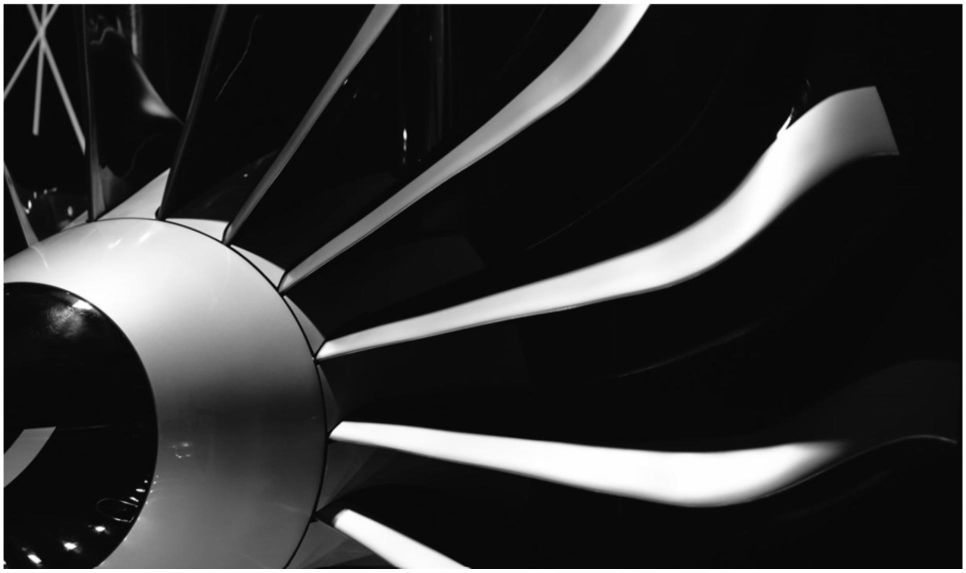
Level 3 Industrial Case Study

Material Properties and Selection of Superalloys



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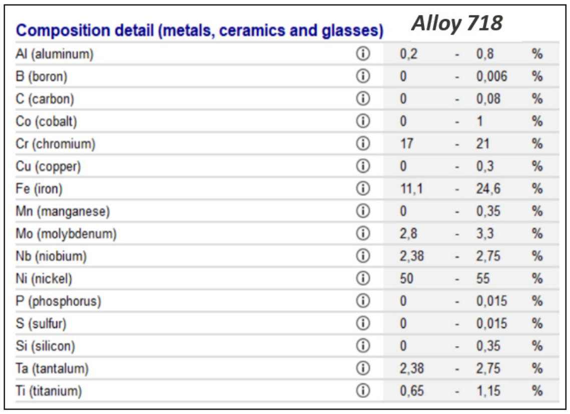
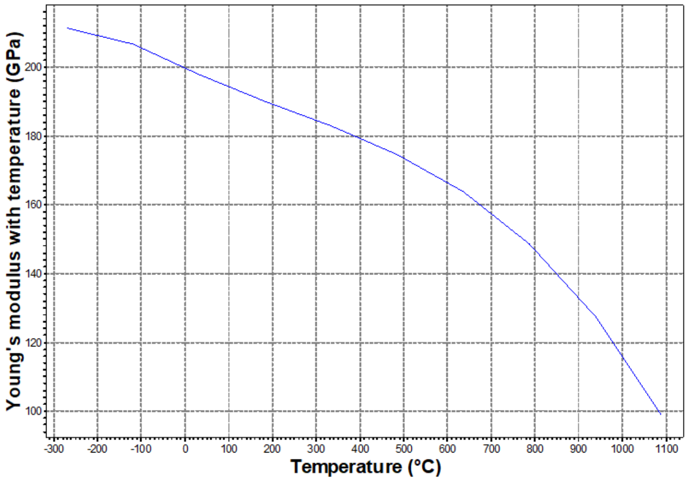
Material properties of superalloy blades

Superalloys are high-performance metal alloys that exhibit excellent mechanical properties such as strength and creep resistance at elevated temperatures. They generally display good surface stability as well as durability to corrosion and oxidation. It is not surprising then that they have found extensive use in demanding aerospace, automotive and marine applications. They are also common in chemical processing industry. The three main types are Nickel base, Nickel-Iron, and Cobalt base super-alloys, all with various specific contributions from other elements to tailor their properties.



