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Gas Turbines – Mechanical & Material Aspects

Lecture notes

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EXECUTIVE SUMMARY

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Gas Turbines – Mechanical & Material Aspects

Lecture notes

REPORT NUMBER
NLR-TP-2026-007

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REPORT CLASSIFICATION
UNCLASSIFIED

DATE
January 2026

KNOWLEDGE AREA(S)
Health Monitoring and Maintenance of Aircraft
Platform Integrity
Aerospace Materials
Aircraft Material and Damage Research

DESCRIPTOR(S)
Gas Turbines
Materials
Lifing
Loads
Design Philosophies

Executive summary

This report addresses the fundamental principles of design, mechanical engineering and materials development and selection for gas turbine components throughout the complete engine: inlet, fan, compressor, combustor, turbine and augmentor. Temperature, pressure and speed conditions in a gas turbine are indicated, including the different types of loading, i.e. mechanical, thermal and environmental loading of components, and their consequences on materials selection and performance. Low and high cycle fatigue in relation to component design and materials selection is explained. The traditional and new lifing philosophies (e.g. damage tolerant design) for the design of turbine components are given, including their effect in relation to overhaul, maintenance and repair.

A detailed insight is given of the various manufacturing and machining processes/routes of gas turbine components, including the intrinsic relation with materials phase diagrams, (superalloy) strengthening mechanisms and performance. Fundamental and essential materials properties for gas turbine application, such as specific strength and stiffness, high temperature stability,

manufacturability, and corrosion and oxidation resistance are highlighted. Design criteria for components are indicated.

Background and use of protective coatings on gas turbine components, including many high temperature application processes have been described in detail. The fundamental differences in the application of coatings in the past and nowadays (life extension versus the current integral part of design approach) is highlighted and explained.

The report also contains extensive information based on aircraft accident investigation and failure analysis, showing a clear relationship between design aspects, manufacturing principles and materials performance and the effect of 'minor' deviations on aircraft and engine safety.

This course material has been compiled by the first author. It is partly based on work and research performed in the past by the Royal Netherlands Aerospace Centre NLR. It has now been brought together to become part of a lecture series on turbomachinery by Prof. Sikke Klein of the Department of Mechanical Engineering at the Technical University of Delft.

In order to safeguard the copyright of this material, it was decided to publish it in the form of an NLR document. This was edited by the second author.

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DIVISION NLR	**Aerospace Vehicles**
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AUTHOR	**EDITOR**	**MANAGING DEPARTMENT**
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Summary

This document contains teaching material on gas turbines and, in particular, on their mechanical aspects and constituent materials. This course material has been compiled by the first author. It is partly based on work and research performed in the past by the Royal Netherlands Aerospace Centre NLR. It has now been brought together to become part of a lecture series on turbomachinery by Prof. Sikke Klein of the Department of Mechanical Engineering at the Technical University of Delft.

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2 Manufacturing processes, phase diagrams & superalloy strengthening mechanisms, protective coatings 46

1 Gas Turbine build up, materials, lifing philosophies and loads

The Australian EA-18G Growler aircraft (variant of Boeing F/A F18 Super Hornet), lost in an accident at Nellis Air Force Base (AFB), Australia, on 27 January 2018.

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The aircraft experienced an uncontained F414 engine fan disc failure during the latter stages of its take-off roll at Nellis AFB.

The righthand engine failed; uncontained material from that engine caused the simultaneous failure of the lefthand engine and a fierce fuel/airframe fire.

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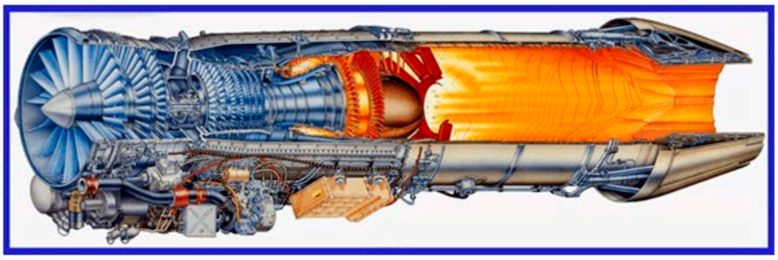
The crew conducted an emergency abort and brought the aircraft to a safe stop. Fire brigade was very fast. The two crewmembers were uninjured, only “a little shaken”.



