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Aerospace and Automotive Turbine Blades

Claes Fredriksson and Charlie Bream
Granta Design, 300 Rustat House, 62 Clifton Rd, Cambridge, CB1 7EG, UK

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Summary

This case study demonstrates how CES EduPack can help to suggest alternative materials for turbo blades, which relates to typical aerospace or automotive applications. We show how to ensure that requirements on material properties, such as high temperature and resistance to fast fracture and centrifugal loading are met. The case is inspired by an industrial R&D project presented at a conference.

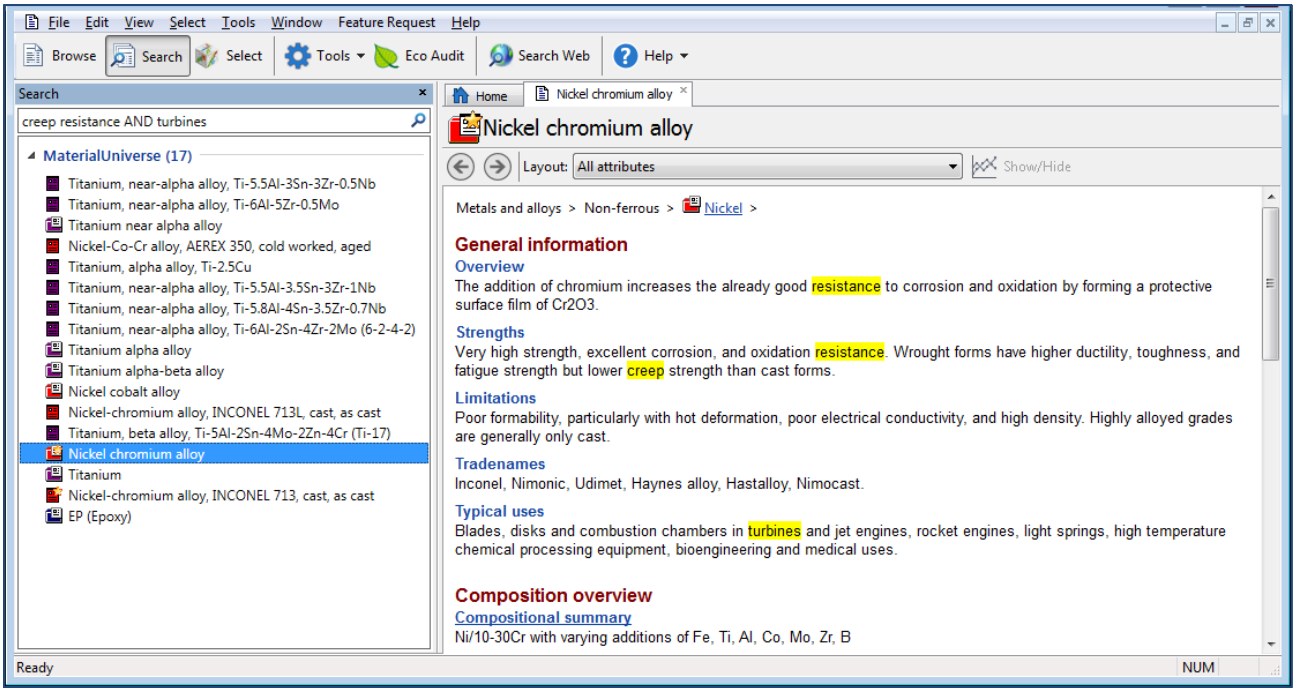
CES EduPack provides a rational and systematic approach to material selection, invaluable to engineering. It enables informed materials choice while clearly showing the steps of the process for the purpose of teaching and training. Among the users of Granta software in these areas are Honeywell Aerospace and NASA, for example.