Composition detail (metals, ceramics and glasses)		Alloy 718			
Al (aluminum)	ⓘ	0,2	-	0,8	%
B (boron)	ⓘ	0	-	0,006	%
C (carbon)	ⓘ	0	-	0,08	%
Co (cobalt)	ⓘ	0	-	1	%
Cr (chromium)	ⓘ	17	-	21	%
Cu (copper)	ⓘ	0	-	0,3	%
Fe (iron)	ⓘ	11,1	-	24,6	%
Mn (manganese)	ⓘ	0	-	0,35	%
Mo (molybdenum)	ⓘ	2,8	-	3,3	%
Nb (niobium)	ⓘ	2,38	-	2,75	%
Ni (nickel)	ⓘ	50	-	55	%
P (phosphorus)	ⓘ	0	-	0,015	%
S (sulfur)	ⓘ	0	-	0,015	%
Si (silicon)	ⓘ	0	-	0,35	%
Ta (tantalum)	ⓘ	2,38	-	2,75	%
Ti (titanium)	ⓘ	0,65	-	1,15	%



The alloying elements are carefully controlled at the ppm-level and each one has a specific purpose. The composition of Alloy 718 (IN718) is shown above. This is the most commonly used of the nickel base superalloys in these applications. If the specific strength of the most common aerospace materials is compared, titanium alloys are the best at low and moderate temperatures (a few hundred degrees C), better than steels and much better than aluminum alloys. At higher temperatures, superalloys maintain their specific strength all the way up to the thermal conditions at the hottest part of the compression chamber.

They typically have a matrix with an austenitic face-centered cubic crystal structure. nickel-based alloys have the widest range of applications, particularly in the aerospace industry. The essential solutes in the nickel-based alloys are aluminum and titanium, with concentrations of less than 10 wt. %. This allows the generation of a two-phase equilibrium microstructure that consists of the phases known as gamma (γ) and gamma-prime (γ’). The matrix of superalloys is composed of the γ-phase, while their primary hardening is a result of the γ’-phase. The high-temperature strength, as well as other mechanical properties of superalloys, are also a result of the presence of the γ’-phase. The high-temperature properties of superalloys are provided by alloying the matrix element (nickel, cobalt or iron) with various other elements such as chromium, titanium, aluminum, boron, and iron. In some cases, refractory metals are added, such as molybdenum, niobium, zirconium, amongst others.

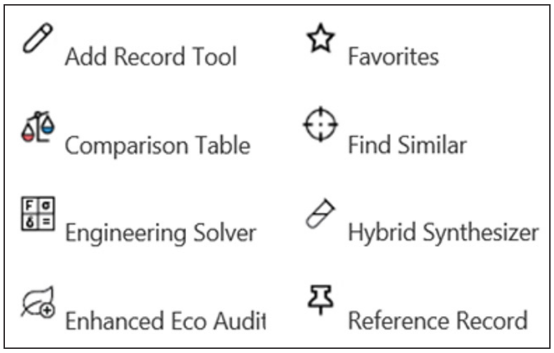
The cobalt-based superalloys have higher melting point compared to nickel- or iron-based alloys and superior hot corrosion resistance. They also have higher thermal fatigue resistance and weldability compared to nickel-based alloys. All nickel compounds should be regarded as toxic and there are many issues with the other alloying elements too. They are considered scarce or strategically critical due to production being concentrated to few countries. Cobalt is also subject to ethical problems due to conflicts where it is mainly sourced.

What can Granta EduPack do?

The Standard edition of Granta EduPack has an entire database dedicated to aerospace that contains many of the materials property data and tools that is needed to explore these applications. This database is aimed at higher-year University teaching, project work and real design projects. It contains a comprehensive set of mechanical, thermal, optical, electrical, magnetic and environmental properties for over 4,000 engineering materials. You might also be interested in the Elements database in order to scrutinize elements in superalloys (Cr, Co).

