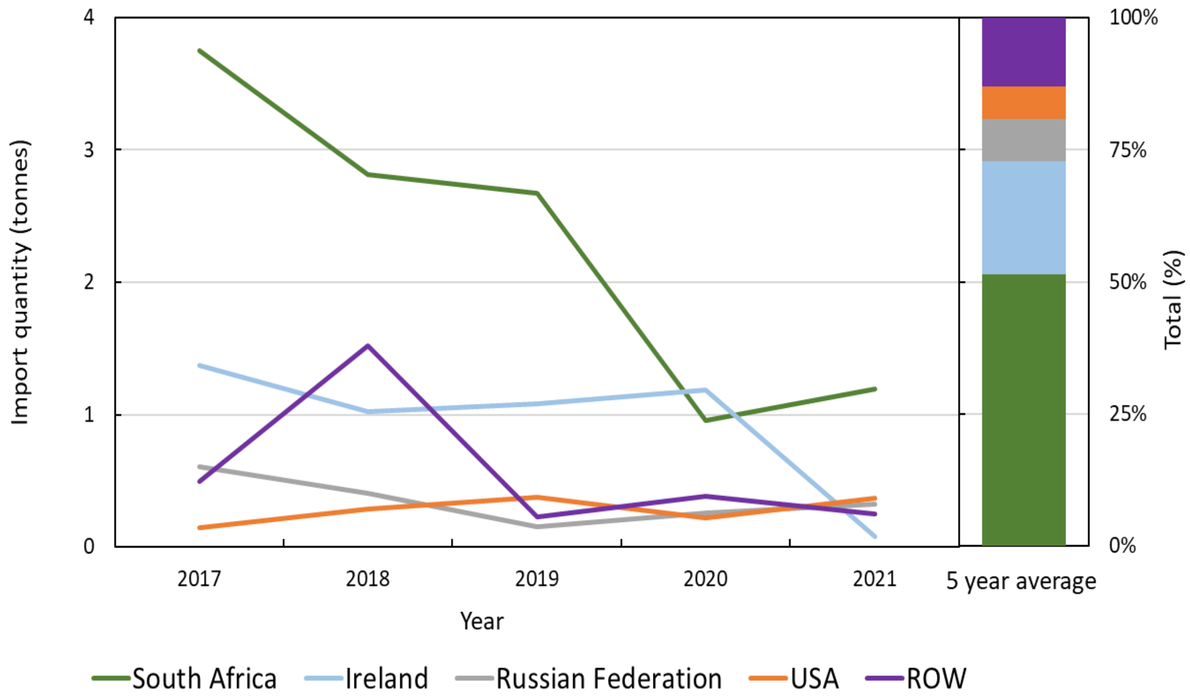


Figure 18 The UK's import of metals; iridium, osmium, ruthenium, unwrought or in powder form between 2017-2021. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 711041; USA = United States of America; ROW = Rest of World.

8.3 SUMMARY AND KEY OBSERVATIONS

Despite the lack of trade data for certain important alloying metals, such as hafnium (that has two relevant HS codes but no data reported against these) and scandium (that cannot be discriminated from the rare earth elements), and the limitations and potential inaccuracies of the trade data that is available, this study highlights the dependency of the UK on several countries for the supply of metals that are vital for the domestic production of a range of specialist alloys. The overall decline in total imports of alloying metals to the UK is likely to reflect reduced demand, owing to the downturn in manufacturing during the COVID-19 pandemic. The commercial aviation sector was particularly affected by reduced demand and remained weak during 2021. The USA is the largest supplier of nickel, titanium and zirconium to the UK, accounting for 63 per cent (based on an average of 5 years data) of UK imports of the latter. The importance of China, as the UK's leading source of tungsten and molybdenum is in line with expectations given its global dominance in the production of these metals. This dependency will probably continue to increase based on the trend of growing imports of these metals from China. China is also an important supplier of tantalum to the UK (36%, based on an average of UK imports over 5 years) and makes a minor contribution to total UK imports of titanium and zirconium.

