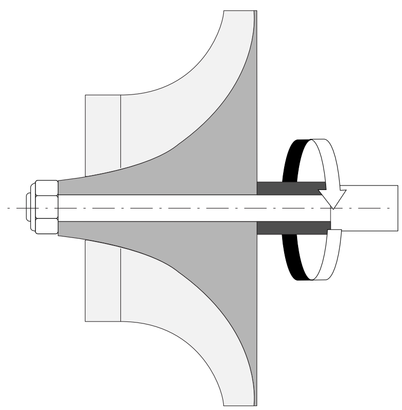
4. Component Behaviour, Influenced by the Material.

4.1 The Use/Application of High Strength Materials.



Higher loads/stresses are only possible with a better non destructive testing!

Is a material exchanged against one with higher strength, this will be frequently misleadingly equalized with an increase of safety. But, rather the opposite may be the case, if at the same time the strength of the usually also more expensive material, because due to material savings, is utilized with a rise of the load/stresses (Lit.4.1-5). This results in problems:

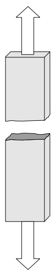
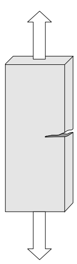
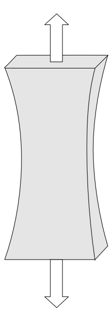
- Smaller **faults** lead to incipient cracks and crack growth. To find these faults sufficient sure, a more sensitive **non destructive testing** can get necessary (NDT, Ill. 4.1-4 and Ill. 4.3-7). This could be an insurmountable hurdle.
- The crack growth will be faster (Ill. 4.3-3).
- The sensitivity for **surface damages** increases.
- Crack forming effects like **stress corrosion cracking** (=SCC, chapter 5.6.3.1.1), **hydrogen embrittlement** (chapter 5.7) and **liquid metal embrittlememnt** (=LME, chapter 5.8) occur. This is also true if the load/stress is not increased (Ill. 4.1-1).

So the use of a higher strength material must be very exactly examined. This begins already with the **purchasing of the raw material**.

Must be reckoned with the same fault size like in a proved part in case of the utilization of the higher material strength in the semi-finished products? In the case of lower loads/stresses these can possibly be still tolerable weak points, Ill. 3.2.2-1.1. However if these are under the higher load/stress able to grow, they get dangerous. For a sufficient safety, these are therefore unacceptable and must be specified outside the dimensioning limits. This demands a **more sensitive non destructive testing method**, which, if necessary, must be first developed. From experience the likelihoood exists, that for this smaller fault size no series suitable, safe process is at the market available. Therefore the realization chances are low and the **material change** fails.

Trend of the use of materials.

Development trend

Symbolic load.	Dimensioning and load.	Materials properties.	Failure behaviour.
	Lifetime limited parts: - Low safety factors. - High load/ stress level.	High strength, low ductility up to brittle material, very sensitive against types of stress corrosion and notches (e.g., material inhomogenities and production caused weak points/faults).	Failing at dimensioning load: - Static: Improbable if no unforeseen additional effects (e.g., brittle coatings) and the relevant materials behaviour is fully understood. - Dynamic: Increased risk, because small deteriorating effects can get dangerous through crack growth. Notch sensible. - Unfavourable fracture mechanic properties (size of incipient crack, crack propagation, critical crack length). During overload: - Spontaneous failing with widely brittle forced fracture. Very small critical crack length. "Intercepting" of a catastrophic failure is unlikely.
	Lifetime limited parts - Medium safety factors. - Medium load/stress level.	Ductile material with low yield ratio. Increasing sensitivity for types of crack corrosion and notches (e.g., material inhomogenities and production caused weak points/faults).	Failing during design/dimensionig based load: - Static: Improbable. - Dynamic: Improbable within the "safe" lifetime, if occurring crack formation and crack growth. - Acceptable fracture mechanic properties. During overload: - Ductile forced fracture with low plasic defor-mation. Interception of a failure less probable, because plastic deformations and small critical crack length hardly become noticeable from the outside.
	Over dimen-sioned parts: - High safety factors. - Low Load/ stress level.	Ductile material with high yield ratio. Relatively insensitive against types of crack corrosion and notches. Steels are corrosion senitive.	Failing during design/dimensioning based load.during: - Static: Can be ruled out. - Dynamic: Improbable if loaded below the fatigue strength. - Favorable fracture mechanic properties. During overload: - Ductile forced fracture with high plastic deformation. Chance of an "interception" " of a catastrophic failure (unbalances, rubbing) or a failure limitation (e.g., loosing the rotorblades).

