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Lifetime prediction for Turbocharger Compressor Wheels - Why Use Titanium-?

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INTRODUCTION

The trend towards using smaller highly charged diesel engines continues. The advantages regarding fuel consumption and emissions as well as installation dimensions and weight are evident. Often such engines are installed in delivery trucks, city buses and light duty trucks. The common characteristics of such applications are high cyclic loading.

In most cases of cyclic loaded applications the lifetime determinant component in today‘s commercial diesel turbochargers is the aluminium alloy compressor wheel. It therefore requires a very close look at the lifetime of the compressor wheel. The damage mechanism is based on material fatigue under cyclic loading at low frequency. This phenomenon is known as “Low Cycle Fatigue“.

LOW CYCLE FATIGUE (LCF)

From the industrial revolution circa 1830 there have been failures in mining and railway applications which could not be explained from the standpoint of static loads. Since then scientists have tried to explain material and component behaviour under time dependent variable load. Today we distinguish between time dependent loading and fatigue at high frequency (HCF) and low frequency (LCF). The operating life until failures occur can be significantly different. The damage mechanisms are very similar but never the less a closed theory of fatigue behaviour was not available until today.

Professor Otto Buxbaum, former director of LBF (which is part of the Fraunhofer-Institute) in Darmstadt/Germany, is a well known German scientist in the field of material and component fatigue in operational conditions and stated that:
“The coming into being of vibration fatigue failures is a highly complicated process, because the number of possible influences is so high. This number is only exceeded by the number of scientists who have written about it.“
See reference1)

Today‘s knowledge about LCF can be summarised as follows
- Fatigue behaviour of metallic materials is closely connected with local plastic deformation
- An accumulation of cyclic plastic deformation leads to micro fatigue cracks
- Initial micro cracks are the starting point for macro cracks
- After a certain time the macro crack growth lead to component failure

A good impression of what LCF means with regard to centrifugal compressor wheels is shown in Figure 1. Starting from the bore there is a half moon shaped fatigue crack which increases until the remaining hub area fails.

Conclusion
From an economical standpoint, it is a normal trend to use materials very close to their limits but this requires a deep knowledge about material behaviour and loading.
In addition to the above mentioned difficulties in describing LCF, the statistical nature of failure and loading needs to be taken into consideration. Therefore, statistical likelihood methods are needed to define material characteristics as well as load cycles.
A method has been developed for lifetime calculations, which takes into account the acquired information.
Accurate predictions will highlight more clearly the limits at which more expensive material is required.

LOAD CYCLE

The load cycles for compressor wheels are expressed by tip speed versus time. The nature of load cycles are mainly determined by application (e.g. heavy-duty trucks, delivery trucks, city buses, light duty trucks, off road, railway, industrial,...) topography, altitude and driver style. Examples for different load cycles are shown in Figure 2. It is evident, that this influences compressor wheel lifetime to a great extent.

The characterisation of load cycles must include maximum tip speed, cycle depth (difference between max and min speed of successive cycles) and cycle frequency. This is carried out by a computer program based on the Rainflow Method[2,3)] and the results are used as the input data for the following lifetime calculation.

MATERIAL

Material for rotating components is loaded by centrifugal force and is also linearly dependent on density. A useful ratio to judge material capability under centrifugal loading is the ratio of strength to density, which has the dimension of a length:

$BL = UTS / (\rho * g)$

BL: breaking length
UTS: ultimate tensile strength
ρ: material density
g: constant – gravity

The physical explanation of this ratio is, that BL is the length of a bar or wire, which breaks under its own weight. In Table 1 some data for aluminium alloys is shown. Additionally a common standard steel used for turbocharger shafts is also shown and the usual Titanium alloy TiAl6V4. The UTS values except for steel are taken from in-house test results.

The typical materials for compressor wheels are the aluminium alloys C355 and 354. These materials have a very good ratio between strength and density as well as good cast capability

Material	Density	UTS	BL	
	kg/m^3	MPa	km	
Aluminium Alloy C355	2.760	360	13,3	Cast
Aluminium Alloy 354 HIP	2.760	390	14,4	Cast
Aluminium Alloy 2618	2.760	420	15,5	Forged for milled wheels
Steel 42CrMo4V	7.850	1.100	14,3	
Titanium Alloy TiAl6V4	4.450	970	22,2	Cast

Table 1 : Breaking length for different materials

and reasonable cost. Aluminium 2618 is primarily used for milled wheels. The breaking lengths of the materials shown in Table 1 show a clear order although the differences between them are not huge. Steel has a high UTS value but the high density compensates for this. Only titanium shows a remarkably high BL value. This is the reason, why titanium is widely used in weight sensitive areas such as aircraft, aerospace or Formula One.