The UK is reliant on imports from a few European countries for several of the alloying metals assessed, however, these do not always represent the locations of primary mining and refining capacity. France is notable for the proportion of total imports of chromium and beryllium that it supplies to the UK. NGK Berylco France is a world leader in processing high-precision strips, wires and bars in copper-beryllium alloys. France and Germany are both important sources of zirconium for the UK, with France being a major producer of nuclear-grade zirconium. France is also an important source of chromium for the UK, as French-based DCX Chrome, a subsidiary of Delachaux group, produces chromium metal by aluminothermic reduction. Although Malta makes a relatively small contribution to UK chromium imports, this supply does appear to be based on domestic processing. UK imports of nickel and cobalt from Belgium do reflect domestic recycling and refining capacity for these metals. In contrast, despite being an important source of imports of several alloying metals for the UK, the Netherlands is not a producer of cobalt, molybdenum, tungsten, and chromium. In common with some other European countries, the trade data reflects the location of the ports from which the metals were shipped. It is necessary to look further back along the value chains to identify the location of the extraction and processing stages which led to the production of these materials.

The USA is the largest supplier of titanium to the UK, however, imports have declined significantly since 2017. The reason for the decline in imports during 2018 and 2019 is unclear, however, the continued decline since the COVID-19 pandemic is attributed to reduced industrial demand. Although China is the largest producer of titanium minerals and titanium sponge globally (BGS, 2022; USGS, 2022b), it only accounted for 2 per cent of UK titanium imports (based on an average of UK imports over 5 years). After the USA, Japan is the most significant source of UK titanium imports. This is in line with expectations, as Japan is the world's second largest producer of titanium sponge (USGS, 2022). Russia is the world's third largest producer of titanium sponge (USGS, 2022b). Whilst the UK does receive imports of titanium from Russia, average UK imports over a 5-year period do not place it in the top four countries supplying the UK. However, since 2017 UK imports of titanium from Russia have been growing in importance, increasing by nearly 5-fold in 2020 over the previous year. Most importantly, Russia was the largest supplier of aerospace-grade titanium, producing half of the world's titanium used in aerospace prior to 2022 (AeroTime, 2023).

Considering average UK imports over 5 years, South Africa, the world's largest producer of PGM supplied more than 50 per cent of the UK's iridium, osmium and ruthenium. The second most important source of imports for the UK was Ireland, which does not have primary production of PGM. The USA and Russia, which are major PGM producers also supplied these metals into the UK market. Imports of iridium, osmium and ruthenium from Russia have fluctuated since 2017 but were greater in 2021 than the previous year.

9 Findings of the stakeholder consultation

Specialist alloys are such a diverse group of materials, in terms of their compositions, properties, market size and volumes traded, with an equally broad range of applications in the aerospace industry and beyond that gaining a clear overview of their end-uses, importance and supply chains is challenging. In line with expectations, it was found that respondents were not generally willing to disclose specific information on the use of materials at a company- or application-level owing to concerns about intellectual property and/or security classification. This was particularly the case for specialised/proprietary processes and the materials required for the manufacturing of high added-value products and/or those with defence applications. Details about their individual supply chains and markets were generally also considered commercially sensitive. Accordingly, quantitative data on volumes of material traded or handled by individual companies, material prices and information on supply and purchasing relationships was not forthcoming.

Despite the varying nature of the organisations engaged (spanning design, manufacturing and distribution of power systems for aviation and other industries, supplying pure alloying metals, processed revert, and providing toll-process services, such as storage facilities for the UK superalloy industry), several common themes emerged during the interview with stakeholders, and these are summarised under the headings below.

9.1 MATERIAL REQUIREMENTS, APPLICATIONS AND DEMAND

Irrespective of the scale or focus of the business, all companies are dependent on raw materials sourced from overseas. Their specific metal and material requirements are determined by the nature of their business and stage in the value chain that they operate, with variable dependence on nickel, titanium, tantalum, vanadium, rhenium, ruthenium, zirconium, hafnium, scandium, aluminium, tungsten, chromium, cobalt, and niobium. The significance of nickel-based superalloys was emphasised by many, due to their importance in aircraft engines and defence applications. Generation 1–4 single crystal nickel-based superalloys are particularly important in turbine blades and turbines (Figure 4). Nickel-based superalloys containing very minor quantities of hafnium, rhenium, tungsten and tantalum provide unique properties required for specific aircraft components. Hafnium is incorporated in superalloys used in the turbine section and rhenium in materials for turbine blades. Zirconium and ceramics are used as thermal barriers, diffusion and overlay coatings in superalloys to protect the substrate from thermal degradation, oxidation and corrosion, respectively. These properties are important in both aircraft and submarine applications. Cobalt, chromium, tungsten and tantalum are common additives to superalloys used in the structure and landing gear of aeroplanes.