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Cause of failure: uncontained Ti fan disc failure

The uncontained failure of the 1st stage fan disc was considered to be an unusual event by metallurgists. Subsequent discussions with the OEM sub-contractor responsible for producing the 1st stage fan disc forgings revealed that they had previously experienced three cracked forgings during manufacture, affirming the conclusion that the failure of A46-311 engine component was introduced during the forging process.

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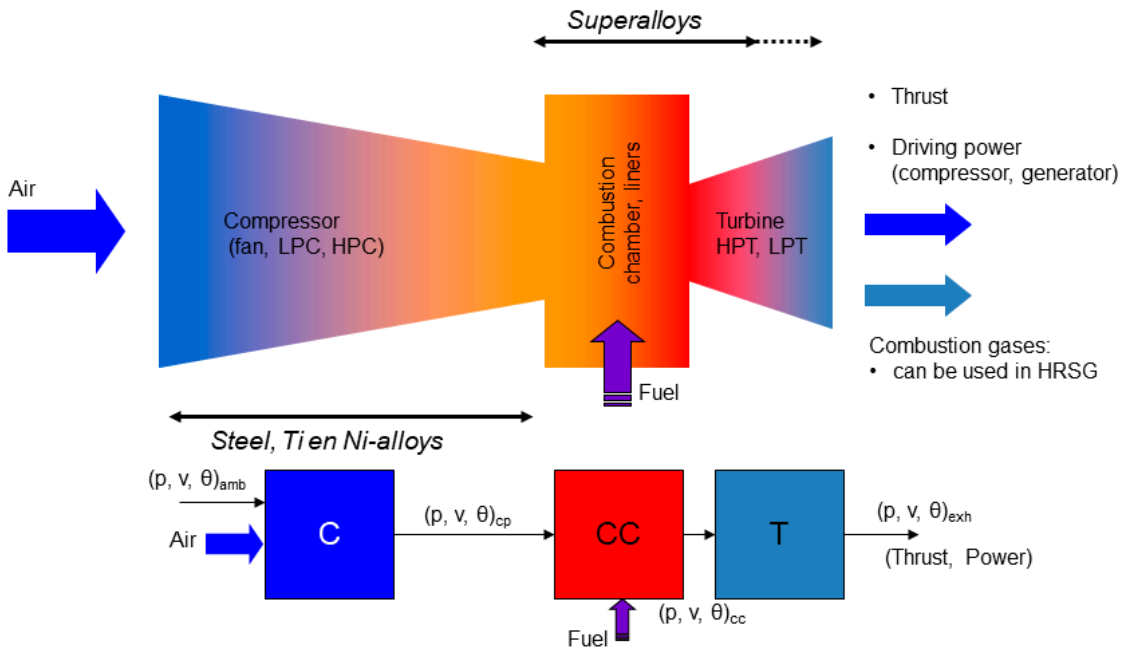
Turbines, thermodynamics



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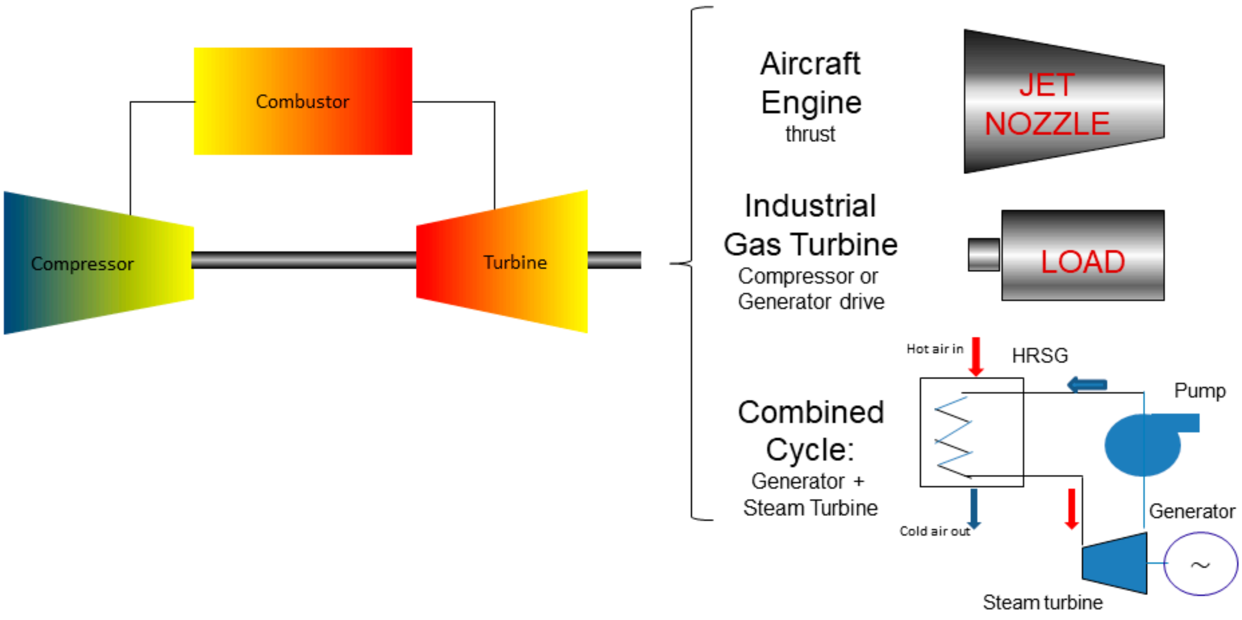
Gas Turbine Applications



