12. A System Dynamics Assessment of the Supply of Superalloys using WORLD6; Sufficiency for Civilian and Military Aviation Needs

Harald Ulrik Sverdrup ✉, Anna Hulda Olafsdottir, Peter Schlyter ✉

Abstract

The extraction, supply, market price and recycling of the metals used for superalloys were modelled using the systems dynamics model WORLD6. Peak production per capita (Supply Security) and stock-in-use per capita (Utility of Use) as well as resource stock lifetime during self-supply (Resilience) are key indicators. The resource estimates made resulted in significantly larger estimates than previous studies for nickel, tantalum, niobium, wolfram, molybdenum, cobalt, rhenium, titanium, zirconium and hafnium. The study shows that while for some elements (Co, Nb, Ta, W, Ni, Re), the size of the extractable resource may pose a challenge. For other elements, the intricacies and interdependencies of production will provide challenging limitations (Co, Re, Hf). Resource stocks of key metals are asymmetrically distributed among the larger powers and their dependants, posing strategic challenges for the future. Future patterns of scarcity, in space and time, of key resources may jeopardize strategic supply advantages presently enjoyed by major state actors. On the global scale, many of the key metals will run into hard scarcity around 2080-2100 AD, where the amounts demanded simply cannot be delivered. The recycling rates are too low for some of the key metals used in superalloys. This is contributing to shorter society service time that what could have been achieved otherwise. Both market mechanisms and other incentives through governance can be used for getting a better recycling of the important metals. Without these metals, several technologies will become difficult to produce, with serious implications for both military and civilian uses of high performance hardware. Additionally, increased competition between various technology sectors, e.g. aerospace, energy production and the IT-sectors.

Keywords: Aerospace, Turbines, WORLD6 Model, Superalloys, Energy Production.

Introduction

In modern society, some of the most important and promising uses of metals like tantalum and niobium, but also other metals are in the use of superalloys (Co, Cr, Hf, Zr, Ti, Re, Mo, Ru, Ir, Al, W). Superalloys are metal mixes that have high strength at elevated temperatures and also good corrosion resistance at such conditions. A superalloy has high mechanical strength, resistance to thermal creep, excellent corrosion resistance also at high temperatures and surface structural stability. Chemical and petrochemical processing, combustion power plants, and oil and gas industries use superalloys in their technical installations. They find use in turbine blades, jet engines, rocket engines, nuclear energy technologies and specialized chemical environments. Superalloys mainly rely on dispersion of coherent L12 γ'-austenitic precipitates in a face-centered cubic γ metal matrix for excellent high temperature mechanical properties (Collier et al. 1988, Harada 2012). Corrosion resistance is enhanced by components creating corrosion resistant oxide coatings at high operation temperatures. The resistance to corrosion also makes them difficult and expensive to decompose and refine to single metals for recycling, as well as difficult to melt, and reuse. Thermal barrier used to reduce heat conductance and allow for higher temperatures (Clarke et al. 2012).

The extraction, supply, market price and recycling of the metals used for superalloys were modelled using the systems dynamics model WORLD6. The resource estimates made resulted in significantly larger estimates than earlier studies for nickel (URR=300 mill ton), tantalum (URR=0.32 million ton), niobium (URR=80 million ton), wolfram (URR=30 million ton), molybdenum (URR=100 million ton), cobalt (URR=28 million ton), rhenium (URR=0.02 million