1. Introduction

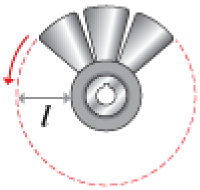
The power to weight ratio for engines is particularly important for high-performance automotive and aerospace applications. The power of a piston engine is directly dependent upon the injected amount of air. The purpose of turbo-supercharging is to increase the inlet manifold pressure and density so as to increase the mass of air ingested into the cylinders during each intake stroke. A turbocharger is a single-stage radial-flow ("centrifugal") air compressor, which is driven by a single-stage radial-flow turbine. The turbine takes kinetic and thermal waste energy from the high-temperature exhaust gas flow to drive the compressor, at the cost of a slight increase in pumping losses. This has been widely used in automotive engines since the 1970's. Turboprop airplane engines can also have radial flow turbines while 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 deliver high power to weight ratio and involve challenges to the design and material choices of turbine blades.

2. What are the turbine blades made of?

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 those gases. There is some expansion of the gas across the turbine nozzle which reduces the temperature but, at the tips of the turbine rotor, it can approach exhaust gas temperatures. The turbine blades of jet engines work in similar or worse conditions from around 800°C upwards. Moreover, the rotor system on many turbochargers operate in excess of 100 000 RPM. Huge tensile loads result from the centrifugal forces, in addition to vibrational and bending loads. Thermal shock and Creep are also issues. Nickel-based superalloys are therefore used for such turbine discs. These alloys retain high strength values even at high temperatures. Typical turbines are investment-cast from Inconel 713 C or 713 LC and turbine wheel castings can be treated with Hot Isostatic Processing (HIP) for improved structure, then heat-treated for the required strength[1]. In this case study, we look for alternative material candidates to Inconel 713 for turbine blades in automotive or aerospace applications. You can use the search function of CES EduPack to search for ***'creep resistant AND turbines'***, or use the browse directly to read the folder level record and data record for *nickel chromium alloys* and *Inconel 713*, respectively. In this study, we have used the ***Favourite*** function to mark Inconel 713 cast, as cast, as a reference.



3. What is the Problem?

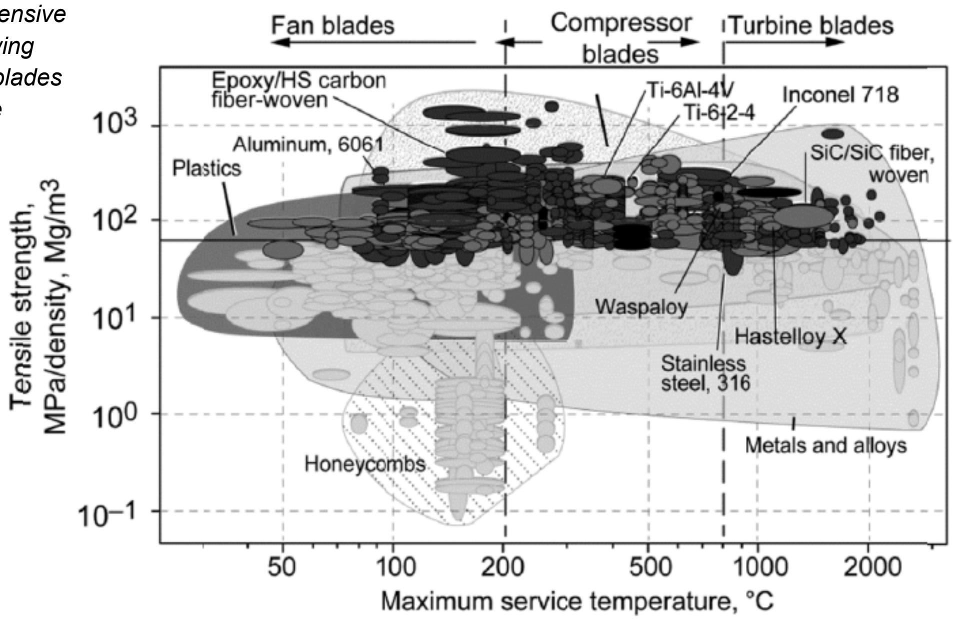


A turbine blade is subjected to huge centrifugal load, which will be one of our critical factors in selecting the material. The blades also must not fail due to bending during sudden turbine acceleration or vibrations. This requires high strength and resistance to brittle failure. The radius of the turbine (length of the blades, *l*) will be determined mainly by flow and space considerations and is therefore treated as fixed.