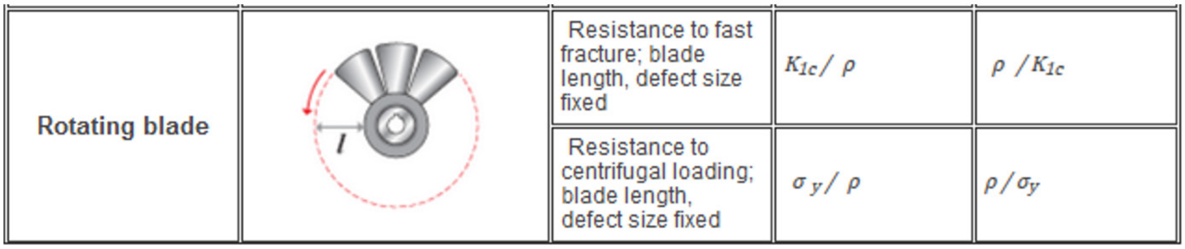
Data on temperature-dependent properties are included. These are taken from the Metallic Materials Properties Development and Standardization (MMPDS) database, which is also included in its entirety. This is the preeminent source for aerospace component design allowables relating to alloys and fasteners, containing over 2,000 records of statistically-derived design data for aerospace alloys in various forms and thicknesses, as well as fatigue curves, and corrosion rankings. It also contains a complete fastener database comprising over 400 sheet metal/fastener combinations. The Composite Materials Handbook, MIL-HDBK-17 and is the leading source of test data for advanced polymer, metal, and ceramic matrix composites; containing numerous properties as a function of temperature, lay-up and orientation. There is also a table of materials data for simulation, containing additional materials and data which may be useful for simulation work

The “Find Similar” and “Comparison Tables” tools are useful in order to find equivalent (or very similar) aerospace materials, since these are often named by tradename which might be difficult to navigate. This can be utilized in substitution projects where a certain material for some reason have to be replaced. It can also be used in cases where improvements are needed in some property. The reference record makes it easy to compare and replace while the comparison table is used to compare properties from other materials side by side.

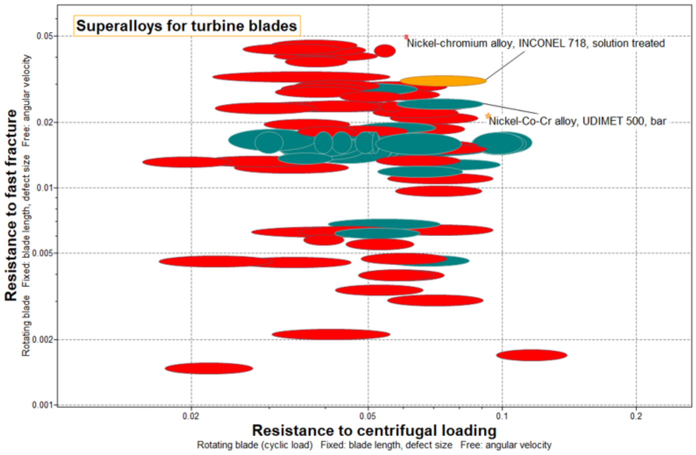


Jet engine turbine blades – high pressure, high temperatures

The first specific application of this superalloy case study. The hottest part of a modern jet engine is found in the front end of the combustion chamber. We have previously shown how to use performance indices for fan blades in the case study on Selection and Sustainability of High-temperature Aerospace material. The performance index table can be found under the Learn button in EduPack and is useful for visual material selection. Fan blades are somewhat special and can be found under damage-tolerant design. The objectives concern fast fracture and centrifugal loading. To minimize cost, you can use the same criteria with ρ modified by a factor C_m for price. In this case study, we use the performance index finder to make a quick and easy chart some relevant superalloys.