Results in the form of static data from pull tests such as UTS and breaking length describe only one aspect of the properties. Good quality information with regard to cyclic load capability such as S/N-curves (Woehler Lines[4)]) produced using pull test specimens cut from wheels and spin test results from real components is not generally available. Figure 3 shows the Woehler lines of two aluminium alloys. At high loading the differences are relatively small according to pull tests. In the region of the endurance limit remarkable differences are visible that are not seen by means of UTS. To calibrate such pull tests from using specimens spin tests with compressor wheels are necessary. Figure 4 shows spin test results at the same load for the same wheel type with two different materials shown as a Weibull5) distribution. The scatter in the results from pull and spin tests describes the statistical nature of material properties and must be included in the lifetime calculations.

STRUCTURAL AND AERODYNAMIC DESIGN

Stress reduction by structural design

The major mechanical stresses of rotating components are created by centrifugal forces. The highest values are located at the bore, in the plane of maximum mass concentration at the largest diameter. This is usually the backwall region of centrifugal compressors. A second relatively highly loaded region of wheels is the root area of the blades which are connected to the backwall near to the outer diameter. Figure 5 shows an example of reducing hub stress by approximately 10% without any disadvantages to the aerodynamics for a new “O“-wheel design as opposed to the former “M“wheel design. The principle is to reduce hub material accumulation at larger diameters which leads to a “lean“ hub and extended back in the bore area. Additionally the blade root area is modified from a 90 degree connection to one with a 60-degree link. This leads to a significant stress reduction in this region as shown in Figure 5.

Stress reduction by aerodynamic design

The basic aerodynamic design influences tip speed and therefore as a direct consequence the wheel stress level. To reach a given pressure level, there is the need for a defined tip speed which it is well known from Euler’s6) equation. In achieving this some important compressor characteristics are influenced. These are mainly

- Efficiency
- Map width (maximum difference between surge line and choke limit)

Pressure number; the pressure number □ gives a relationship between generated pressure and tip speed and is defined as

$$\psi = \frac{\Delta h_s}{u_2^2/2} = \frac{c_p T_1 \left[(p_2/p_1)^{R/c_p} - 1 \right]}{u_2^2/2}$$

Δh_s	isentropic head
c_p	specific heat
T_1	inlet temperature
p_1	inlet pressure
p_2	discharge pressure
R	gas constant
u_2	tip speed at CW outlet diameter

The most important influence comes from the compressor blade outlet angle. State of the art turbocharger compressors have backward curved blades at the outlet. Strong backward curvature leads to higher efficiencies and maximum map width but also leads to high tip speeds with the consequence of relatively high stresses.

Compressors with high pressure capability (high characteristic pressure numbers) show different characteristics. Tip speed may be reduced but efficiency is reduced and map width decreased. Figure 6 shows, as an example, the comparison of two compressor wheels designed as described above. The “mid pressure“ compressor has a characteristic pressure number $\psi = 1.07$. Map width is excellent and efficiency is high with efficiency islands which approach the surge line. For the “high pressure“ compressor, the characteristic value is $\psi = 1.22$. Efficiency is approximately 3% less and the surge line is located at higher mass flow for the same choke flow. Especially at maximum speed, the effect of the different design philosophies is evident. The high-pressure compressor needs 10% less tip speed than the mid pressure compressor to reach the same pressure ratio of 4.0. This leads to a significant reduction in stress.

LIFETIME CALCULATION

The lifetime calculation method for compressor wheels is based on the idea that each load cycle which has a current mean stress value in combination with a stress amplitude above a certain level, leads to a part damage of the given material. Linear accumulation of all part damages up to component failure gives the lifetime. This is known as the Miner Rule[7)]. This includes the statistical distribution of material and spin test results.

Prerequisites

1.	Woehler-Curve (S-N-Curve) for each different type of compressor wheel	> Spin Test
2.	Representative load cycle for the Application in question.	> Vehicle Measurement (Customer)
3.	Rain-flow method for statistical counting of the load cycles	> Program Code
4.	Miner Rule for linear damage accumulation	> Program Code

Result
Lifetime in km or hours for a given probability of failure (e.g. 2, 5, 10%)

For the load cycle examples given in Figure 2, the corresponding lifetimes are shown in Table 2.