It is well known that some superalloys and technical ceramics have sufficient properties to resist high temperatures, corrosion and creep. CES EduPack can be used to investigate other 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 strength in combination with low density for this particular application. *Tensile strength*, *Yield strength* or *Fatigue strength* are possible mechanical properties to consider. Here, we have chosen Fatigue strength, which is used for cyclic loads. 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 starts, stops, thermal shocks etc.

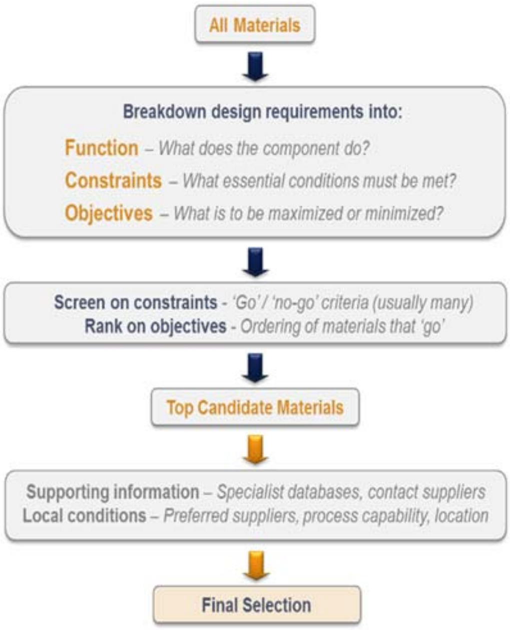
A more thorough case study of material properties for jet turbine blades using the same database and selection methodology has been published by NASA[2]. In the NASA study, blade bending loads and vibrations were considered as well as centrifugal load. Temperature ranges are shown below. Here, we want to provide a realistic case study of high temperature applications but we will not explicitly consider bending and vibrations. We are interested in service temperatures around the melting points of superalloys, *900-1000°C*, without taking into account internal cooling, thermal barrier coatings or single crystal designs.

Examples of data from an extensive materials selection case showing the temperatures of different blades in a turbine jet engine. Source NASA[2]



4. How to use CES EduPack to perform material selection

In order to select potential materials, we will follow the rational selection methodology by Ashby *et al*[3], illustrated schematically in the diagram below. We will use level 3 of the ***Aerospace database*** but the Standard Level 3 MaterialUniverse data can also be used. The selection is started by clicking ***Select*** in the main toolbar and choosing ***All bulk materials***.



Function:

We are looking to determine materials for a ***radial turbine blade***, for a turbocharger in an aerospace or automotive application. The **blades of fixed length, *l*, *are rotating*** with high speed, where the angular velocity is a free variable. ***Cyclic load*** and ***Strength-limited design*** are considered.

Constraints:

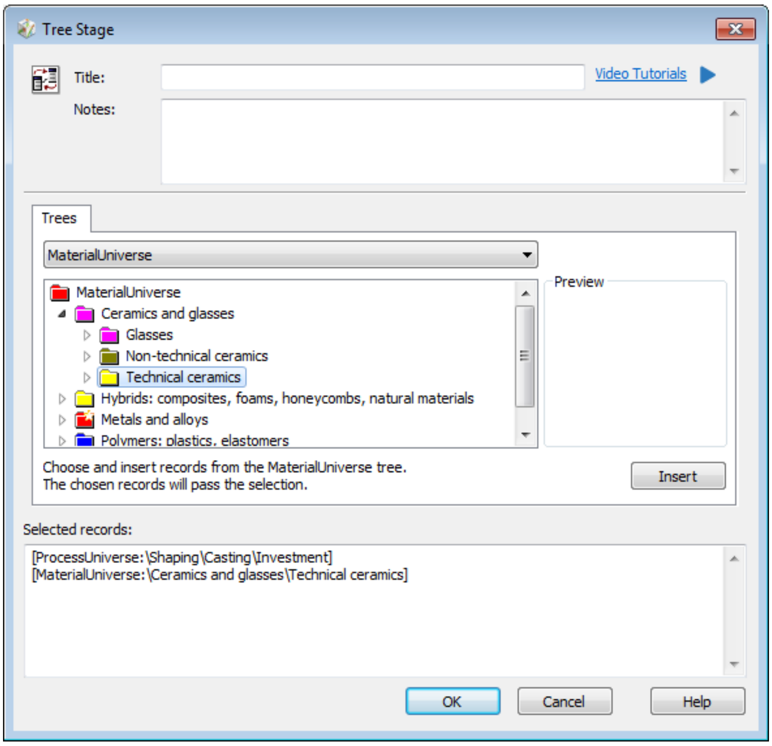
The constraints can be applied in any order, before or after plotting the relevant chart. Here, we will begin by screening, then specify the objectives to put on the axes of the property chart for ranking.