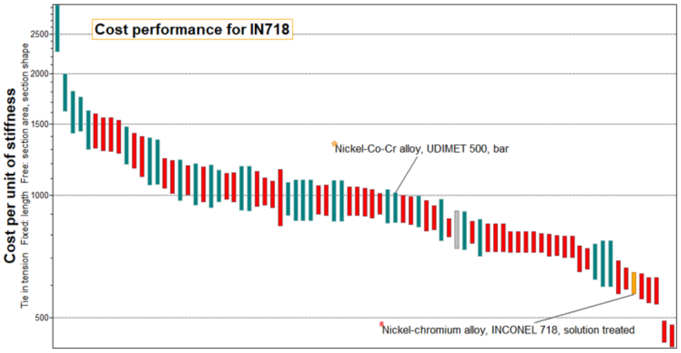


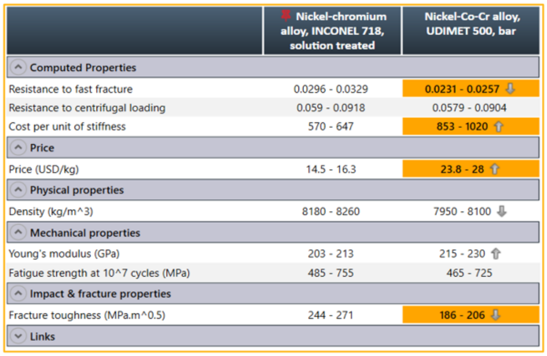
Rotating blade	*l*	Resistance to fast fracture; blade length, defect size fixed	K_{1c}/ρ	ρ/K_{1c}
		Resistance to centrifugal loading; blade length, defect size fixed	σ_y/ρ	ρ/σ_y



Focusing on the material classes that perform best in resistance to fast fracture and to centrifugal loading, a custom subset of cobalt-base as well as nickel-chromium and nickel-cobalt, we can quickly make an overview plot and identify the main candidates. As expected, the Nickel-Chromium superalloy, Inconel 718 is one of the best materials in both these objectives. That holds true also for cost performance, as seen below. A comparison table shows how several key properties are compared.

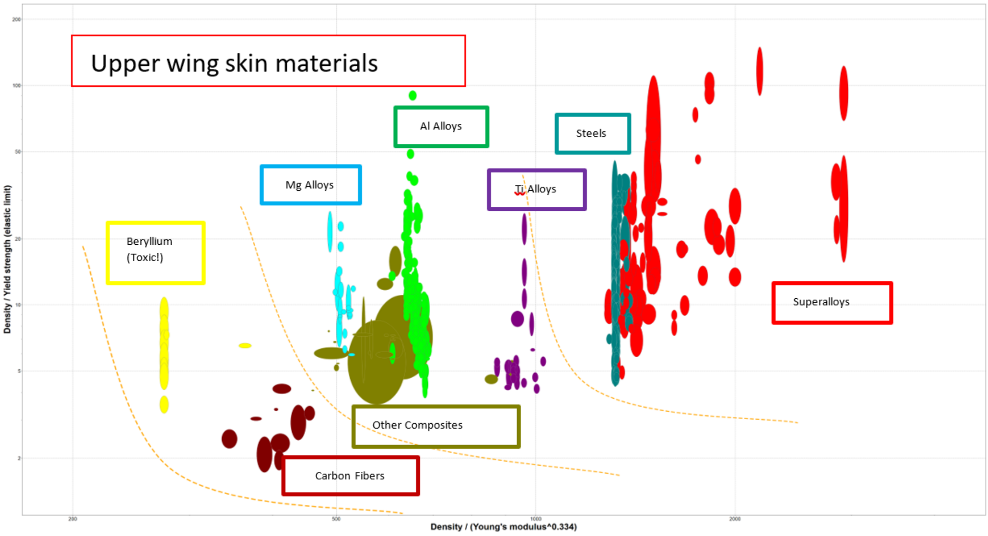
Airplane wing upper skin





	Nickel-chromium alloy, INCONEL 718, solution treated	Nickel-Co-Cr alloy, UDIMET 500, bar
Computed Properties		
Resistance to fast fracture	0.0296 - 0.0329	0.0231 - 0.0257 ⇩
Resistance to centrifugal loading	0.059 - 0.0918	0.0579 - 0.0904
Cost per unit of stiffness	570 - 647	853 - 1020 ⇧
Price		
Price (USD/kg)	14.5 - 16.3	23.8 - 28 ⇧
Physical properties		
Density (kg/m^3)	8180 - 8260	7950 - 8100 ⇩
Mechanical properties		
Young's modulus (GPa)	203 - 213	215 - 230 ⇧
Fatigue strength at 10^7 cycles (MPa)	485 - 755	465 - 725
Impact & fracture properties		
Fracture toughness (MPa.m^0.5)	244 - 271	186 - 206 ⇩
Links		

The second application is materials selection at minimum weight for the upper wing skin of an aircraft. The wing is the most heavily loaded component of an aircraft. In particular during the flight, the wing has to withstand the entire weight of the aircraft. Lift bends the wing upward causing a state of compression stress in the upper wing skin. Therefore, material selection for upper wing surface is dominated by resistance to compression and buckling. A customized chart is shown below. The best performance means closer to the bottom left corner. A number of Pareto fronts are added imagining that progressively some materials are not chosen.