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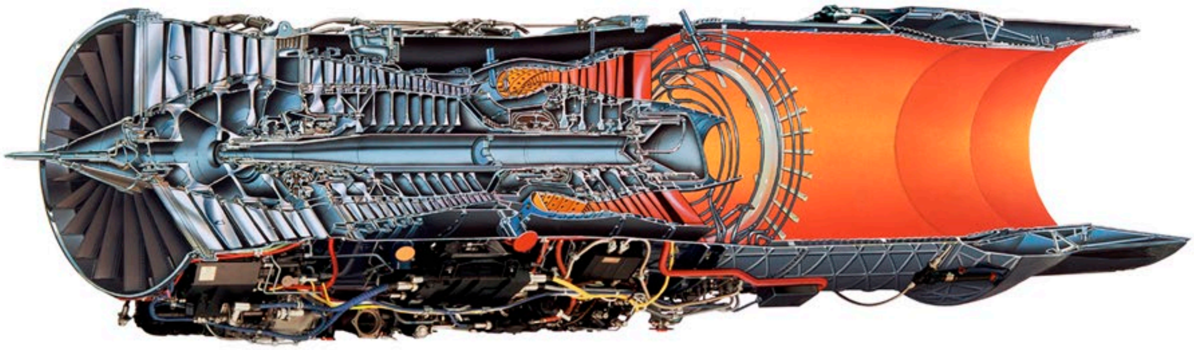
F-16 engine (PWA F100-220)



Overall pressure ratio: 25:1
Bypass ratio 0.36
Turbine inlet temperature: 1450 °C
Max. metal temperature: ~ 1100 °C