Ill. 4.1-1

Ill. 4.1-1: *The trend to* ***rising, as far as possible utilized material strength, supports the tendency to a potential risky behaviour of the components*** *(Ill. 4.3-7). This can be compensated with an increased effort in quality assurance, better analytic control of all relevant loads/stresses,* ***damage-tolerance concepts*** *and extensive operation near testing.*
Risiks for the component safety are influenced from three main factors:

- Design/dimensioning respectively load/stresses.
- Materials properties.
- Failing behaviour.

Design/dimentioning and loads/stresses: *With the strength usually rise also usually the dimensioning caused operation stresses. With this the crack growth increases. The crack growth alreadx takes place at smaller initial faults. The residual fracture occurs at smaller critical crack length (Ill. 4.3-3 and Ill. 4.3-7). The consequences show some typical examples:*
Smaller materials faults/weeak points become lifetime influencing failures. Demands at series suitable NDT methods increase. Production processes must be defined and controlled more exactly. Damages like scratches are less tolerable during maintenance and assembly.
High mean stresses lower the bearable stress amplitudes and increase the danger of fatigue failures.

- ***Materials properties and failing behaviour****:* *The* ***yield ratio*** *is the ratio of the ultimate strength to the yield strength. With increasing load, material versions with higher yield strength and similar as former ultimate strength, are applied. So the yield is reduced.*
The larger the distance of the yield stremgth from the ultimate strength, the rather arises a ***plastic deformation before the final failing*** *(fracture).* ***So warnings*** *like intense unbalances can be certainly identified.*

*Is the elongation of fracture reduced with increasing strength, the material gets more brittle. This must be expected during a maximization of the strength. So notch stresses can be not so easy released by plastic deformation without deterioration. At hot parts, materials with the high temperature strength increases the possibility of high internal/****residual stresses****. A high creep strength markedly limits a stress relief. The higher internal stress acts as mean stress and lowers the cyclic load capacity (Ill. 5.4.3.2-4). Overload can already lead to brittle fractures at thinner cross sections and low* ***critical fracture toughness*** *(Ill. 4.3-2, Ill. 4.3-3 and Ill. 5.2.1-4). With higher strength usually rises the sensivity against* ***envirionment influences*** *of a material. Concerned are* ***crack developing and crack growth supporting corrosion types*** *(Ill. 4.3-12, Ill. 4.3-13 and Ill. 5.6.3.1.1-5).*
*Goes the increase of the material strength and with this the load/stress t****ogether with smaller grain sizes*** *(e.g., powder metallurgical materials), the unfavourable fracture mechanic parameters can act additionally riskincreasing. For example the crack propagation speed can rise (Ill. 4.1-4) and the fracture toughness drop. This leads like a stress increase to smaller propagation able faults and smaller critical crack sizes. Smaller grain sizes can have the advantage of a better* ***ultrasonic testing*** *(less disturbances, „****grass****“). Parts from the same material, however conventional produced by casting and forging, ,can show bigger grains as powdermetallurgical versions (Ill. 4.1-4). With this the ultrasonic test ability gets worse. The probability of bigger faults rises and the possible* ***strength utilization*** *drops.*

The assumption, that the properties of a material will be preserved during operation can lead to bad surprises.