In Summary:

- Beryllium: good mechanical performance but toxic, used in some space applications.
- Carbon fiber composites: great choice, but expensive (one example of a plane that used composites heavily is Boeing 787 Dreamliner).
- Magnesium alloys: they would get discarded if constraint on minimum modulus was added.
- Aluminum alloys: a very familiar choice in aeronautics, e.g., Boing 777.
- Going higher in the chart: Titanium, which was used by the Blackbird to withstand the high temperature generated by the supersonic flight.
- Superalloys: expensive, heavy, but great for high temperatures.

Function

- Upper skin, compressed panel

Objectives:

- Minimize **mass** per unit **strength**: $\frac{\rho}{\sigma_y}$
- Minimize **mass** per unit of **buckling stiffness**: $\frac{\rho}{E^{1/3}}$

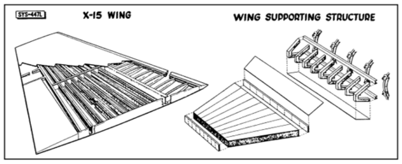
Constraints:

- **Toughness**: $K_{Ic} \geq 10\ MPa\sqrt{m}$
- **Stiffness**: $E \geq 50\ GPa$ - Optional
- **Shape**: flat sheet

Reality check - the X-15 hypersonic aircraft


https://history.nasa.gov/SP-60/i-9-1.jpg

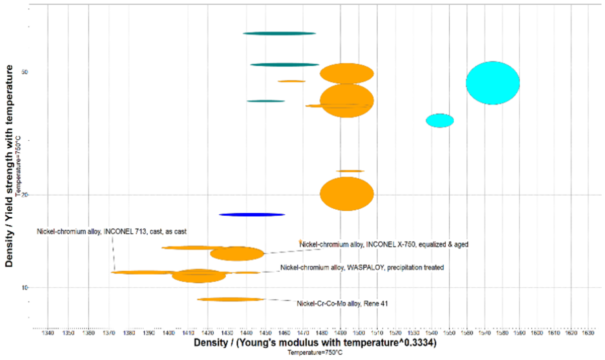
The X-15 was a single-seat, mid-wing monoplane research aircraft that was designed to explore the areas of high aerodynamic heating rates, stability and control, physiological phenomena, and other problems relating to hypersonic flight (above Mach 5). The US Airforce and Navy started a joint project in the 1950's and decided to develop three X-15 research aircraft in September 1955. The aircraft flew over a period of nearly 10 years and set the world's unofficial speed of 4,520 mph (Mach 6.7) and an altitude record of 354,200 feet in a program investigating all aspects of piloted hypersonic flight. Although the second and third aircraft was later modified, the basic X-15 outer skin consisted of a nickel-chrome alloy called Inconel X, employed in a heat sink structure to withstand the results of aerodynamic heating when the aircraft was flying within the atmosphere. The cabin was made of aluminum and was isolated from the outer structure to keep it cool.



https://history.nasa.gov/monograph18.

The wing of the X-15 was made of Inconel-X skins over a titanium structure. Inconel-X was a Nickel-Chromium Superalloy developed in the late 50s. At the time, it was the only feasible option for a reusable rocket plane. As the speed of the airplane is increases and the supersonic or hypersonic regimes are entered, the temperatures experienced by the wings (and other parts) start to rise (attrition with the atmosphere, aerothermodynamic effects).

When the temperature is increased to around 750°C, we are left with superalloys (and some steels). In particular (see chart), Nickel-chromium alloys in orange would be the best option (bottom left corner, dashed box, Inconel X-750, Inconel 713, Rene 41, and more). There are also some Nickel-Cobalt in blue, and cobalt-base superalloys in aqua in the top-right corner. Inconel X-750 would have the highest value of thermal conductivity among the top candidates.



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