ton), titanium (URR=3,600 million ton), zirconium (URR=405 million ton) and hafnium (URR=9 million ton). While for some elements (Co, Nb, Ta, W, Ni, Re) the size of the extractable resource may pose a challenge, for others the intricacies and interdependencies of production will have challenging limitations (Co, Re, Hf). The integrated systems dynamics models can be shown to reconstruct the observed extraction rates and price histories well. The model outputs show that all these metals are finite resources, and that they will soon be exhausted unless the degree of recycling will be significantly improved. Peak production is estimated to take place 2030-2055 for tantalum, in 2055 for niobium, and molybdenum and rhenium production reaches a maximum in the same time interval. They will run into hard scarcity around 2100 AD, where the amounts demanded simply cannot be delivered.
The recycling rates are generally low for some of the key metals (Zr, Hf, Re, Co, Mo, Nb, Ta) used in superalloys. This is contributing to shorter society service time that what could have been achieved otherwise. Both market mechanisms and other incentives through governance should be used for getting a better recycling of these important metals. If not, they will become scarce within the coming decades with significant negative effects for the industrial economy and the technological potential. Without these metals, several technologies will become difficult to produce, with serious implications for both military and civilian uses of high performance hardware. The superalloys are used in a rapidly expanding range of applications from aerospace; disks, bolts, shafts, cases, blades, vanes, combustion chambers, thrust reversers. They are much used in civilian power plants; bolts, blades, stack gas reheaters, in high performance turbines for better thermal efficiency of energy conversion, in automotive vehicles for turbo-changers and exhaust valves. They are also becoming important in medical components because of their good resistance to corrosion and strength. In nuclear power generating systems they are used where repairs can only take place with huge difficulty because of radiation challenges such as for control rod drives, valve stems, springs, ducting and such places where great strength and corrosion resistance is needed. Chemical industry it is used for chemical reaction vessels, piping, valves, bolts and pumps. They are used in space vehicles in aerodynamically heated skins, rocket nozzles, turbo-pumps, rocket engine compressors and service turbines (Donachie and Donachie 2002, Sims et al. 2008, Clarke et al. 2012, Harada et al. 2012, Kawagishi et al. 2012). Price and available amounts seems to be the limitation to wider use.

Objectives and scope

The goal was to assess the sufficiency of the molybdenum, rhenium, niobium, tantalum, cobalt and nickel supply for production of superalloys, considering its technical use in rocketry, high performance turbines and advanced jet engines. Further, superalloys are being considered as candidates for inert electrodes for aluminium and light metal smelting.

System dynamics modelling

The main modelling method uses systems analysis and systems dynamics. We analyse the system using flow charts based on box-arrow symbols, causal loop diagrams defining the mass balance expressed differential equations and numerically solved using the STELLA® systems dynamics methodology (Sverdrup et al. 2014a,b, 2015a,b). The model is used to first reconstruct the past (1900-2015) to assess performance and robustness of the model. When the performance is satisfactory, then the model is used to simulate the possible future (2015-2300), having the support of being able to reconstructed the observed past pattern (Sverdrup et al. 2015).

Metals and metal uses

Table 12-1 shows an overview of important alloying metals for superalloys. The metal production numbers are taken from a number of earlier studies by the author. Table shows our estimate of the civilian aircraft demand and superalloy needs for the next 20 years. The amounts depend on engine weight, number of engines per aircraft and the lifetime of the superalloy parts inside the engines. Each new civilian aircraft are assumed to be twin engine planes with an average engine weight of about 3 ton per engine. In addition to these amounts comes turbines for land-based power production and superalloys for different types of rocketry. Tables 12-2 and 12-3 shows the demand for metals during the next 20 years. The assessment is based on new resource estimates by the authors (Sverdrup and Ragnarsdottir 2014, Sverdrup et al. 2016a,b,c, 2017a,b,c) for this study. The flow of superalloy components is shown in Figure 12-1. We have also indicated if these metals are in soft scarcity (compensated with higher price) or hard scarcity (compensated with higher price and with limited amounts that can actually be delivered. Typical for this are the platinum group metals, which at times cannot be delivered at the amounts desired). Superalloys are alloys developed for heat resistance, shape stability at high temperature and corrosion resistance. They have either iron, cobalt or nickel base as the majority meta l, and then additions of other metals that contribute to strength, chemical resistance to corrosion, thermal stability and resistance to fatigue failure. Recent research seem to suggest that there will be an upper temperature around 2,200^{o}C where the ceramic coatings start to lose their mechanical strength and be susceptible to corrosion. Most alloys are nickel-based at present, but cobalt-based alloys are going through improvements and seems to be set for a come-back. Characteristic for all these components are that they have high melting points, low vapour pressure at the melting points and that they tend to make very hard alloys. Metals like wolfram, molybdenum, niobium, tantalum, rhenium and hafnium are needed in the superalloy to increase the heat tolerance of the superalloys. Ceramics and metal-ceramics composites are used in the combustion section to increase heat resistance and insulation and corrosion resistance. The ceramics have poor resistance to shocks and movement, but there are few of these in the combustion compartments. A bit further down in the engine, in the hot turbine, the gasses have cooled only slightly, and the metal must have extraordinary strength, good corrosion resistance implying superalloys. The turbine blades are often single crystal blades. Earlier in jet engine development, stainless steels were used, but as higher performance is demanded, superalloys with several layers of barriers are used). The exhaust nozzle use Inconel or stainless steel alloys (nickel-chromium-iron alloys). When the temperature over the turbine is allowed to increase from 500^{o}C to 1,600^{o}C, then the thermic conversion efficiency of the engine increase from about 27-30% to 48-52%. Superalloys have been composed for heat resistance, shape stability at high temperature and corrosion resistance.