Influence.	Effects/mechanism.	Examples.	Literature.
Operation atmosphere: Corrosion:	- Corrosion pittings, notch effect. - Roughening, - Mechanical properties of the reaction products/coatings. - Longtime structure change.	Dynamic fatigue. Flow disturbance. Brittle surface, Crack formation (Intercrystalline C, SCC)	Ill. 5.6.1-2 Ill. 5.6.1-8 Ill. 5.6.1-3 Ill. 5.6.1-2 Ill. 5.6.1-8 Ill. 5.6.1-6 Ill. 5.6.3.1.2-2
Foreign material/ contaminations.	- Reactions with hydrogen. Diffusion. Influence of melt (liquid metal embrittlement = LME).	Crack formation, Removal/drop of lifetime.	Ill. 5.8.2-2 Ill. 5.8.1-4 Ill. 5.3-6 bis Ill. 5.3-8 Ill. 5.8.1-2 Ill. 5.8.1-3
Temperature:	- Creep damage. - Oxidation. - Structure orientation. - Formation of brittle phases. - Aging: Embrittlement, swelling, drop of strength.	Lifetime, repair. 'Rafting' at Ni casting. Single crystal. Sigma phase Elastomer seals	Ill. 5.3.2-6 Ill. 5.3.2-7 Ill. 5.3-4 Ill. 5.3-5 Ill. 5.3.1-5 Ill. 5.6.3.1.1-11
Mechanical load/stress:	- Plastic, internal stresses. - Vibration fatigue without macrocracking.	Plastics/elastomeres. e.g., tires. Exceeding of the yield strength, creep. Problem during reuse	Ill. 5.6.3.1.1-12 Ill. 5.3.2-9 Ill. 5.3.2-10
Wear: Abrasive wear.	- Changes of the geometry. - Dimensional changes.	- Flow disturbances. - Efficiency drop. - Vibrations. - Supporting problems/ contact problems positioning problems.	chapter 5.9 Ill. 5.1-2 chapter 5.5 chapter 5.5.1.1 Ill. 5.6.1-8
Fretting:	- Material deterioration - Abrasion of protecting oxide layers.	Drop of the fatigue strength. - Increased oxidation. - Increased sulfidation.	chapter 5.9.3

no claim for completeness

Ill. 4.1-2

***Bild 4.1-2**: Although it is obvious, the designer is not always aware, that the selected **material can change unfavorable during operation**. With this it looses the, for the operation necesssary respectively the design safety, underlying properties. Typical examples are:*

***Operation atmosphere**: It must be considered, that it can change. For example aggressive contaminations are possible, which occur only temporarily and/or develop only over longer time periods. The **surface region** will be influenced at several ways. During **corrosion** attack in form of **pittings** can occur. These act as notches and lower the fatigue strength markedly (Ill. 5.6.1-2). Already a **roughening** through **corrosion products** can influence unforseen a flow, e.g., in a **pipe line** or ta **fluid flow engine**/turbo-engine. This can also effect other components. For example if a downgraded efficiency in a turbo-engine must be compensated with higher process temperatures. These can crucial shorten the creep life of the hot parts (Ill. 5.3.2-4).*

*At corroding **anti friction bearings**, e.g., during stand still of the engine, an early dropout caused by the **fatigue of a raceway** (pittengs) must be expected.*

*Also the absorption of components from the operation atmosphere by **diffusion** can change the surface dangerously. An **embrittlement** promotes incipient cracks and lowers the fatigue strength. This is also true for changes of the **chemical resistance** with increasing corrosion. Does an attack change the geometry and with this the function of the component e.g., aerodynamic and thermodynamic assumptions during design get invalid.*

***Operation lifetime**: Basically first it must be assumpted that the materials change during design relevant operation temperatures (Ill. 5.3-4).*

*From the outset a consistent **material structure** can not be expected. Material specific structure components can dissolve, coarsen or orientate correspondent the outer load. Brittle and/or low strength components (phases) can precipitate. With this the strength and the fracture mechanical behaviour (Ill. 4.3-4) are influenced. Also the corrosion behaviour can change dangerously (Ill. 5.6.3.1.2-2).*