Demand for hafnium is generally increasing across a range of end-use applications and there is little that can be done to manage this. Demand remains strong in the established end-use sectors, of aerospace and defence and the nuclear power industry. Demand from these sectors is expected to grow in several countries, particularly in China. Growing demand from the electronics and the high-end automotive sector is linked to use of the MAR-M247 superalloy. A notable increase in hafnium demand is associated with the rapidly expanding use of the C-103 (89% Nb, 10% Hf, 1% Ti) superalloy, employed in reusable rockets for satellite deployment and this trend is likely to continue.

9.2 UK IMPORT DEPENDENCY, SUPPLY RISK AND PRICE

UK-based Tier 1 companies have established, long-term contracts with suppliers in the UK and overseas for the materials and components used in their businesses. The principal dependencies, for the supply of finished components used by assembly or equipment providers and system integrators in the civil and defence aviation industries in the UK, are with the USA-based companies, such as PCC Aerostructures, ATI Aerospace, and TIMET.

Since the invasion of Ukraine by Russia, UK businesses have been forced to identify alternative metal sources, in particular nickel and titanium (Russia accounted for about 7% and 13% of world production of refined nickel and titanium sponge, respectively in 2020; BGS, 2022; USGS, 2022b). UK companies are now receiving material from additional countries, particularly the USA and those in Europe. UK supply of rhenium and ruthenium is dominated by the USA and Canada.

The hafnium available to the market is essentially the surplus that the nuclear industry is unable to absorb. It was indicated that the USA and France supply most of the UK's hafnium, which is consistent with the UK's trade dependencies for zirconium. However, these countries are focused on zirconium and hafnium production for their domestic nuclear industry and not the international market. It would not be feasible or economic for them to create a zirconium stockpile, simply to increase hafnium supply. It was also indicated that once producers have satisfied domestic demand from the nuclear industry, producers prefer supplying hafnium tetrachloride ($HfCl_4$), required by the electronics sector. This is because supplying crystal bar, the main material form used in superalloy production, requires additional processing and yield losses. Although the market is opaque, shipping records from the USA in 2022 indicate a significant flow (estimated to be about 30 tonnes) of hafnium to Korea and Japan for their electronics industries.

It was emphasised that most 'traded' hafnium that is not tied into long-term supply agreements with producers in the USA and France (and therefore, potentially available to other consumers) is originating in China. Although levels of Chinese hafnium production are unclear, it is estimated to be more than 20 tonnes. However, expanding domestic demand for hafnium in China and export control restrictions, owing to its strategic applications in the nuclear and defence industries, including nuclear submarines, has led to Chinese suppliers being unable to honour existing supply agreements with the UK and other countries. Historically, both Russia and Ukraine have been suppliers of hafnium to the international market. However, neither is currently an option due to self-imposed sanctions by many consumers.

Chinese hafnium production was affected by a reduction in nuclear-grade zirconium production during the COVID-19 pandemic, owing to lower demand. Some of this capacity has not been reinstated. Subsequent industrial lockdowns and increased environmental regulations have also impacted on Chinese supply. Furthermore, the hafnium market still appears to be in a post-COVID-19 pandemic recovery phase, with consumers attempting to replenish stocks drawn down during the pandemic.

These supply challenges, coupled with the increasing demand for hafnium discussed above, resulted in a market shortage during 2022 and record prices. Over the previous five years hafnium prices had been relatively stable, trading in the range of US$650–950 per kilogram. However, as of November 2022 quotations for superalloy grade were US$3000 per kilogram, with some suppliers not willing to quote on new businesses (with many UK deliveries already delayed, some by up to 6 months) and warning of extremely constrained availability going forward. In November 2022 certain suppliers were indicating that there would be no material available for immediate (spot market enquiries) delivery in 2023, and only very small amounts if consumers were willing to book for unconfirmed dates in 2023. It is suggested that if the Chinese authorities revoke or do not issue export licenses this may provide Chinese suppliers with adequate justification to break commercial supply contracts with UK buyers. According to the price reporting agencies, hafnium prices were approaching US$4000 per kilogram by late December 2022, but traders were reporting prices of more than US$5000 per kilogram. At this time, it was reported that the hafnium required by a UK Tier 1 gas turbine engine manufacture for 2023 production had not been covered. January 2023 saw continued price escalation, with price reporting agencies indicating hafnium prices of US$4750 per kilogram and reports of trade being done in the US$5500–6000 per kilogram range and offers being made at over US$7000 per kilogram.