List of constraints

- Adequate Fatigue Strength (at 10^7 cycles) >*360 MPa*
- Thermally stable at Service temperatures > *900°C*
- Resistant to oxidation at high temperatures: *Excellent*
- Only *Technical ceramics* and *Metal alloys* considered
- Metals should be manufactured by *Investment casting*

In the CES EduPack, screening can be carried out in several ways. We begin our selection by screening for *Fatigue strength*, *Max service temperature* and *Resistance to oxidation* using the ***Limit*** stage, which is activated by clicking. The values are simply entered in the dialogue box. Here it is easy to explore the effects of different service temperatures and compare screened materials at *900°C* and *1000°C*, for example. In our case, the reference material, Inconel 713 has a *Maximum service temperature* below *1000°C*.

Then the ***Tree*** stage is used to specify requirements on manufacturing processes and ceramic class. From the ***ProcessUniverse*** tree, choose: Shaping > Casting > Investment casting. Furthermore, from the ***MaterialUniverse*** tree, choose: Ceramics and glasses > Technical ceramics. This results in less around 50 materials that pass these constraints at *900°C* and slightly fewer at *1000°C* or above. All the constraints considered for the turbine blade material are summarized in the list above.



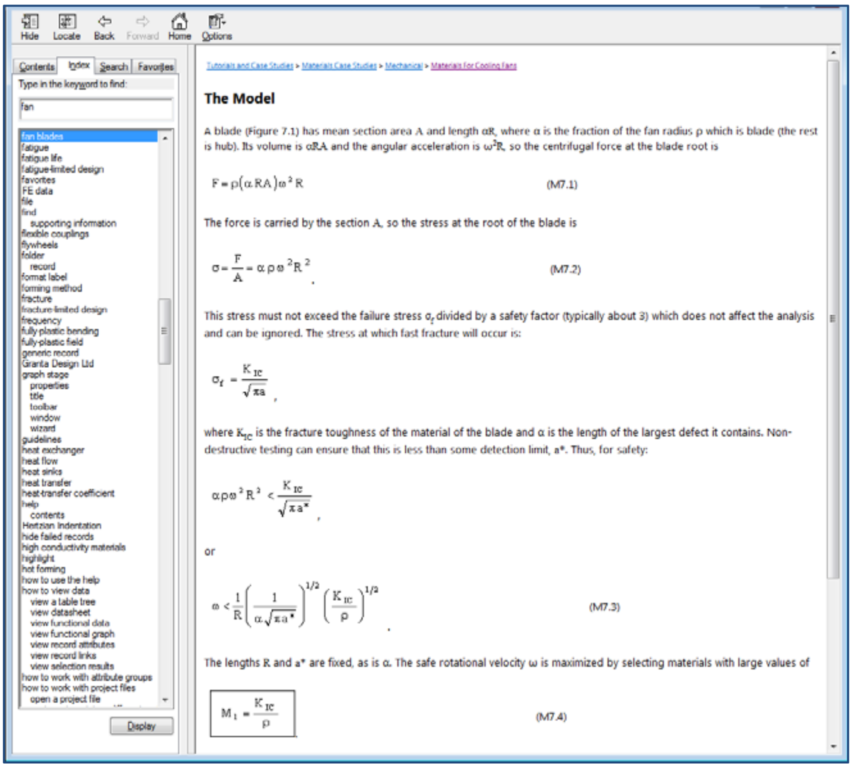
Objectives:

The table of Material Indices available via the *CES Help* button does not cover rotating blades. What we would like to do is to maximize:

- Resistance to fast fracture
- Resistance to centrifugal loading

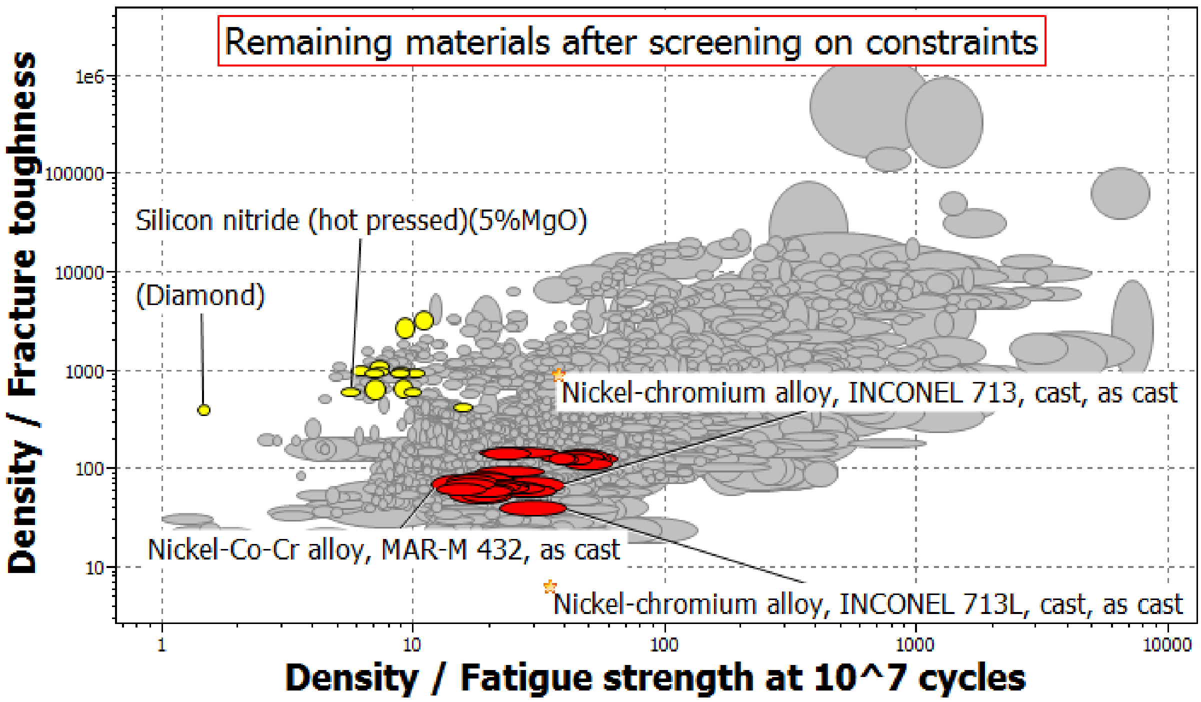
However, the Index in *CES Help* contains information on how to derive the index for resistance to fast fracture (as well as cost minimization, not shown). The equations and the resulting Performance index are shown to the right.

We want to maximize equation M7.4 shown in this derivation. This is equivalent to minimizing the inverse, $M1=\rho/K_{Ic}$,. For the resistance to centrifugal loading, we will minimize the specific strength[2]: $M2=\rho/\sigma_e$, where σ_e is the Fatigue strength (used for cyclic loading). Both these objectives can now be plotted using the *Advanced* feature of the graphing tool.