Compare F135 engine:
Pressure ratio: 28:1
TIT: 1982 C

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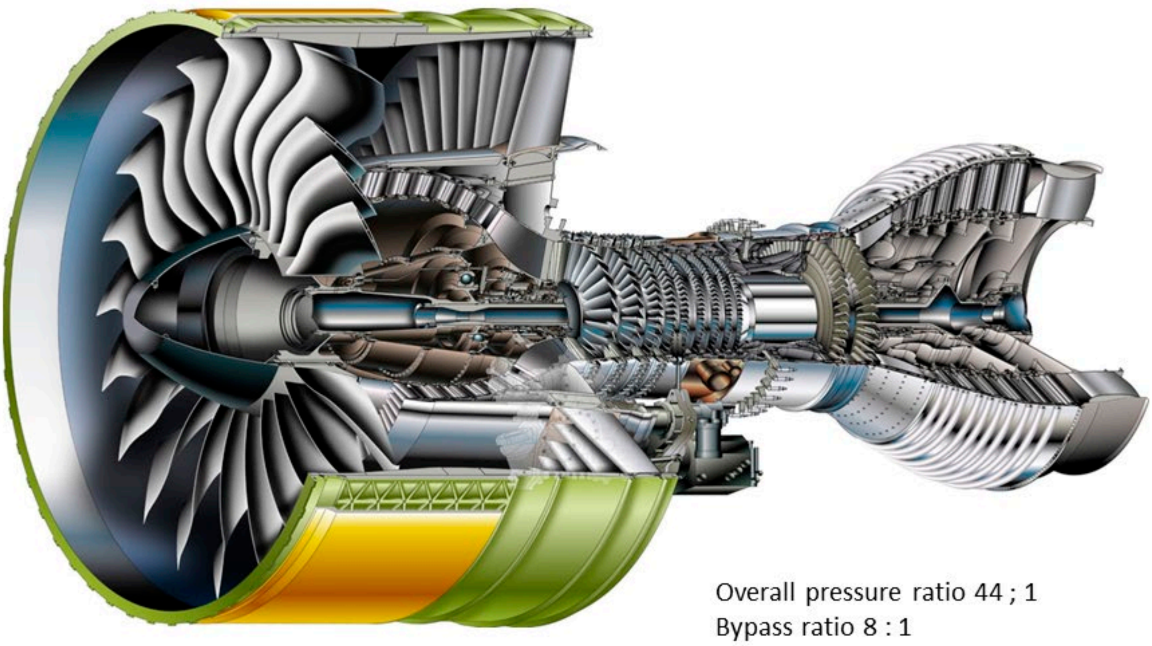
GP-7000 (P&W + GE) for Airbus 380; engine cutaway
24 hollow titanium fan blades



Overall pressure ratio 44 ; 1
Bypass ratio 8 : 1

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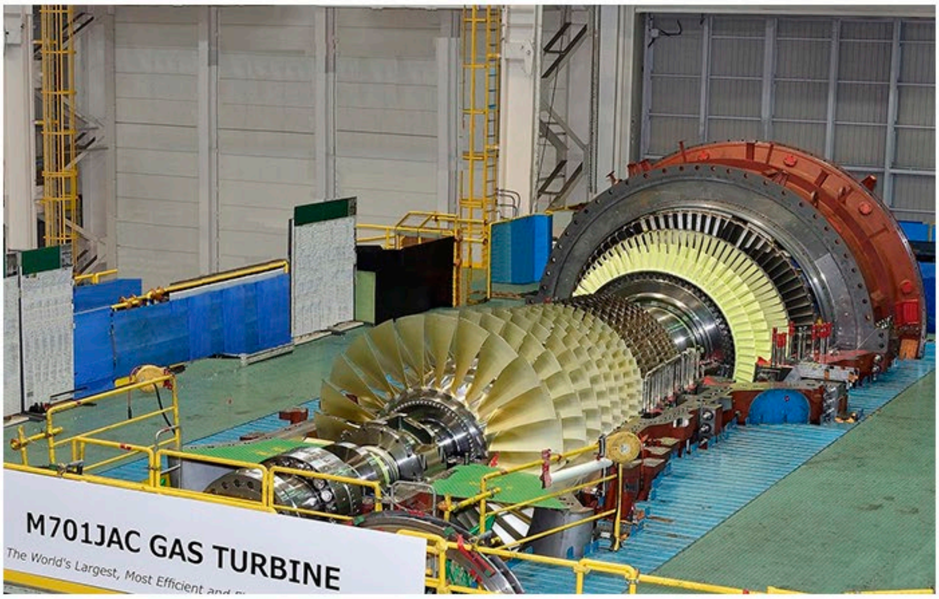
Mitsubishi M 101 J class Gas Turbine World's largest



