Level 3 Industrial Case Study

Selection and Sustainability of High-Temperature Aerospace Materials

Claes Fredriksson & Luca Masi

Ansys Materials Education Division

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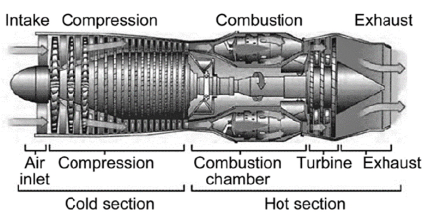
1. Materials for Aerospace

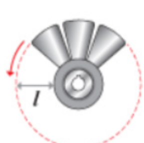
Aerospace materials are frequently associated with metal alloys that require exceptional performance, strength or heat resistance. In recent time, composites have also become an important class of materials for aerospace purposes, with obvious advantages in terms of lightweighting. All aerospace materials must entail long-term reliability and resistance to fatigue for safety reasons. Although they may mean considerable expense in their production or machining, they are considered essential to space applications, aviation and in some cases also to the high-performance automotive industry.

The power to weight ratio for engines is particularly important for these applications. Therefore, the combination of mechanical performance and weight matters greatly. One way to boost the power of internal combustion engines is to add turbo. A turbocharger works in a very hostile environment. Exhaust gases that drive the turbine can sometimes exceed 1000°C and are very corrosive. The turbine disc is located in a high-velocity jet of these gases. Turboprop airplane engines can have radial flow turbines whereas turbine jet engines have several types of axial-flow blades, operating at different temperatures: fan blades (low), compressor blades (mid-range) and turbine blades (high temperatures).



All these technologies involve challenges to the design and material choices of turbine blades. Huge tensile loads result from the centrifugal forces in addition to vibrational and bending loads. Thermal shock and creep are also issues. Nickel-based or Cobalt-based superalloys are therefore generally used for turbine parts. These retain high strength values even at high temperatures.

2. What is the Problem?



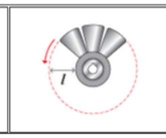
The centrifugal load on turbine blades will be one critical factor in selecting the material. The blades also must not fail due to bending during sudden turbine acceleration or to vibrations. This requires high strength and resistance to brittle failure. The blade length, l, is determined mainly by flow and space considerations and is therefore fixed.

It is well known that some superalloys and technical ceramics have sufficient properties to resist high temperatures, corrosion and creep. Granta EduPack can be used to investigate potential materials for this challenging situation. In this example, we will focus on resistance to *fast fracture*, which would result in catastrophic failure with blades becoming projectiles, as well as resistance to *centrifugal loading*. The fracture will be governed by crack propagation properties (*Fracture toughness*). For the centrifugal forces, we look for high fatigue strength. Both properties are considered in combination with low density for this particular application.

3. What can EduPack do?

To implement the objectives discussed above, the Performance indices are identified using the Learn button and following links to this Table, Damage-tolerant design.

Material selection » Performance indices » Damage-tolerant design

FUNCTION AND CONSTRAINTS			MAXIMIZE[1]	MINIMIZE[1]
Rotating blade		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

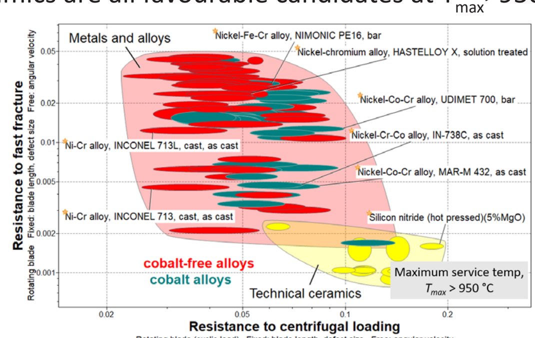
To minimize *cost*, use the above criteria for minimum mass, replacing density ρ by $C_m\rho$, where C_m is the material cost per unit mass.

To minimize *embodied energy* or *CO_2 footprint*, use the above criteria for minimum mass, replacing density ρ by $H_m\rho$ or $CO_2\rho$, where H_m is the embodied energy content per unit mass and CO_2 is the CO_2 footprint per unit mass.

K_{1c} = fracture toughness;
E = Young's modulus;
σ_y = failure strength (the yield strength for metals and ductile polymers, the tensile strength for ceramics, glasses and brittle polymers loaded in tension; the flexural strength or modulus of rupture for materials loaded in bending).

Tensile strength, Yield strength or *Fatigue strength* are possible mechanical properties to consider. Here, we choose to plot a chart using the *Performance Index Finder* which can plot the resistance to the two failure modes. If the *Cyclic loading* box is ticked, Fatigue strength is used. The cyclic load does not refer to the rotations of the turbine, as one might think, but rather to the load caused by frequent and repetitive start/stops, thermal shocks etc.

The constraints are oxidation@500°C and σ_e>360 MPa. Ni-based and Co-based superalloys and some technical ceramics are all favourable candidates at T_{max}>950 °C:



4. The Sustainability Database

There is considerable support for design and selection in all Level 3 databases. Searching for “Turbocharger” or “Jet Turbine” result in a selection of existing candidates, for example, Ni-Co-Cr alloy MAR-M 432 and Inconel 713L superalloys as well as Silicon nitride as one main option for a technical ceramic. If Inconel 713 is taken as the reference material, as it is currently used for turbochargers, there are several Ni/Co/Cr superalloys that have better failure-resistance performance (towards the upper right corner of the chart on the previous page).