*Basically at a material specific **temperature level** (Ill. 5.3.2-1)a **time-load- dependent, consistent deterioration** must be expected (Ill. 5.3.2-4 and Ill. 5.3.2-6). So in this case the safe operation time must be correspondent considered.*

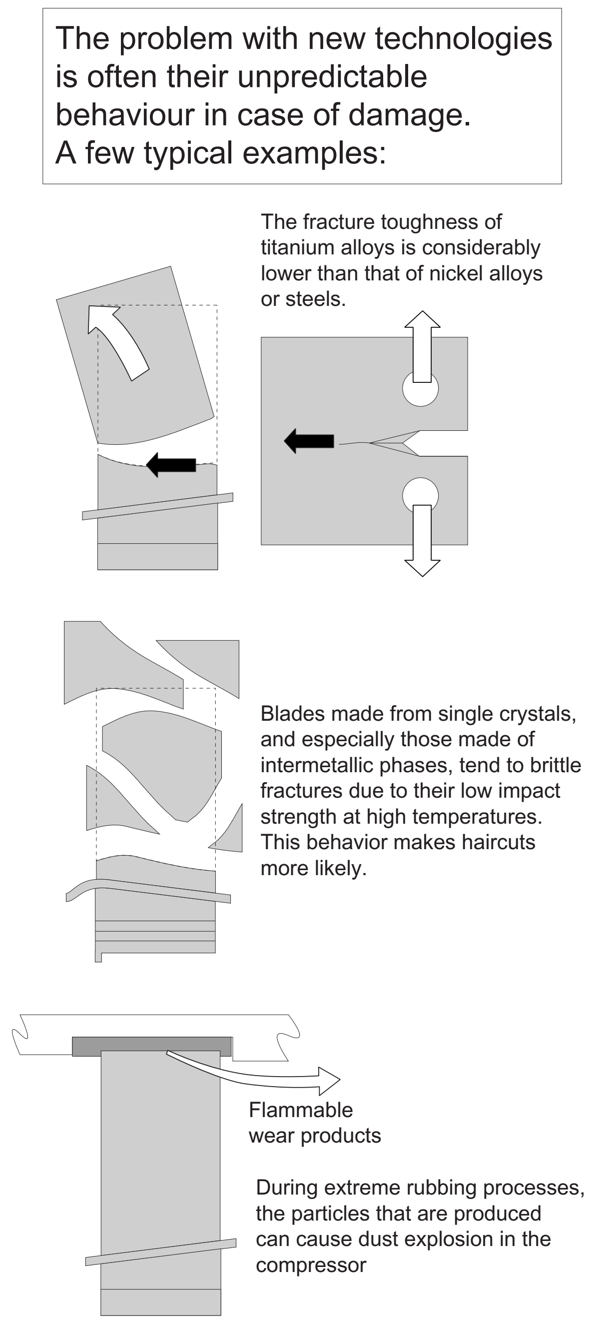
*Occurs noticeably **creep**, i.e., **time dependent plastic deformation** (Ill. 5.3.2-3), different component configurations can be affected (Ill. 5.3.2-10). This is especially also true for plasics (Ill. 5.6.3.1.1-12)*

***Operation forces**: An often creeping increase of the acting loads can in many cases not be ruled out and must be therefore considered. Such a situation can develop, if decreasing efficiencies (wear, corrosion, roughening) demand higher engine parameters, like increase of rotation speed. An unfavorable change of the geometry of flowed components (e.g., erosion, deposits/ 'fouling') can trigger flow **stalls**, which **excite** the part itself and/or neighboured components to **dangerous vibrations** (chapter 5.4.3).*