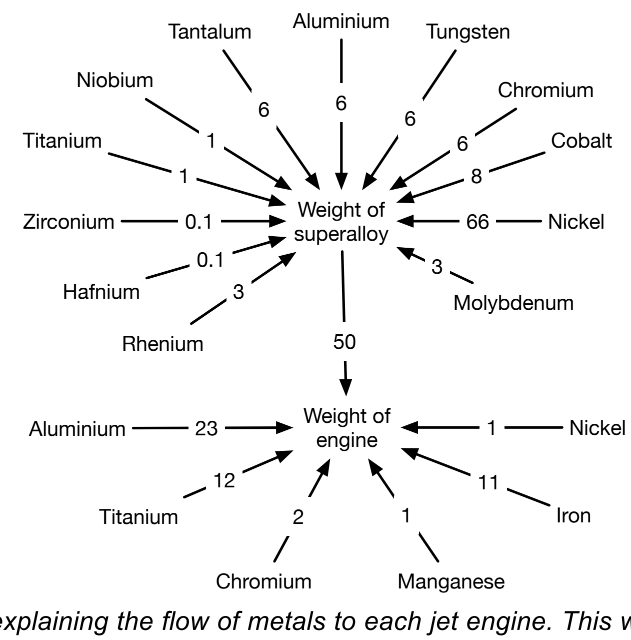

Figure 12-1: *Diagram explaining the flow of metals to each jet engine. This was used in the WORLD6 model.*

The WORLD6 model

Data and materials

Table 12-4 shows a summary of total superalloy demand during the next 20 years. As a basis for this analysis we also look back on earlier work done to verify the performance of the WORLD6 model on specific groups of metals.

Strategic considerations leading to metal demand

With the new fifth generation jet fighter planes and very high performing jet turbine engines, a significant amount of superalloys will be needed for turbine blades. The United States and its allies in NATO intend to build about 3,100 new F-35 during the next 10 years (50% of the total present production). In addition, comes other 1,000 US high performance military aircraft. Possibly, other big military powers (China, Russia, France, Great Britain, Ukraine, India) will possibly need superalloys for their comparable number of aircraft with possibly 3,000 or more of high-performance military type of jet engine turbines for the next 10 years and the demand for the next 20 years will be 8,600-10,000 aircraft. Rolls Royce estimated in 2011 that 149,000 jet engines will be demanded during the next 20 years, used to power 68,000 civilian jet aircrafts of different types. Military aircraft come in addition to these estimates.

Metal (2015)	Metal production ton/year	Dynamic model peak year estimate	URR Mill ton	Dependent Extraction
Molybdenum	0.27	2032	55	**Partly,** Cu
Rhenium	50	2035	0.016	**Yes,** Mo
Cobalt	120,000	2040	29	**Yes,** Cu, Ni, Cr, PGM
Niobium	65,000	2055	52	No
Tantalum	1,200	2045	0.5	**Partly,** Nb, Sb
Titanium	310,000	2080	3,600	No
Zirconium	45,000	Cost limited	410	**Partly**, Ti
Hafnium	80	Cost limited	11	**Yes,** Zr, Ti
Nickel	2,500,000	2030	300	No
Wolfram	85,000	2045	55	No

Table 12-1: *Overview of important alloying metals for superalloys. The metal production numbers are taken from a number of earlier studies by the author. Million metric ton.*

Country	Military aircraft	Number of engines for new craft	Number of planes with engine retrofits	Total number of engines	Engine weight per plane, ton	Superalloy weight per engine, ton	Superalloy weight demanded ton
USA	3,000	4,500	2,000	6,500	1.8	0.9	5,850
Russia	1,400	2,000	2,000	4,000	2.6	1.4	5,600
China	2,000	3,000	2,000	5,000	2.2	1.2	2,640
India	500	600	300	900	2.4	1.3	3,120
Turkey	200	300	-	300	2.4	1.3	3,120
Sweden	500	500	400	900	1.7	0.8	1,360
Europe	1,500	2,200	2,000	4,200	1.9	1.0	1,900
Canada	200	350	350	700	1.8	1.0	1,800
Other	200	300	600	900	2.2	1.2	2,640
Sum	9,000	13,750	9,650	23,400			28,030