Stand alone: ~ 500 MW; in CC: ~ 750 MW; CC efficiency 64%

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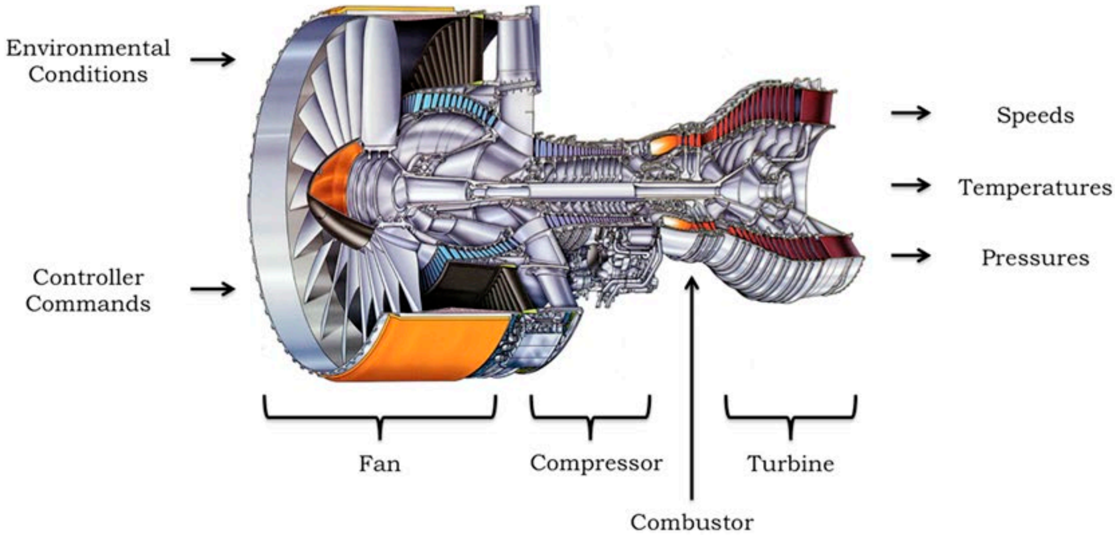
Gas Turbine Materials

Steel, Aluminium, Titanium, Nickel, Cobalt, Composites, Ceramics



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Conditions in Gas Turbines

Compressor:
- ❑ Temperatures from – 70 C up to 700 C
- ❑ Pressures up to 50 bar
- ❑ Air speeds around Mach 1 (at tip)
- ❑ Ingestion of sand, dust, rain, ice, salt, birds (Foreign Objects)

Combustor:
- ❑ Temperatures from 400 up to 1800 C
- ❑ Pressures up to 50 bar
- ❑ Large T differences (in flame, at surface of components, 'cooling' air

Turbine:
- ❑ Temperatures from 1800 C towards ~ 500 C
- ❑ Pressures from 50 bar towards 0
- ❑ Large T differences
- ❑ High air speeds

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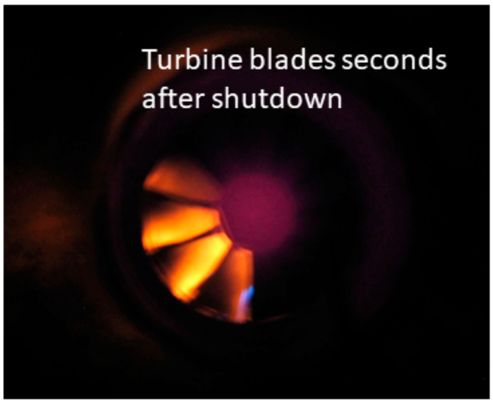
Requirements for gas turbine materials

- Light weight
- High Strength
- Stiffness
- Corrosion resistance
- Oxidation resistance
- High temperature stability
- Manufacturability
- Surface quality/smoothness



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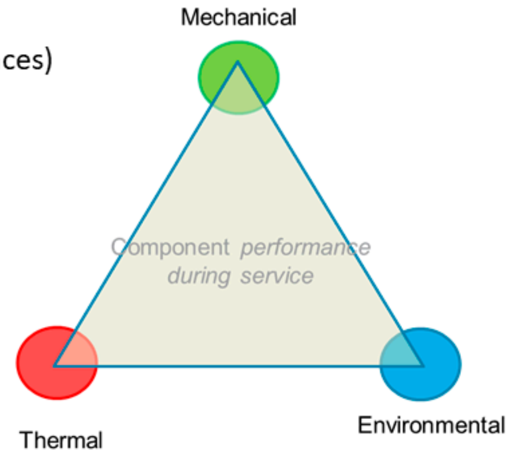
Used where?

Gas turbines are in nearly all aircraft and helicopters

Gas turbines are in power plants, compressor stations, platforms for electricity and driving power

Type of Loading

- Mechanical loads
  - Centrifugal loads
  - Aerodynamic loads (pressure differences)
  - Vibrational loads
- Thermal loads
  - Difference in heating up
  - Difference in thermal expansion
- Environmental loads
  - Sand, dust, rain causes erosion
  - Corrosion, oxidation
  - Fretting/contact wear



NB: Loads will often be higher than elastic limit of the material !