Load cycle	Lifetime B2	
Highway	750,000 km	
Country Road	1,012,000 km	
Highway Bus - Urban Area	247,000 km	Not acceptable
City Bus	98,000 km	Not acceptable
All cycles Titanium Alloy	“endless“	All applications

Table 2 : Compressor wheel lifetime for a probability of failure of 2% (B2)

By means of the lifetime calculation it is possible to predict the effect of tip speed reduction on life of the compressor for all speeds in a cycle as shown in Figure 7. Here it is assumed that the measured load cycle has to be matched with various aerodynamically designed compressor wheels or by changing application parameters. The dependence of lifetime on tip speed is evident.

In several applications it is possible to find a compromised solution which allows the use of a high pressure compressor but for other applications the aerodynamic performance and hence speed of a mid pressure compressor is required. For these applications a totally different solution is required.

TITANIUM COMPRESSOR WHEEL

Manufacturing

In most cases the geometric compressor wheel design is a given based on the known aluminium wheel. Therefore the first question to be resolved is how to produce an aerodynamically equivalent titanium wheel. The two obvious methods are by casting or milling.

5-axis-milling for aluminium wheels is a well known process. It permits the highest flexibility and freedom in design. However, because of its special material properties titanium makes very high demands on manufacturing technology.

With the knowledge to cast aluminium and INCO it seems advantageous to manufacture titanium wheels as cast parts. However, titanium has also very special properties as a cast material. As with turbine wheels it requires a die cast process based on wax positives. To produce waxes the freedom of design is restricted due to the fact that a so-called “pullable design“ is necessary in order to pull out the tool slides. Strong backward curved blades are not possible due to this requirement. With two or three segmented dies to shape the required backward curvature it is theoretically possible, but because of the requirements for precision, it is not a practical alternative. Molten titanium is highly reactive to its environment hence the need to cast in an Argon atmosphere. Chemical reactions to the ceramic shell are present which lead to a very brittle surface layer. This layer must be removed by a so-called “chemical milling“ process with an extremely aggressive acid. To meet the final wheel dimensions after chemical milling all dimensions must be modified with an equivalent offset before casting. This normally leads to difficulties with the impeller due to the space requirement between the blades.

Against the background of all these problems and the comprimises in design required for the given application, this make the achievement of the customer‘s requirements very difficult, it was decided to procure milled titanium compressor wheels as opposed to castings.

Qualification
To qualify a new compressor wheel and release for production a set of specifications must be fulfilled. Some important points are:

1. Natural burst shows the potential of the material. The wheel is accelerated until burst occurs. Three compressor wheels were tested with the result that no compressor wheel burst occurred before the turbine wheels burst at 777m/s, 888m/s and 908m/s compressor wheel tip speed, see Figure 8.
2. Containment shows the capability of the compressor cover to prevent piercing in the case of a wheel burst. The damaged parts must not pierce both the compresor cover and a sheet metal cover made from 0.5mm aluminium. As a compressor wheel burst did not occur the titanium wheels were weakened by milling a slot into the wheel back so that a wheel burst occured at approx. 650m/s, see Figure 9. This very deep slot showed the enormous capability of titanium to resist failure. The compressor back plate remained intact and no pressurised oil escaped.
3. Spin Test results are required for the judgement the wheel capabilities under cyclic loading and for the lifetime calculation. In the case of titanium compresor wheels the test was halted after 5 months without a failure occuring, with lifetime increased by a factor 13 compared against cast aluminium wheels. Inspection at the material laboratory showed the titanium wheels were in an absolute perfect condition without any micro cracks Figure 10.
4. Moment of inertia

The higher density of titanium leads to an increase in the moment of inertia for the whole turbocharger rotor assembly aproximately 24% which affects the dynamic behaviour. Engine tests carried out on an electronically controlled dynamometer show a negligible influence on emissions, because the engine electronics compensates for this small adverse effect.

5. Dimensions of milled wheels are highly accurate. From this it follows that the balancing process is quite simple and many wheels are found to be within the balance limits without material removal.

6. Blade natural frequency is important to prevent the wheel running in fourth order. One large advantage with milled wheels is the relatively small statistical variation compared against cast wheels.