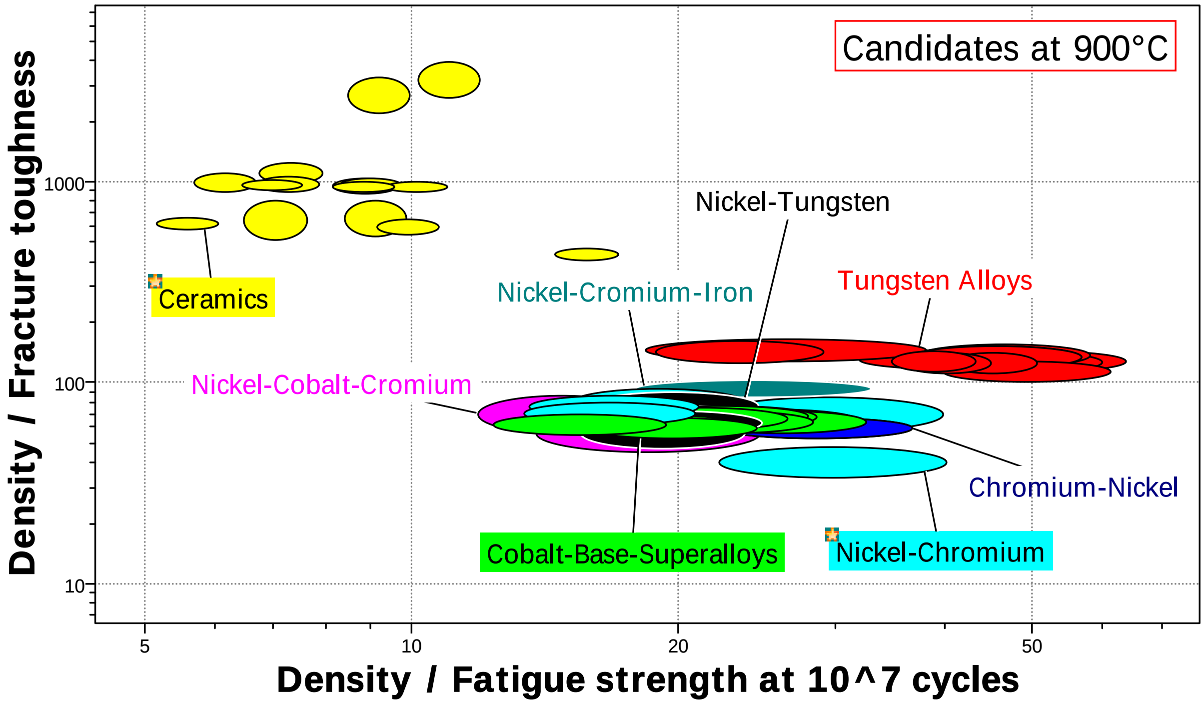


5. Result

The resulting property chart of the materials remaining after applying the constraints is shown below. (the screened materials are greyed out). The two main performance indices M1 and M2 are plotted on the Y-axis and X-axis, respectively, allowing visual minimization of the objectives. Diamond is classified as a ceramic in the database and appears in this chart. It will however be eliminated in the next step due to unrealistic cost.