Conclusion,

but this is just the start:

The Metallic and Non-metallic materials have to fulfil their tasks in an extremely harsh environment for thousands of hours:

This is the top of the bill for materials !

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Materials Science

An interdisciplinary field: *chemistry, physics, and mechanical properties*

- Chemical properties:
  - Tendency to react with other species (e.g. oxide formation, corrosion), timescale of reaction is important
  - Painting, anodizing , plating or coating are ways to prevent metal corrosion
- Physical properties:
  - Thermal and electrical conductivity,
  - Density,
  - Crystal structure,
  - Specific heat capacity,
  - Young’s modulus, linear expansion
- Mechanical properties
  - Ductility, Elastic limit, Youngs’ modulus (stiffness):
  - The re-action on an applied force
  - Dependency on temperature

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Mechanical Properties + Material Characterization

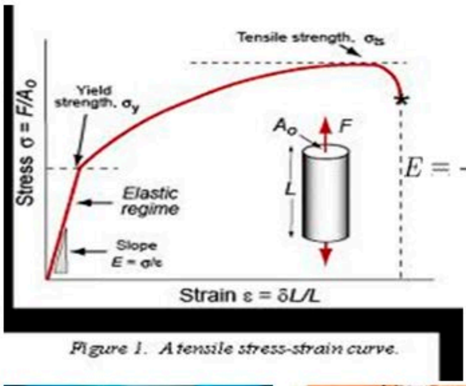
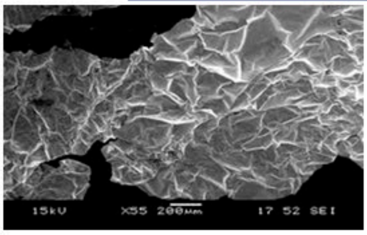


Figure 1. A tensile stress-strain curve.

$$E = \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{\sigma}{\varepsilon} = \frac{FL}{A\Delta L}$$



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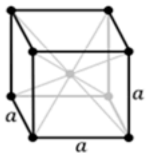
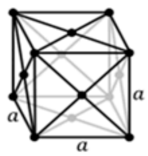
Mechanical + physical properties of some 'pure' metals

Element/ Metal	Ultimate tensile strength [MPa]	Yield strength [MPa]	Young's modulus [GPa]	Density [kg/dm³]	Melting point [°C]	Coefficient of linear expansion [um/(m K)]	Crystal structure
Al	70	10	70	2.7	660	23.6	Face-centered cubic
Ti (grade 1)	345	220	110	4.5	1668	8.41	Hexagonal close packed
Fe	180	120	200	7.9	1538	11.8	Body-centered cubic; Face-centered cubic between 912–1394 °C
Ni	450	150	210	8.9	1455	13.4	Face-centered cubic

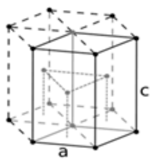
Conclusion: pure metals are very weak! Note: stress at service conditions (high T) often 600 – 1000 MPa or higher



body-centred cubic (bcc)



face-centred cubic (fcc)



hexagonal close packed (hcp)

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Typical tensile strengths of some materials

Material	Yield strength (MPa)	Ultimate strength (MPa)	Density (g/cm³)
Structural steel ASTM A36	250	400	7.8
AISI 4130 Steel, water quenched 855°C, 480°C temper	***951***	***1110***	***7.85***
Titanium Ti-6Al-4V	***860***	***930***	***4.43***
Polypropylene	12-43	19.7-80	0.91
Stainless steel AISI 302 - Cold-rolled	520	860	8.19
Cast iron 4.5% C	130	200	
Aluminium 2014-T6	414	483	2.8
Aluminium 6061-T6	241	300	2.7
Ni-alloy (Inconel 718)	***1125***	***1300***	***8.23***
Iron (pure mono-crystal)		3	7.874

Note: Many of the values depend on manufacturing process and purity/composition

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Materials in the compressor section

Rotating & stationary

Requirements

- ❑ Capable to withstand temperatures from – 70 C (front stages) up to 700 C (last stages)
- ❑ Lightweight (specific strength σ_u/ρ)
- ❑ Stiffness (specific stiffness (E/ρ), aerodynamic requirement: slender blades
- ❑ Erosion resistant
- ❑ Rub resistance

- ❑ Forgiving - redundancy

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Materials in the compressor section
Rotating & stationary

History and current situation
- ❑ Aluminium in early engines (max 200 C)
- ❑ Martensitic stainless steels, PH (precipitation hardened) stainless steels
- ❑ Titanium alloys
- ❑ Nickel alloys (later stages in compressor)
- ❑ Composites, up to 250 C (fan, casings)

Important reasons
- ❑ Specific strength (σ_u/ρ) and stiffness (E/ρ)   ($F = mv^2/r$)
- ❑ Corrosion behaviour
- ❑ Strength at higher temperatures
- ❑ Lower weight counts on in every ‘connected’ component!