There is consensus among UK hafnium end-users and traders that there is insufficient global production capacity to meet current and forecast demand, and there is no immediate solution to this issue. A deterioration in political relations with China and/or greater emphasis on fulfilling growing domestic demand, potentially leading to export licences being revoked is a major risk to UK consumers, as it could result in existing booked orders not being fulfilled.

It was indicated that UK supply of chromium is dominated by China and South Africa. Some UK-based alloy manufacturers obtain half of their raw material requirements from the European Union and the remaining material from China. Certain high-purity chromium metal, for very specialist applications is only produced in China.

It was indicated that for certain alloying metals, a significant amount of material imported into the UK from China to be processed by UK companies operating in the alloy sector, is classed as ‘waste and scrap’.

In summary, most of the UK companies consulted are primarily dependent on suppliers from the following regions and countries, ordered by importance of imports: North America (USA and Canada), the European Union (especially Germany, France, and Netherlands), China, Russia, South Africa, the Middle East, South America, Japan, and Singapore.

9.3 ESG MONITORING AND COMPLIANCE

The growing emphasis being placed on the ESG compliance of supply chains and material traceability, and the importance of being able to verify and evidence this was emphasised by all stakeholders. Tier-1 companies indicated that their contractual agreements with suppliers include stipulations on ESG standards and the traceability of materials, and this is stringently monitored as far as is practicable. It was emphasised that this is particularly important if the metal is designated a so-called ‘conflict mineral’ with associated regulations (e.g., tantalum), or if greater risks exist because of governance issues and/or poor human rights track record in the country of origin.

The challenges with monitoring and compliance were highlighted. Lack of consensus on international standards and agreed metrics, variable national standards, poor data quality and the time it takes for paperwork associated with a shipment to move through the system, complicate the verification process, introduce subjectivity, and make comparing different sources of materials difficult. It was suggested that the industry lags behind some other sectors in terms of ESG monitoring and the capture of relevant data. It was highlighted that as a mineral and metals move through the value chain (between countries and/or companies) there is a significant risk that information that could be used to verify ESG compliance is lost or not transferred. This lack of data and traceability increases the risk of ‘metal washing’, whereby small amounts of non-ESG compliant material enter ESG-compliant flows, which attract a market premium. It was indicated that it is very difficult for UK-based companies to demonstrate and ensure ESG compliance when they are sourcing material from Chinese ‘satellite’ companies, operating in countries with weak ESG standards and in which metal washing is prevalent. Even if international suppliers provide appropriate documentation for shipments they are challenging to authenticate. It was highlighted that due to a lack of material passports, ensuring the ESG-compliance of secondary supplies of metal is currently impossible. Businesses involved in material processing and supply and trading metals indicated that major initiatives, including significant investments in supply chain monitoring in consuming companies (primarily Tier 1-3), are strongly driving the ESG agenda. Ensuring ESG compliance adds cost to materials procurement, but businesses consider this acceptable because of the ethical importance and potential reputational risk.

9.4 PRICE-DRIVEN SUBSTITUTION AND RECYCLING

It was emphasised that the recycling of end-of-life alloys and associated metals or specifically ‘revert’ (see section 5.2) is of great importance to the industry to minimise the demand for primary raw materials and diversify supply. This has led to significant investment in recovery, closed-loop recycling, and reusing end-of-life metals in manufacturing. However, it was indicated that there is still much greater potential here due to current ineffective recycling practices and downcycling. It was suggested that the total levels of recycling quoted by the aerospace industry as achievable for an aero engine are misleading, because the more complex alloys that contain the most critical metals are often downcycled. For example, if a pressure turbine blade that contains elements such as cobalt, tungsten, tantalum, rhenium and hafnium is used to produce stainless steel these specialist metals are lost.