Designation ⓘ

Nickel-chromium alloy, INCONEL 713L, cast, as cast (INCO Inc. proprietary alloy INCONEL 713LC)

Typical uses ⓘ

High temperature applications where creep resistance is important, aircraft engines, industrial turbines, diesel turbocharger parts, press-forging dies, extrusion dies, die-casting dies, integral rotor castings

Composition overview

Compositional summary ⓘ

Ni72-77 / Cr11-13 / Al5.5-6.5 / Mo3.8-5.2 / Nb2 / Ti0.4-1 / Zr0.1 / C0.03-0.07 / B0.01

Designation ⓘ

Nickel-Co-Cr alloy, MAR-M 432, as cast

Condition	ⓘ	As cast

Typical uses ⓘ

Integrally cast turbine wheels, jet engine components, e.g. turbine blades

Composition overview

Compositional summary ⓘ

Ni50 / Co20 / Cr16 / Ti4.3 / W3 / Al2.8 / Nb2 / Ta2 / B0.015

Notes

Warning ⓘ

All nickel compounds should be regarded as toxic. Some can cause cancer and/or fetal abnormalities.

The Sustainability database now makes it possible to go far beyond mechanical properties in materials selection. It contains links to the Elements subset which has, e.g., criticality data of the components of a chosen alloy,

Links	
Elements in this material	↗
Nations of the World	↗
ProcessUniverse	↗
Producers	↗
Reference	↗
Shape	↗

Both Cobalt and Chromium are considered *Critical materials* by the EU and USA, as indicated by green ticks.

Critical materials information		
In EU Critical list?	ⓘ	✓
In US Critical list?	ⓘ	✓

Cobalt has also attracted negative publicity in relation to sourcing for Li-ion batteries in electric cars, for example. If we are interested in finding facts pertaining to Cobalt, which constitutes 20% of Ni-Co-Cr alloy MAR-M 432, we can investigate both geo-economic data, like main mining areas, and material risks, such as price volatility. At the bottom of Elements datasheets, there are relevant links to investigate the social sustainability of countries of source.

Links	
Legislations and Regulations	↗
Materials containing this element	↗
Nations mining this element	↗
Reference	↗

In the case of Cobalt, we can see that the (Democratic republic of the) Congo is dominating the mining of this element and we can explore facts about this country.

Geo-economic data					
Typical exploited ore grade	ⓘ	0.523	-	0.578	%
Minimum economic ore grade	ⓘ	0.1	-	1	%
Abundance in the Earth's crust	ⓘ	25	-	30	ppm
Abundance in seawater	ⓘ	8e-5			ppm
Annual world production	ⓘ	1.53e5			tonne/yr
World reserves	ⓘ	7.2e6			tonne

Main mining areas (metric tonnes per year) ⓘ

Australia, 6.5e3
Brazil, 3.9e3
Canada, 8e3
China, 7.1e3
Congo, 57e3
Cuba, 4.3e3
Morocco, 2.1e3
New Caledonia, 3.3e3
Russia, 6.7e3
Zambia, 5.2e3
Other countries, 13e3

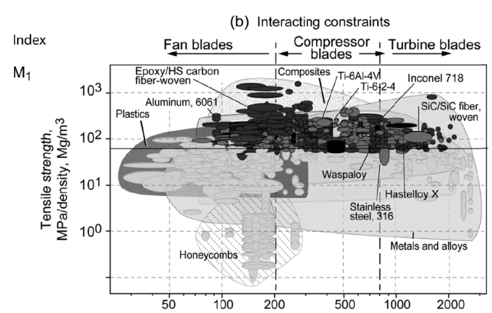
Although there is a time-lag in some of this data and it may not be updated every year (there are currently many considerable changes in the world), the database provides a platform for critical discussion about many sustainability issues. It is based on data from official sources, such as UN or the World Bank.

Human Rights & Good Governance		
Death penalty	ⓘ	Applied
Rule of law index (0 - 100)	ⓘ	3
Control of corruption index (0 - 100)	ⓘ	9
Political stability/no violence (0 - 100)	ⓘ	4
Political freedom (1, complete freedom - 7, no freedom)	ⓘ	5
Press freedom index (0, constrained - 100, free)	ⓘ	47.3
The good country index	ⓘ	153
Ongoing conflict?	ⓘ	✓
Child labor (hr/week)	ⓘ	7.1
Forced labor and slavery (% of population)	ⓘ	1.37
Voice and accountability (0-100)	ⓘ	8.87
Regulatory quality (0 - 100)	ⓘ	5.29

These facts highlight problems, such as an ongoing conflict as well as lack of political stability and rule of law. Reports from stakeholders in the materials supply-chain to assure sustainable mining and recycling can be found via: https://www.cobaltinstitute.org/superalloys.html.

5. Reality Check

A more detailed case study of material properties for jet turbine blades using the same selection methodology has been published by NASA. In this case study, we have also explored unique additional aspects of sustainability.



S. Arnold et al., Materials Selection for Aerospace System, NASA Tech Memorandum 2012-217411

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Document Information

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ANSYS, Inc.
Southepointe
2600 Ansys Drive
Canonsburg, PA 15317
U.S.A.
724.746.3304
ansysinfo@ansys.com