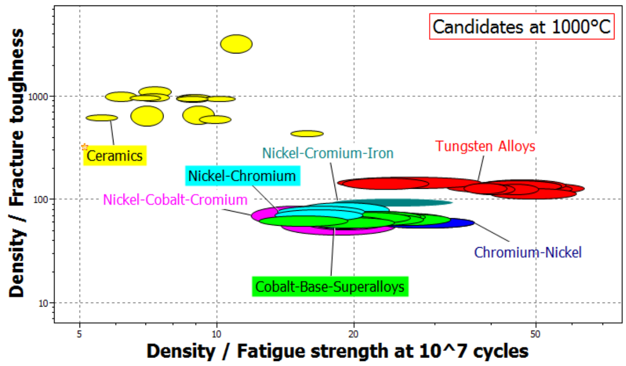


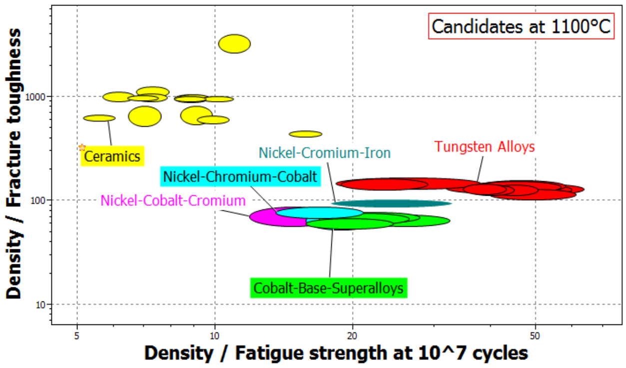
As can be seen in the chart above, there are Ni-based alloys that perform ‘better’ than the reference Inconel 713 superalloy, both with regards to *Fast fracture* and to *Fatigue strength*. A few non-dominated solutions are shown in the chart. If the specific *Fracture toughness* can be allowed to be one order of magnitude ‘worse’ than Inconel 713, then a few technical ceramics with competitive *Fatigue strength* performance can be found. The ‘best’ combined performance of the ceramics is displayed by a silicon nitride material with 5% MgO. This one is now highlighted as *Favourite* in the chart below together with the reference superalloy. The different classes of alloys are color-coded to aid the understanding of alternative turbine materials.



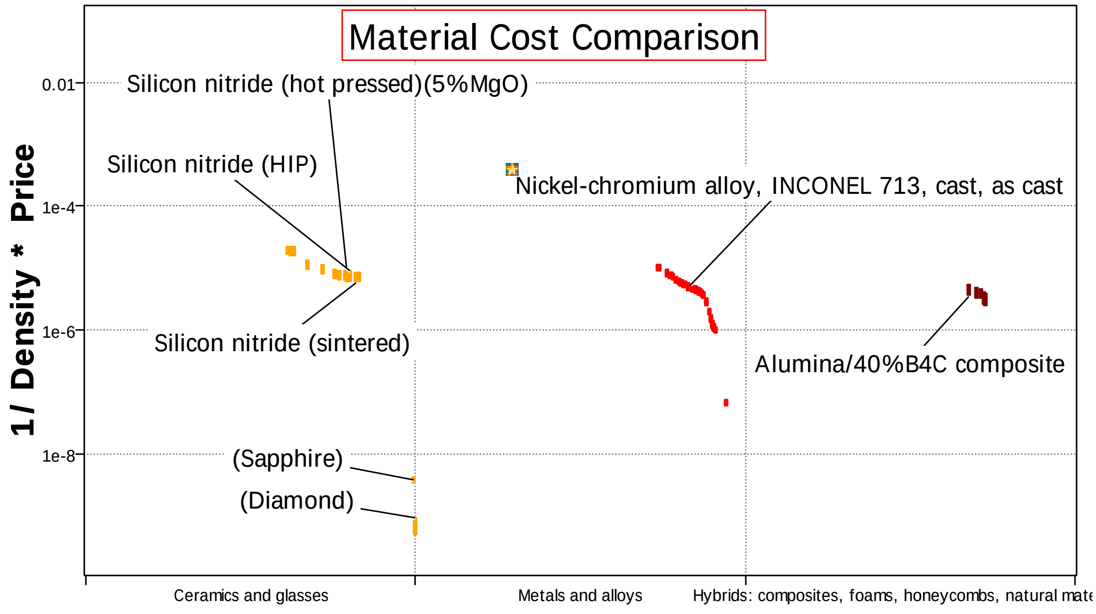
6. Analysis and reality check

The selection can consider all materials of the MaterialUniverse database or concentrate on a subset. In this example we have explored alternative *bulk materials* to Inconel 713. The software makes it quick and simple to input the constraints outlined previously, including the investigation of limit values to capture different temperature conditions. The chart above shows that technical ceramics have superior *Fatigue strength* performance compared to the superalloys but that they are at least one order of magnitude worse in *Fast fracture* performance. In the charts below, the evolution of remaining materials is shown as the Maximum service temperature is increased to *1000°C* and *1100°C, respectively.* The technical ceramics persist while Inconel 713 and nickel tungsten alloys are screened at *1000°* and, e.g., chromium nickel alloys at *1100°C*.