Table 12-2: *Superalloy demand for military aircraft during the next 20 years. A total of 24,000 new engines are estimated to be needed.*

Country	New aircraft	Engine per plane	Engines	Engine retrofits	Sum	Engine weight	Total amount, ton
United States	14,000	2.2	31,000	10,000	41,000	3	123,000
Russia	2,000	2.2	4,400	500	4,900	3	14,700
China	4,000	2.2	8,800	6,000	14,800	3	44,400
India	1,000	2.2	2,200	2,000	4,200	3	12,600
Europe	10,000	2.2	22,000	10,000	32,000	3	96,000
Canada	3,000	2.2	6,600	2,000	8,200	3	24,600
Brazil	2,000	2.2	4,400	2,000	6,400	3	19,200
Other	2,000	2.2	4,400	7,500	11,900	3	35,700
Sum	38,000	2.2	83,600	30,000	113,600	3	370,200
Demand	1,900	-	-	1,500			18,510

Table 12-3: *Civilian aircraft demand and superalloy needs for the next 20 years. The amount depend on engine weight, number of engines per aircraft and the lifetime of the superalloy parts inside the engines. Each new civilian aircraft are assumed to be twin engine planes with an average weight of about 3 ton per engine. In comes turbines for land-based power production and superalloys for different types of rocketry. Amounts are in ton metal.*

	Civilian aerospace	Military technology	Technical and chemical	Sum
Demand next 20 years	370,200	28,030	15,000	413,230
Annual demand	18,510	1,402	750	20,662

Table 12-4: *Summary of superalloy demand during the next 20 years, 2017-2037, ton metal.*

Metal		Content in super-alloy, %	Content in engine, %	Amount per year used for super-alloy, ton/year	Annual supply ton/year	% of annual supply	Risk for scarcity
Molybdenum	Mo	5	-	1,050	320,000	0.3	No
Rhenium	Re	1	-	210	80	260	**Yes**
Niobium	Nb	2	0.3	460	60,000	0.8	No
Tantalum	Ta	1	-	210	1,400	11	**Maybe**
Cobalt	Co	10	-	2,100	60,000	4	No
Platinum	Pt	0.1	-	21	180	12	**Yes**
Nickel	Ni	63	1	13,400	2,500,000	0.5	No
Titanium	Ti	1	12	2,730	310,000	0.9	No
Zirconium	Zr	0.1	-	21	45,000	0.05	No
Hafnium	Hf	0.2	-	42	74	57	**Yes**
Wolfram	W	5	-	1,050	60,000	2	No
Chromium	Cr	10	2	2,500	7,000,000	0.04	No
Aluminium	Al	1	23	4,830	80,000,000	0.04	No
Manganese	Mn	-	1	210	18,000,000	-	No
Iron	Fr	-	11	2,200	1,500,000,000	-	No

Table 12-5: *Need for individual metals for aviation technologies.*

Metal	Aviation super-alloys, ton/year	Power plant Turbines, ton/year	Chemical plants ton/year	Sum ton/year	Priority use	Annual total supply ton/year	Risk for scarcity
Molybdenum	1,050	500	250	250,000 1,800	Stainless Superalloy	320,000	No
Rhenium	210	100	50	360 10	Superalloy Catalyst	80	**Yes** **Yes**
Niobium	460	220	110	790 50,000	Superalloy Steel alloys	60,000	No **Yes**
Tantalum	210	100	50	1,000 360	Electronics Supoeralloys	1,400	**Yes**
Cobalt	2,100	1,000	500	3,600 120,000	Superalloys Batteries	60,000	**Yes**
Platinum	21	-	-	21 140	Superalloys Catalysts	180	**Yes** **Yes**
Nickel	13,400	6,000	5,000	24,300 2,000,000 500,000	Superalloy Stainless Other	2,500,000	**No** **Yes** **No**
Titanium	2,730	1,000	4,000	7,730 250,000 10,000	Airframes Structural Medical	310,000	No No No
Zirconium	21	10	30	61	Nuclear	45,000	No
Hafnium	42	-	-	42	Superalloy	74	**Yes**
Wolfram	1,050	500	250	1,800 30,000	Superalloys Cutting tools	60,000	No No
Chromium	2,500	1,500	1,500	5,500	Stainless	7,000,000	No
Aluminium	4,830	1,000	200	6,030	Structures	80,000,000	No
Manganese	210	100	100	410	Iron alloys	18,000,000	No
Iron	2,200	300,000	300,000	602,200	Structural	2,200,000,000	No