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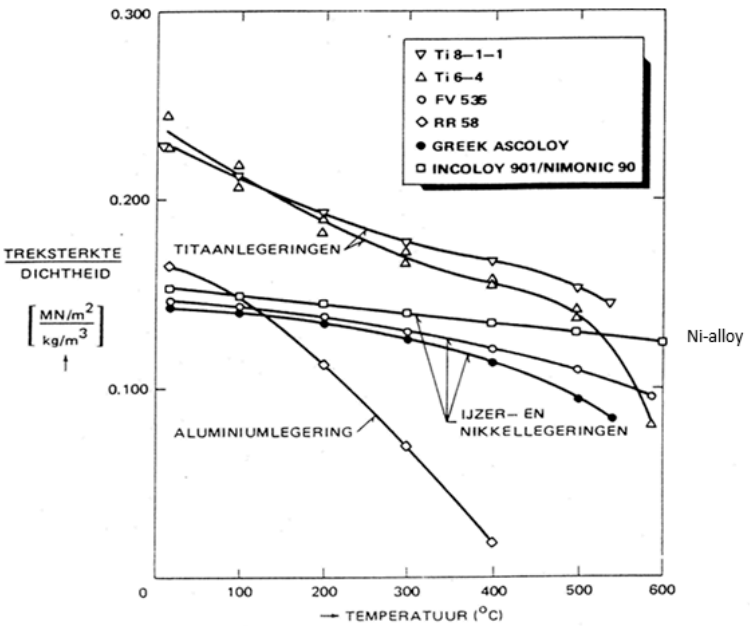
Specific strength for a range of alloys



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Materials in the combustor section

Stationary

Requirements

- Capable to withstand temperatures from 500 C – 1300 C (sometimes uncooled)
- Long term stability (strength, shape, stiffness)
- Corrosion resistance
- Oxidation resistance
- Manufacturability (forging, welding)
- Reparability

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Materials in the combustor section

Stationary

History and current situation

- Austenitic stainless steel
- Solution hardened nickel alloys
- Cobalt alloys
- ODS (oxide dispersion strengthened) alloys

Important reasons

- Manufacturability (forming, welding, heat treatment)
- Long term stability
- Thermal fatigue resistance
- Oxidation behaviour

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Materials in the turbine section

Rotating & Stationary

Requirements

- ❑ Capable to withstand temperatures from 1800 C – 500 C (sometimes uncooled)
- ❑ Creep resistance
- ❑ Long term stability (strength, stiffness)
- ❑ Corrosion resistance
- ❑ Oxidation resistance
- ❑ Manufacturability
- ❑ Forgiving - redundancy

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Materials in the turbine section

Rotating & Stationary

History and current situation

- ❑ Austenitic stainless steel (early engines)
- ❑ Cobalt alloys (early engines)
- ❑ Creep resistant nickel alloys (forged, later cast)
- ❑ Directional solidification
- ❑ Single crystals

- ❑ Solidus temperature of modern Ni-alloys is somewhere between 1250 en 1300 C
- ❑ Enormous development in blade internal cooling
- ❑ Enormous development in coatings
- ❑ Development in thermal barrier coatings
- ❑ ODS alloys (for stationary applications)
- ❑ Ceramic Matrix Composites (?)