Although the cost performance was not the primary aim of this case study, the performance index for cost is also given in the same location in *CES Help* as the fast fracture Performance index. In order to minimize cost, the value of $M3=1/C_m{}^*\rho$ can be plotted in a bar chart to be maximized. The product in the denominator represents the price per volume of each material, which is a good measure of the total material cost, since the volume remains approximately the same for all considered materials due to fixed blade length. A chart including also composite materials shows that silicon nitrides are at the more expensive part of the ceramics range (low M3) but that it is more competitive than the reference superalloy or the composites. Sapphire and diamond are, of course, eliminated as unrealistic alternatives at this stage since they cost at least 1000 times more.



CES EduPack, combined with an educator's materials expertise, suggests the following conclusions:

- The charts above show that for the turbine blade, some technical ceramics have superior *Fatigue strength* performance (M2) compared to existing superalloys but, that they are at least one order of magnitude worse in *Fast fracture* performance (M1).

- Among the technical ceramics (neglecting diamond), *Silicon nitride (hot pressed) with 5% MgO* has the best combined performance, as determined by the two main Performance indices. silicon nitrides are at the more expensive part of the ceramics range (low M3) but that it is more competitive than the reference superalloy.

- Changing the *Maximum service temperature* from *900°C* to *1100°C*, does not change the ranking of the ceramic materials but affects the metal alloys that pass this screening. The reference material Inconel 713 has a maximum service temperature of around *900°C*.

The suggested material, silicon nitride, is the same ceramic material as proposed by Ingersoll-Rand Energy Systems and Kyocera Research Center in a collaborative R&D project with American Research Institutes and Department of Energy for power generation turbines. Silicon nitride was presented as a potential substitute for Inconel at a conference on a conference on Composites, Materials and Structures[4]. There is constant research in the aerospace industry to develop ceramic alternatives for superalloys in turbine applications.

7. What did CES EduPack contribute?

CES EduPack makes use of Granta's MaterialUniverse™ data resources, providing complete property data for virtually every class of purchasable engineering material—more than 3000 potential candidate bulk materials. As property values are either populated with known, referenced data or with values estimated systematically by Granta, you can be confident that potential candidate materials have been considered: no suitable materials will be excluded simply because their properties aren't known.

The range of possible materials was quickly reduced from 3000 materials by screening using a *Limit stage* selection then using a *Tree stage* selection by restricting the choices to those materials that met the *processability* criteria for metal alloys or were technical ceramics. Depending on service temperature chosen, around 50 materials remain for ranking. This pool could easily be investigated by changing the *Limit stage* to regarding Maximum service temperature. Using CES Edupack, it is easy to graphically display the objectives and remaining materials to analyze the trade-off between the performance indices.

The Performance index (a formula describing the combination of properties that must be minimized or maximized in order to make an optimal choice for a particular design objective) was based on fast fracture performance. CES EduPack gives support for many standard Performance indices (sometimes referred to as material indices) via Tables available in the CES Help function of the toolbar. In some cases, such as the turbo blade, information could be found in the extensive embedded searchable documentation (also available under CES Help) using the keyword ***Fan blade***.

Overall, CES EduPack is a powerful tool to aid systematic, rational and objective materials selection, providing results that are easily auditable. It is simple to use and quick to investigate a broad range of potential materials before looking into more specific data about manufacturer's grades as the search progresses. Industrial case studies and realistic projects are facilitated by the links at the bottom of data records, showing examples of suppliers for each type of material.

References

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2. Steven M. Arnold, David Cebon and Mike Ashby, "Materials Selection for Aerospace Systems", NASA/TM-2012-217411 (Technical Memorandum). Available online: http://everyspec.com/NASA/NASA-General/NASA_TM-2012-217411_47675/

3. For example, in Ashby, M.F. (2005) "Materials Selection in Mechanical Design", 3nd edition, Butterworth Heinemann, Oxford, UK. ISBN 0-7506-6168-2.

4. Jim Kesseli et al. "Comparative Materials Evaluation for a Gas Turbine Rotor", 27th Annual Conference on Composites, Materials and Structures, January 27-30, 2003. Available online:

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