Rhenium and ruthenium superalloys provide examples of both the potential for metal substitution in certain superalloys and the importance of revert. During the mid-2000s ruthenium was excluded from superalloys and substituted for an alternative minor metal (not disclosed as proprietary) because of unreliable supply and high price volatility.

Rhenium prices reached very high levels during the 2000s, however, it was not possible to exclude or substitute it in the same way as ruthenium. It is reported that the very high prices meant it was profitable to chemically extract from rhenium-bearing nickel-based superalloy scrap. As prices moderated, greater emphasis was placed on revert (Lipmann Walton & Co Ltd. 2021b). Accordingly, supply concerns and elevated prices were the stimulus for closed-loop recycling of rhenium-bearing superalloys, which involved capturing the rhenium units that were previously lost in the production of other nickel superalloys. In parallel consumers of rhenium superalloys encouraged their suppliers to utilise more superalloy revert. This comprised cleaned foundry casting solids, scrapped blades, and eventually end-of-life blades. Greater use of revert has reduced demand for the virgin addition of rhenium to superalloys and lower associated costs. Currently, typical rhenium-containing superalloy melts include about 40 per cent revert.

Recycling is considered an important option for increasing and diversifying hafnium supply but is not currently commercially viable. There are currently sources of hafnium in the UK that are poorly recycled, for example MarM247. Continued price escalation may change this. However, as most hafnium-bearing alloys contain 0.5–1.5 per cent hafnium the yield from even large volumes of end-of-life materials will be relatively small. Options for substitution of hafnium is being raised by OEMs, however, there are very few alternatives that are readily available and cost effective.

9.5 KEY CHALLENGES FOR INDUSTRY AND THE ROLE OF GOVERNMENT

It was emphasised that there is a general requirement to raise awareness of the industrial and economic importance of minor metals and specialist alloys amongst the public and policymakers. This includes the current risk of potential supply shortages of certain key alloying metals.

It was highlighted that concerns about sanctions and associated market uncertainty caused by Russia's invasion of Ukraine have led to significant price volatility for metals such as nickel and titanium, for which Russia is a globally important producer. Consumers indicated that prior to the conflict they were not excessively concerned by projected demand growth for these metals. However, a potential reduction in supply from Russia would stress an already tight market. There are concerns that should aerospace and defence spending increase, these market developments could affect prices for alloy forgings and castings.

Western aerospace companies were heavily reliant on titanium from Russia but have stopped buying or are reducing reliance on this source. Given the importance of titanium to the UK aerospace and defence sectors, it was suggested that establishing a 'national titanium strategy' would enable a substantial change in the use case, improving aircraft performance and possibly helping to reduce market volatility. It was indicated that there are opportunities to capture more value from the processing and manufacturing of titanium products in the UK, for example from additive manufacturing. Initiatives focussed on raw materials qualification (the process of establishing the source, identity, purity and general suitability of materials) could promote UK productivity and competitiveness.

There was some reluctance to new policies or regulations aimed specifically at increasing the recycling rates of superalloys. This is because recycling of these materials often involves downcycling to produce lower grade alloys such as stainless steels. Therefore, increased recycling rates alone do not directly result in greater availability of the contained minor metals to produce new superalloys. What should be encouraged is greater levels of 'functional' end-of-life recycling, which preserves the properties of the contained metals rather than merging them into larger flows in which the properties are degraded or even lost. Essential to this is recognising the strategic importance of these minor alloying metals to UK industry, understanding superalloy and minor metal stocks and flows in the UK economy, and promoting closed-loop recycling practices. Targets could be established to promote the importance of recovering specific alloy elements during recycling. It was suggested that because functional, closed-loop recycling reduces demand for virgin metal, it represents an important strategy for minimising the impacts posed by supply chain disruption and metal price volatility. In parallel, it was indicated that recycling, facilitated by new technologies will play an important role in helping the aviation sector to achieve its target of net zero by 2050.

It was suggested that technology transfer from friendly, partner countries could be facilitated by Government involvement and support.