Table 12-6: *Need for individual metals for all technologies summarized.*

Superalloy weight in a typical modern jet engine has stabilized at 40-50% of the engine weight. This may lead to a specialty metals demand that is larger than the actual supply at present. The civilian aircraft's new generations high-performing jet engines use superalloys in the turbine blades (Airbus A360, A380, Boeing 777, Boeing 787 and several coming new models from other vendors).
The Boeing Corporation in Seattle estimates that 38,000 new civilian aircraft will be taken into service by 2034 (next 20 years) worldwide (1,900 commercial aircraft per year) (Boeing website 2017). That corresponds to 30,000-60,000 ton of superalloy of at least 4th generation performance during the period, or 1,500-3,000 ton superalloy per year will be needed, at 6% tantalum, that corresponds to about 90-180 ton per year (Donachie and Donachie 2008, INSG 2013)**.** Table 12-5 shows the superalloy demand for military aircraft during the next 20 years. The amounts depend on engine weight, number of engines per aircraft and the lifetime of the superalloy parts inside the engines, and how many retrofits of the engines that will be needed. These are based on rough estimates. Each new civilian aircraft is assumed to be twin engine planes with an average engine weight of about 4 ton per engine. In addition to these amounts comes turbines for land-based power production and superalloys for different types of rocketry. We have taken two of the newest high-performance engines as the average engine and used their weight specifics as the template for the future; the military engines by Pratt and Whitney 135 and General Electric and Rolls Royce F136 engines. These are used in the F-22, a twin engine high performance superiority jet fighter plane, its total empty weight is 19.7 ton, twin engine of each a weight of 1.8 ton, total engine weight in the plane is 3.6 ton. The superalloy weight is about 1.8 ton. F-35 with a single engine, has a single engine, aircraft weight is 13.4 ton, the engine weight 1.7 ton, the superalloy weight is about 0.9 ton. Typically, the turbine rotates at 3300 rotations per minute, resulting in a tip speed of 1,700-2,00 km h^{-1}. Typically, an engine will last about 10,000 flights before it is scrapped. Civilian aircraft engines vary a lot in size and weight. Much efforts have been made in later years to bring down overall weight, increase thrust to weight ratio and increase overall fuels use efficiency. We have looked into

the latest series created by Rolls Royce in the Trent series. The jet aircraft engines are used in planes from Airbus are; A330, A340, A350, A380 and Boeing 777 and 787. They are all twin-engine aircraft. Typical engine weight for these turbofan engines range from 3.5 ton per engine to 7.1 ton per engine depending on the aircraft size and year of production. In 1950, only 10% of a jet engine weight would be superalloy, by 1985 this fraction had reached 50% of the engine weight (Donachie and Donachie 2002). In 2017, this was still the case, with a small upward trend. This is based on averaging constituents in the newer alloys in the market. There the contribution from each metal to the superalloy is shown in % weight of the metal, as well as the metals used for the rig and body of the engine. The superalloys make up about 50% of the engine weight, due to the high density of the constituents (8.8-9.2 g cm^{-3}).

Results

The WORLD6 model was run for the time period 1900-2400, but for some of the diagrams we have chosen to show only the last and the next 100 years, 1900-2100. From the model simulation outputs, we have chosen to show the time period 1900-2100 for both niobium and tantalum. The reason for this was that most of the interesting changes in the dynamics takes place in this time period. Table 12-6 shows the civilian aircraft demand and the superalloys needs for the next 20 years together with an assessment of the sufficiency of provision. It can be seen that there is a scarcity risk for rhenium, tantalum, cobalt, hafnium and platinum in the future. Under certain circumstances, there may be some scarcity risk for niobium and nickel.

Discussion

We have been living in a society for the last two decades dominated with a political climate where “market solutions” have been thought to efficiently self-regulate all markets. It is becoming more and more evident that this is not correct, and that unregulated markets tend to develop into oligopoly (Fukuyama 2015, Roberts 2011), leading to manipulated prices and unchecked speculations. There are sufficiently many empirical cases available to prove beyond reasonable doubt that scarcity issues are not efficiently solved by the market mechanisms alone, and that this approach as a solution is a dead end. Such an approach is inviting failure and will cause irreparable scarcity situations. It should be met with the resistance it scientifically deserves. Most countries do not have any strategic governmental policy on resources, and there are no International unified policies for recycling.