SUMMARY

The life of today's turbochargers is primarily determined by the life of the aluminium compressor wheel. The damage mechanism is material fatigue under cyclic loading at low frequency. This phenomenon is known as "Low Cycle Fatigue" .

To use components close to the limits there was developed a tool to analyse and judge cyclic loadings by using Miner's damage accumulation rule and statistical cycle counting by the Rainflow Method. Material and component properties, e.g. spin test and cyclic pull test results, are taken into account.

Examples for different load cycles and corresponding lifetimes are given.

To increase lifetime of compressor wheels different measures are possible which are often used simultaneously. For example,

- reducing maximum tip speed, by changing the aerodynamic design, and / or
- using material with higher load capability.

For highest demands according to loading and lifetime, titanium compressor wheels are developed. Possibilities to manufacture are discussed and the qualification procedure is described. Lifetime increase against aluminium wheels is more than factor 13. After a time of 5-month spin test stopped without failure.

Series production of titanium compressor wheels started in summer 2001.

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Figure 1: Classic type of LCF hub burst

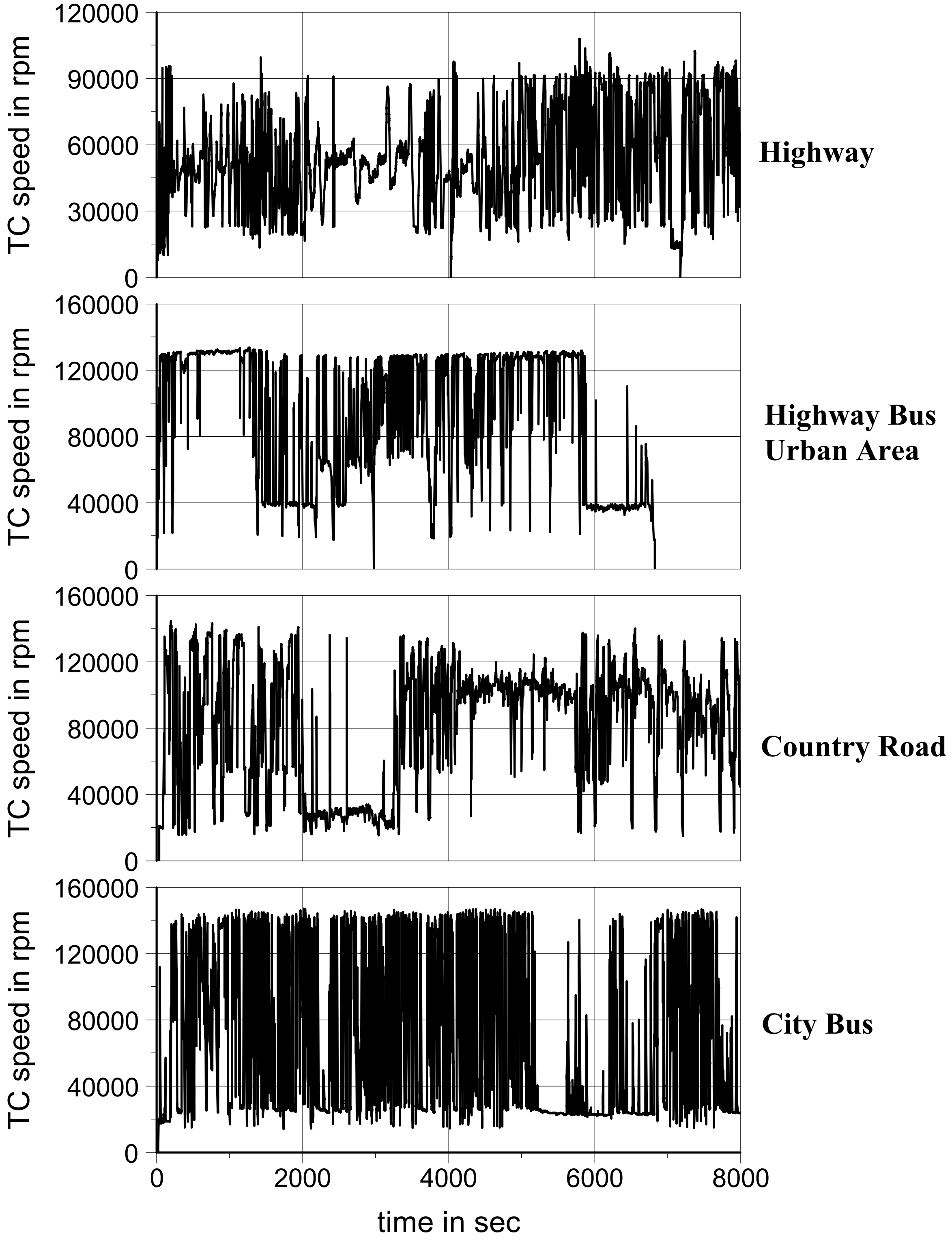

Figure 2: Load cycles for different applications

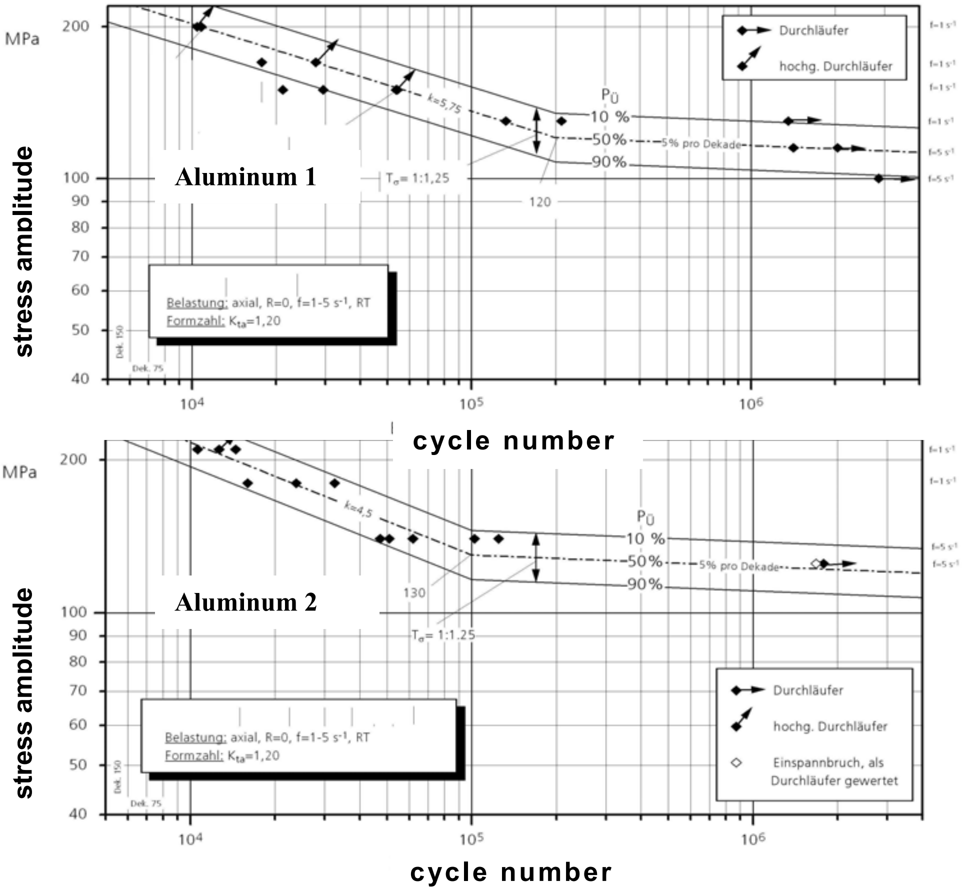

Figure 3: Woehler lines for two different aluminiums

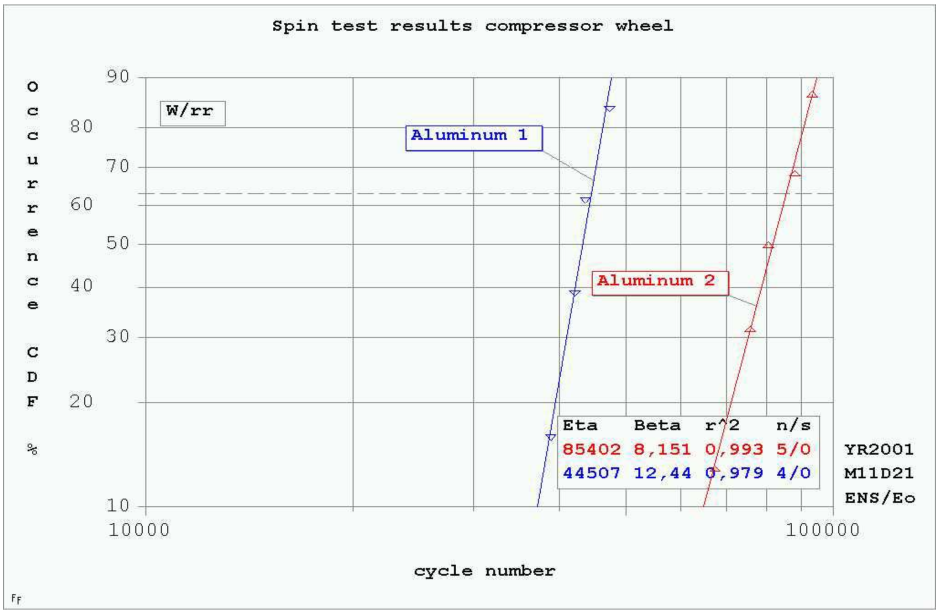

Figure 4: Spin test results as a Weibull distribution

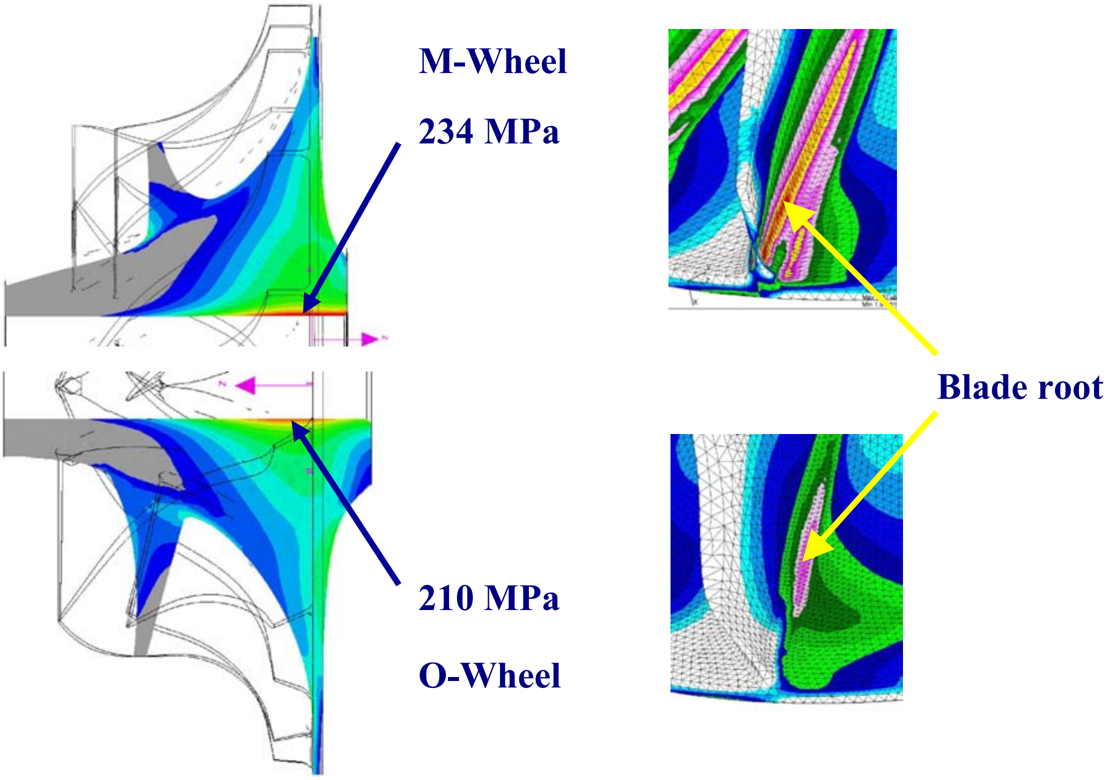

Figure 5: Sress reduction by design optimization

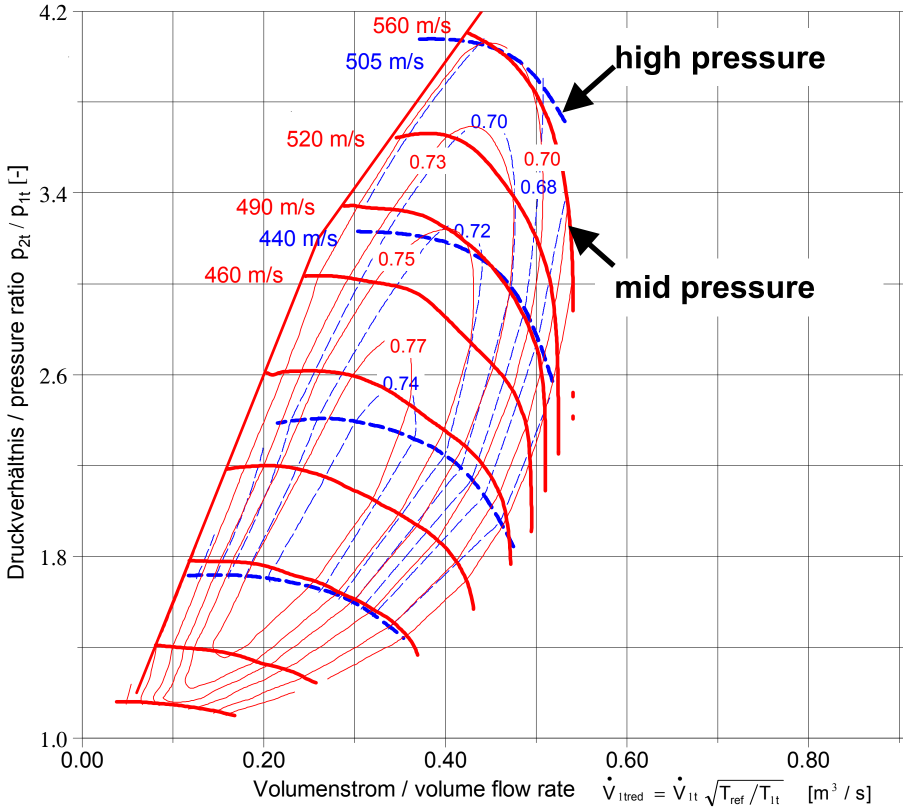