The rapidly evolving global geopolitical landscape and rising international competition for resources is considered to have significantly increased the risk of mineral raw material supply disruption to the UK and general market volatility. Diversification of UK raw material supplies and strengthening agreements with other countries (particularly those in Europe and North America) to cooperate on the security of supply of raw materials is considered vital by UK industries that rely on superalloys and alloying metals. It was emphasised that the UK Government is integral to this and has an ongoing role to play in maintaining and strengthening relationships with countries such as the USA and France that are major suppliers of minor metals to the UK. The Government could also support UK companies to establish links with foreign counterparts working in both raw material supply chains and the manufacturing sector.

Monitoring policy and market developments in countries that are major consumers of minor metals is vital for assessing demand. There are reports of new or significant increases in demand for hafnium from the electronics industries in Japan and Korea. Changes in nuclear energy policy, for example the recent announcements by Japan, is likely to have a significant impact on demand for a range of minor metals used in nuclear power plants (Argus, 2022).

It was indicated that the Government should be aware that due to the exceptional price rises for some of the alloying metals they are now being targeted by organised crime.

Differing views were expressed on whether these minor metals would benefit from being labelled as ‘critical’. Criticality is generally assessed in terms of two dimensions, the likelihood of supply disruption, often termed supply risk (S), and the economic vulnerability of the consumer to potential supply disruption (V). The ‘UK criticality assessment of technology critical minerals’ considered a relatively small number of candidate materials (Lusty et al. 2021). Several important metals used in superalloys were not considered due to time constraints and/or concerns about availability of data to support their inclusion in the assessment. The assessment indicated that rhenium had ‘elevated’ S and ‘low’ V. However, minerals such a rhenium suffered from a lack of data to support the analysis. Titanium was assessed to have ‘low’ potential criticality, whilst nickel has ‘elevated’ potential criticality. Tantalum was assessed to have ‘high’ potential criticality. Neither hafnium nor zirconium were assessed. Given their market characteristics, these metals are likely to have a ‘high’ potential criticality. It was suggested that hafnium fulfils all the criteria for a critical mineral (i.e., production concentration, it is entirely a by-product from a single sector, it is experiencing rapid demand growth from several sectors, it has strategic applications, a high level of price volatility and an opaque market), thereby supporting its addition to critical minerals lists. In contrast, it was also suggested that simply branding a mineral or material ‘critical’ rarely helps to stabilise the market and can lead to greater volatility as buyers respond to this signal. Quantitative criticality assessment requires adequate data for all indicators across the suite of candidate materials. It was indicated that whilst possible to include certain minor metals in an assessment, the outcome would be most likely incorrect, as obtaining consistent, high quality, up to date data is not possible for some of these. This is because producers are reluctant to disclose sensitive production data for these metals as the market is small and comprises few companies. It was reported that obtaining reliable data on their end-use is even more challenging. Accordingly, because of these data limitations, it was suggested that a qualitative analysis of the market is the best achievable.

10 Conclusions and key messages

- The aerospace and defence industries are almost unique in terms of their essential requirements for a suite of minor metals, used to produce alloys that must combine extreme temperature resistance with the highest levels of mechanical integrity and resistance to corrosion and oxidation. It is only through using these superalloys that improvements in the performance, fuel efficiency and emissions of aircraft gas-turbine engines have been achieved.