*The lifetime of parts/components (e.g., rotors) under **LCF loads**, i.e. with a **cyclic load/stress in the plastic range** (Ill. 5.4-1) is limited, correspondent the design/dimensioning (acceptable failure probability, chapter 4.5). If not a sufficient sensitive and safe non destructive test for operation caused microcracks is possible, whose size allows an extension of the operating time, those parts are in many cases no more repairable and must be replaced (Ill. 4.5.2-1). This must be at least planned in the logistics (spare parts supply).*

***Wear** can occur in its **abrasive form** as removal (chapter 5.5) or also as material deterioration/ damage (Fretting, chapter 5.9.3, Ill. 5.9.3-4).*

Does abrasive wear directly influence the component function (e.g., in a flow) or indirectly as overload (misalignment, wobbling/shock load, vibrations), a catastrophic failing must be expected. ***Fretting*** *can material specific (especially at titanium alloys) lower the fatigue strength so dangerously, that also the normal design conform loads/stresses cause failing.*



Ill. 4.1-3

ll. 4.1-3: Unforeseen behavior under unusual loads, *such as in the case of damage, heavy rubbing, or FOD, can prevent or restrict the introduction of a new technology. The following are several examples:*

Typical situations with unusual behavior occur during ***damage incidents.***

High deformation rates, ***such as impact loads****, lead to brittle behavior in metallic and synthetic materials (chapter 5.2.2). The degree of* ***embrittlement*** *is material-specific. Impact loads occur in situations such as containment incidents, bird strikes, or under the influence of other ingested foreign objects or fragments from within the engine itself. The embrittlement can be influenced considerably by the operating temperatures. Contrary to expectations,* ***pronounced embrittlement can be observed at very high temperatures****, as well as at very low temperatures (Ill.5.3-1.1).*

The special tendency of some ***synthetic resins to embrittlement*** *under impact stress can, for example, prevent their use in spinners (rotating nose cone) made from fiber-reinforced synthetics.*

The seemingly ***reduced impact resistance of single-crystal materials*** *at operating temperatures leads to considerably greater consequential damages than in less sensitive, but also less heat-resistant, multi-crystal materials.*

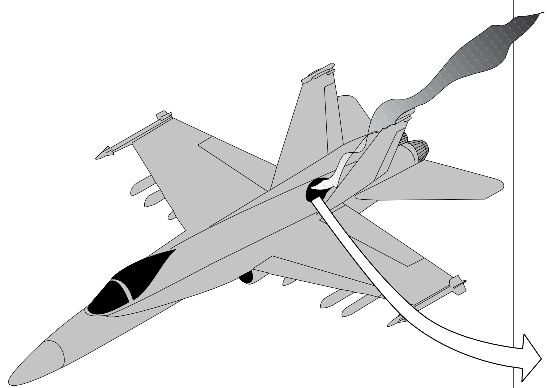
The increasing risk with the use of ***high-strength materials*** *can also be related to their unfavorable* ***fracture-mechanical specific values*** *(Ill. 5.2.1-7)****.*** *If this behavior is not correctly assessed, realization in serial applications is threatened (Ill. 4.1-1). Increased* ***notch sensitivity*** *(e.g. in titanium alloys) can cause unexpectedly large consequential damages after damage due to foreign objects or during a damage process (e.g. haircut of a blade stage).*

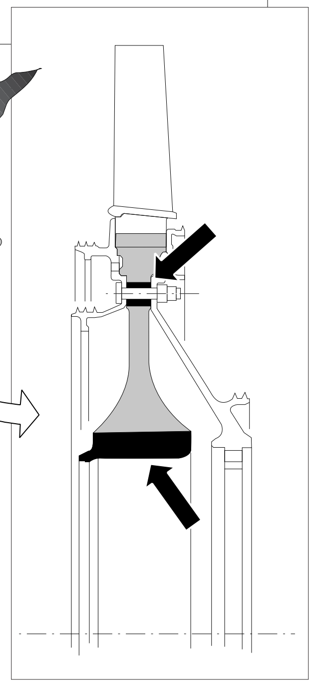
Notches and cracks in hard, brittle, and

, which can be caused by foreign objects, can cause dynamic strength to drop considerably more sharply than it would in uncoated material (Ill. 5.4.4-1 and Ill. 5.4.3.2-10).