Figure 6: Map comparison high and mid pressure compressor

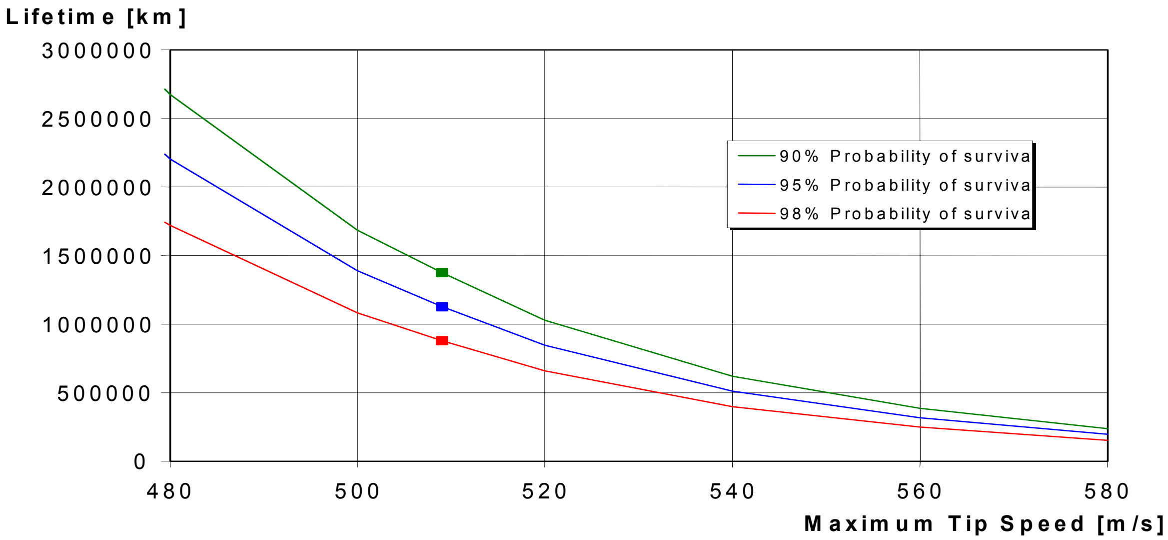

Figure 7: Compressor wheel lifetime as a function of speed level

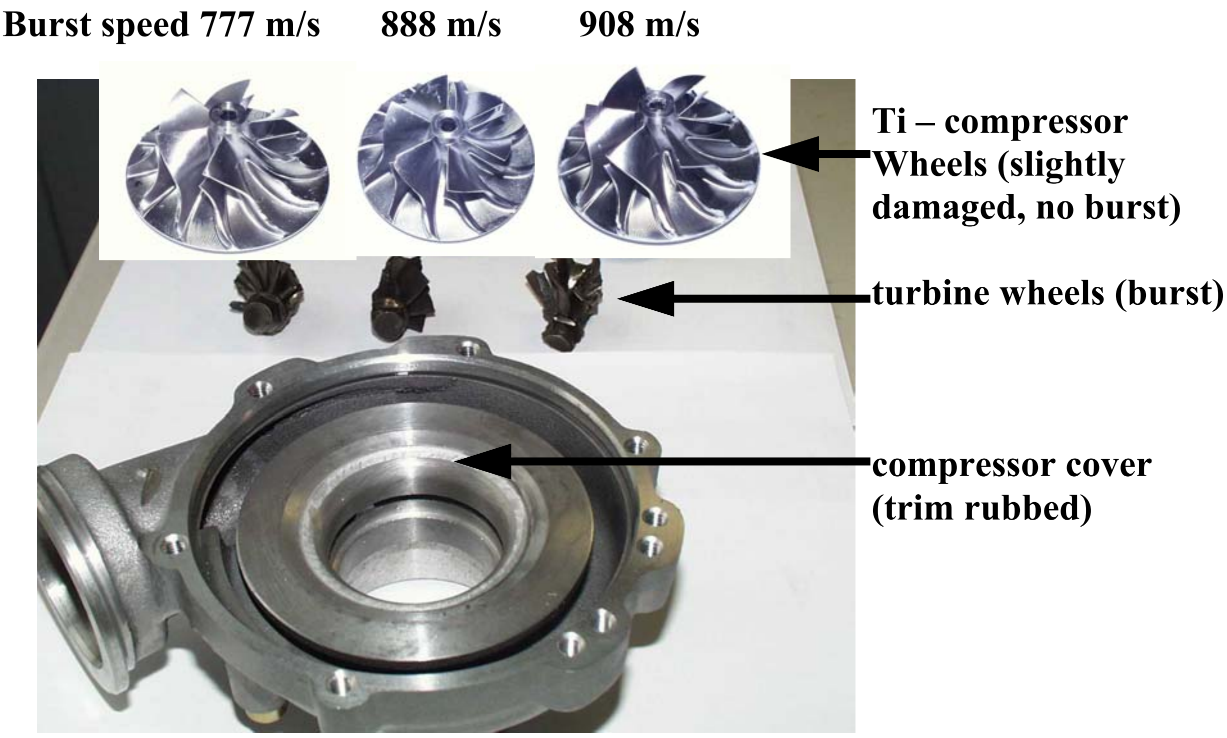

Figure 8: Titanium natural burst

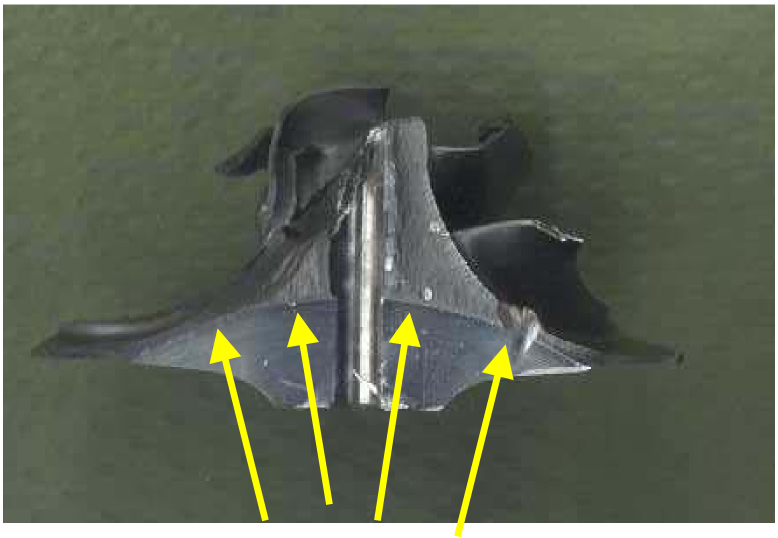

Figure 9: Weakened Titanium wheel for containment test

Figure 10: The Titanium wheel

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