- Superalloys are typically nickel-, iron- or cobalt-based, with much smaller quantities of an array of additional alloying elements that give them their highly specialist properties. The most important additions are chromium, molybdenum, scandium, titanium, ruthenium, tantalum, rhenium, hafnium, tungsten, niobium, yttrium, zirconium, and vanadium. Some of these elements and other metals are used for coating systems to protect the underlying alloy from corrosion and oxidation. Varying the composition allows the superalloys to meet and balance a wide range of performance requirements, including high-temperature strength, fatigue and creep resistance and density.
- Demand for superalloys is forecast to increase as the global aviation sector recovers, orders for new commercial aircraft grow and OEMs tackle major aircraft production backlogs, whilst defence sales increase. There is also growing demand for superalloys and alloying metals from other established end-use sectors, most notably the nuclear power industry. Furthermore, there is increasing or emerging demand from industries including electronics, specialist automotive and space exploration. Therefore, in addition to increasing total demand for the alloying elements there is risk of growing intersectoral competition for these metals.
- Secure and sustainable supplies, of adequate quantities of superalloys and alloying metals, at acceptable levels of price stability are vital to support the international competitiveness of the UK aerospace and defence industries. These industries make a significant contribution to value added and export earnings, and directly employ hundreds of thousands of people across the UK.
- Substitution of the elements used in superalloys is extremely difficult, as each addition yields specific performance benefits. Even when substitutions may be technically possible, strict certification processes for the design of aircraft and all components, mean changing alloys that contribute to the performance of the overall materials system is rarely feasible.
- Recycling and revert are used throughout the manufacturing process and product life cycle of a gas-turbine engine to maximise recovery of metals from superalloys. This helps to reduce demand for virgin materials, thereby helping to mitigate supply chain risk and has significant environmental and sustainability benefits. The energy savings and reductions in carbon emissions associated with increased circularity will play an important role in helping the aviation sector to achieve its target of net zero by 2050.
- The UK is almost entirely dependent on imports for its primary supply of alloying metals. Despite a lack of trade data for certain important metals (e.g., hafnium, rhenium), and the limitations and potential inaccuracies of the reporting, this study highlights some key trade dependencies. Total UK imports of alloying metals have declined since 2017 and reduced sharply in 2020, reflecting reduced demand from the manufacturing sector during the COVID-19 pandemic. The commercial aviation sector was particularly affected and remained weak during 2021.
- Businesses operating in the UK aerospace supply chain are primarily dependent on suppliers from the following regions and countries, ordered by importance of imports: North America (USA and Canada), the European Union (especially Germany, France, and Netherlands), China, Russia, South Africa, the Middle East, South America, Japan, and Singapore.
- The USA is the principal supplier of nickel, titanium and zirconium to the UK. Japan is the second most important source of titanium for the UK. Although China is the largest

producer of titanium globally, it accounted for a minor quantity of UK imports. Since 2017 UK imports of titanium from Russia have been growing in importance, increasing by nearly 5-fold in 2020 over the previous year. The UK imports most of its tungsten and molybdenum from China, which is also an important supplier of tantalum to the UK market. South Africa, the world's largest producer of PGM supplied more than half of the UK's iridium, osmium and ruthenium. The USA and Russia, which are major PGM producers also supplied these metals into the UK market. UK imports of iridium, osmium and ruthenium from Russia have fluctuated since 2017 but were greater in 2021 than the previous year.

- The UK is reliant on imports from several European countries (e.g., France, Netherlands, Germany) for alloying metals, however, these do not always represent the locations of primary metal production. France is notable for the proportion of chromium and beryllium that it supplies to the UK. France and Germany are both important sources of zirconium for the UK, owing to their established nuclear industries. UK imports of nickel and cobalt from Belgium do reflect domestic recycling and refining capacity for these metals. In contrast, despite the Netherlands being an important source of imports of several alloying metals for the UK, it is not a primary producer of cobalt, molybdenum, tungsten, and chromium. In common with some other European countries, the trade data reflects the location of the ports from which the metals were shipped. It would be necessary to look further back along the value chains of these materials to identify the location of the extraction and processing stages which led to the production of these materials.
- Although not evident in the trade statistics, the USA and France supply most of the UK's hafnium, which is consistent with the UK's trade dependencies for zirconium given it is a by-product of this metal. UK traders also purchase hafnium from China. UK supply of rhenium and ruthenium is dominated by the USA and Canada.
- The level of engagement from stakeholders in the UK aerospace supply chain was limited but in line with survey response rates. The stakeholders that participated in this study were very willing to provide high-level, technical information on the UK market for superalloys and alloying metals, and an overview of international supply chains. They spoke openly about supply concerns for specific alloying metals, their 'criticality' status, and the potential role of the Government in supporting the industry. Information on specific supply chains and quantitative data on volumes of material traded by individual companies, material prices and information on supply and purchasing relationships was withheld, owing to commercial sensitives. Building trust with the aerospace industry, partnering with trade associations and/or research organisations and government agencies that are embedded in this sector, and having appropriate levels of security clearance, and non-disclosure agreements in place may facilitate access to the types of data and information required to understand this sector and its supply chains in more detail.
- Concentration of production of the alloying metals and dependence on imports presents supply risks for the UK. Increasing demand for alloying metals globally, including in major producing countries that will prioritise the domestic market; growing intersectoral competition; limited market transparency, owing to long-term supply agreements and certain metals not being traded on exchanges; markets imbalances and price volatility; and the ongoing recovery from the COVID-19 pandemic and Russia's invasion of Ukraine present challenges for UK aerospace material supply chains.
- Some of the alloying elements are entirely or partially by-products of the extraction of another, so called 'parent' metal. Their by-product status introduces an additional level of complexity in their supply, because in the event of a disruption to the supply of the main parent metal it may not be possible to maintain supplies of the by-product. Furthermore, where there is a sharp upturn in demand for the by-product, it may not be feasible or economically viable for producers to quickly respond. Hafnium epitomises this