Extreme rubbing *at blade tips and in labyrinths causes a great deal of material removal from the contact surfaces. If this material is ignited, it can cause a dangerous dust explosion (Ill. 5.11-2).*

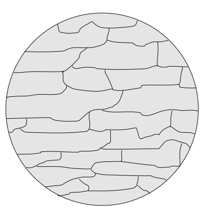
The (temporary?) end of a revolutionary technology:



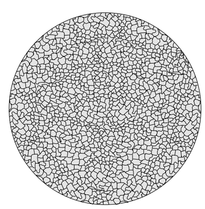


- Weak points get faults, these get failures.
- Quality assurance gets more demanding.
- The Time till failing gets shorter.
- The sensivity of the cracks increases.

Structure schematic.



Forged material
- Coarse grain.
- Structure orientation.



Powder metallurgy Material (PM)
- Fine grain.
- Homogenous.

Application relevant properties.

	Forged material	PM
Crack growth.	+	-
Ultrassonic test	-	+
Strength	-	+
Failing behaviour	+	-
Sensitivity.	+	-

\+ favourable - unfavourable

Ill. 4.1-4

Ill. 4.1-4*: The* ***application of the high strength version of a material*** *can be opposed by other properties. In fact can be expected from an uniform fine grain structure like in parts, produced by by powder metallurgy with the HIP process a high strength, expecially dynamic/fatigue strength. Also very smaller faults can be sure found by* ***ultrasonic testing****. However detrimental is, if such a material has an more unfavourable fracture mechanic behaviour, if it e.g., opposes comparatively little resistance against* ***crack growth****.This shows in a* ***lower critical crack/ fracture toughnes*** *and/or faster* ***crack propagation*** *(Ill. 4.3-3). The consequence is a faster crack spreading. So the time from the starting crack till the catastrophic failing with the fracture of a part gets very short. With this, in such acute cases a monitoring of parts is no more possible. In a safety case or/and if the failure costs are unaceptable high an immediately exchange of all potential endangered parts must take place.*

A forge material can get with a suitable deformation process a part specific optimized structure orientation (fiber flow). In a most favourable case the faults will be oriented parallel to dangerous high operation stresses and so less effective. Additionally a fatigue crack oriented cross to the *structure opposes an elevated resistance to it. This can enable an* ***interception and/or a monitoring*** *(e.g., practical usable inspection intervals) of the crack formation..*

The displayed case can apply examplary for the riks by introducing of new technologies in highly loaded/stressed series components. The depicted fighter was undergoing testing. It crashed after the ***low-pressure turbine disk burst.*** *The probable damage cause was an* ***LCF fracture****, which originated in a critical, highly stressed zone (arrows in right detail). The output power of this engine type had been increased considerably. The low-pressure turbine, which was especially highly stressed due to the* ***single-stage design****, had a disk made from* ***ultra-high tensile strength material****. The material was an* ***AS HIP version*** *of a powder-metallurgical material, i.e. no subsequent forging. This material is distinguished by fine, even grains. Disadvantages include* ***notch sensitivity, low crack toughness, and rapid crack growth.*** *The dangers of this kind of combination of damage-promoting influences should serve as an important experience for anyone who works on the development of these technologies.*

It can be assumed that the high loads made the crack growth phase extremely difficult to control. The major advantage of the powder-metallurgical material, aside from its high strength, was the exceptionally cost-effective ***AS HIP process,*** *which resulted in semi-finished parts with dimensions that were very close to those of the finished part. This production process uses a hollow metal form (can), which is filled with metal powder in a vacuum and welded shut. The filled capsule is then subjected to hot isostatic pressing (HIP) under high argon pressure (>1000 bar) and high temperatures, creating a dense material. The form is then removed.*