relationship, as almost all commercial production is a by-product of purifying zirconium for the nuclear industry. Several stakeholders repeatedly highlighted concerns about the current lack of hafnium availability, owing to increasing demand, it not being commercially viable to recycle, most material being tied into long-term supply agreements and developments in the Chinese market, which have led to dramatic price increases and delays to UK deliveries.

- Businesses operating in the UK aerospace supply chain view ESG monitoring and compliance as vital. It is covered in contractual agreements between Tier-1 companies and suppliers and is stringently monitored as far as is practicable. Responsible sourcing and verifying ESG compliance add to the cost of material procurement. Companies consider this acceptable because of its ethical importance and the potential reputational risks it presents to their businesses. The lack of consensus on international standards and agreed metrics, variable national standards, poor data quality, the potential for loss of information as material moves through the supply chain, and possible abuses of the system complicates the verification process. These factors will grow in importance as ESG reporting becomes mandatory in many jurisdictions.
- Geopolitical developments during the last year contribute to greater supply risk or likelihood of supply disruption for several alloying metals. To mitigate this risk, it was intimated that the UK Government should focus on pursuing resource diplomacy with key producing countries and negotiate supply agreements. It could also support UK businesses in developing links with potential suppliers in partner countries.

Appendix 1

UK Critical Minerals
Intelligence Centre

Study on UK demand and supply of metals for specialist alloys used in aerospace and defence applications

Scope: specialist alloys containing nickel, titanium, tungsten, tantalum, rhenium, ruthenium, hafnium, zirconium, niobium, chromium, cobalt, gallium, and beryllium, used in the UK aerospace and defence sectors.

Selected structured interview questions:

Scale, sector, and metals use

1. How would you describe your business (solely UK-based; UK headquartered with overseas operations; headquartered outside the UK with UK business operations)?

2. How many manufacturing and processing sites do you have across the UK or globally?

3. What is your main type of operation (engineering and manufacture of materials; reprocessing; design and build; distribution)?

4. Approximately what percentage of your turnover is from UK customers?

5. Which of the metals above and/or specialist alloys are essential to your business and customers?

6. In what form do you use/ import the metals above (mineral raw materials, intermediates, or alloys)?

7. How many stages of refining or transformation do you undertake?

Import and supplier dependence

8. What percentage of your metals and/or specialist alloys procurement in the last financial year is based on imported supplies?

9. How many suppliers make up about 70% of these imports?

10. What are your top three supplying countries in terms of procurement spend?

11. How much visibility or monitoring do you have over your supply chains?

12. How concerned are you about international supply chain risk?

13. What do you consider the major risks to be, and how are you mitigating these if at all?

14. How much emphasis do you or the sector place on environmental, social, and governance (ESG) monitoring or compliance?

15. How important is recycling to the current UK supply of the metals above or associated specialist alloys?

16. What are the potential impacts on the aerospace and/or defence sector if you were unable to secure supply of the metals above or associated specialist alloys?

Future supply

17. Do you have a view on the ability of the global market to respond to projected demand growth in the metals above or associated specialist alloys in the period to 2030?

18. Is substitution of the metals above or associated specialist alloys an option in certain applications?

19. Could government policy help to address any of the security of supply issues we have discussed?

General

20. Do you have any additional comments on this topic, or the issues covered?

Ethical procedures for research require that stakeholders explicitly agree to share their data and information and to how the information they provide will be used. We will not share or publish your data or information; however, we will use it to draw high-level, generic conclusions regarding the UK security of supply risk and their potential impacts.

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