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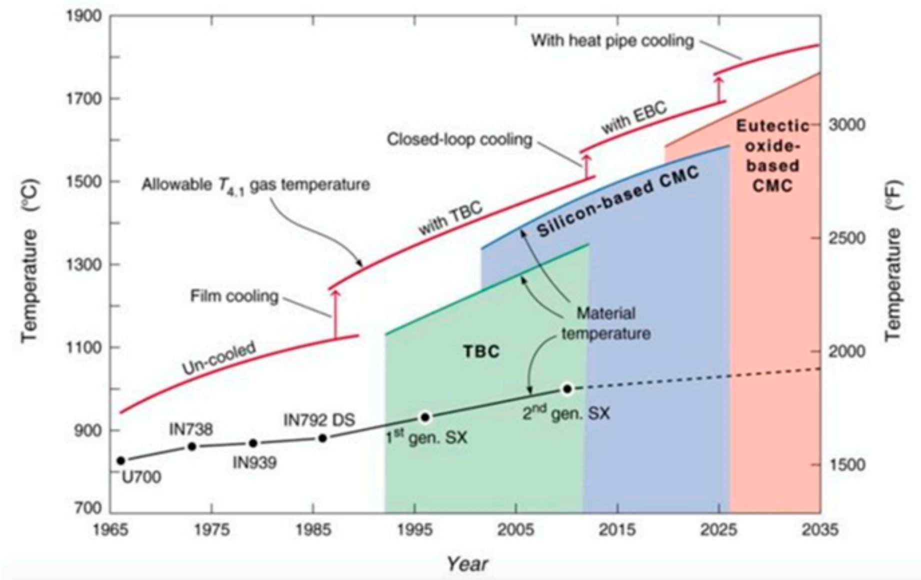
Materials in the turbine section

Rotating & Stationary



Evolution of materials, coatings and cooling system used in gas turbines and the capabilities of CMCs for the future (Alejandro Simó Vesperinas, August 2018)

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Design criteria - basics

1. Static strength
2. Fatigue
   - High Cycle Fatigue
   - Low cycle fatigue
   - Thermal fatigue
   - Fatigue crack growth
3. Creep
4. Thermal degradation
   - Hot corrosion
   - Oxidation
   - Microstructural degradation
5. Combined ‘loads’

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Overview of degradation mechanisms for different parts

Component	Degradation mechanism(s)
Compressor blades	Fatigue, erosion, low T corrosion (water, salt, SO_2)
Discs	Fatigue, corrosion
Drive Shaft	Fatigue
Combustor	Thermal degradation, (thermal) fatigue
Turbine stator vanes	Oxidation, hot corrosion, thermal degradation, (thermal) fatigue
Turbine rotor blades	Oxidation, thermal degradation, (thermal) fatigue, creep

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Gas Turbines, literature

- Superalloys II – High temperature materials for aerospace and industrial power; Sims, C.T. et al.; John Wiley & Sons; 1987 ; ISBN 0471-01147-9
- The Microstructure of Superalloys; Durand-Charre, M.; Gordon and Breach Science Publishers; 1998; ISBN 90-5699-097-7
- The Superalloys: Fundamentals and Applications; Reed, R.C.; Cambridge University Press; 2006; ISBN 0-521-85904-2
- Superalloys, A Technical Guide, M.J. Donachie, S.J. Donachie, ISBN 0-87170-749-7
- Rolls Royce, The Jet Engine Book, : http://airspot.ru/book/file/485/166837_EB161_rolls_royce_the_jet_engine_fifth_edition_gazoturbinnyy_dviga.pdf - free download
- Operating conditions and materials selection and development in gas turbines, A.J.A. Mom, https://repository.tudelft.nl/view/aereports/uuid:b343e80f-8142-48c7-bcac-53c8805c0fd1
- Introduction to gas turbines, A.J.A. Mom, Introductory chapter of Modern Gas Turbine Systems, Woodhead Publishing, 2013.
- Evolution of materials, coatings and cooling system used in gas turbines and the capabilities of CMCs for the future; Alejandro Simó Vesperinas, August 2018

- **Magazines**
  - Metallurgical and Materials Transactions A/B
  - Advanced Materials and Processes
- **Internet, many articles**

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Design philosophies

1. Infinite Life Design
2. Fail-Safe design
3. Safe Life Design
4. Damage –Tolerant Design
5. On condition

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1. Infinite Life Design

- Unlimited safety is the oldest criterion (component should never fail under the applied stresses)
- It requires local stresses or strains to be essentially elastic and safely below the fatigue limit.

- For parts subjected to many millions of cycles, like engine valve springs, this is still a good design criterion.
- This criterion may not be economical (i.e. global competitiveness) or practical (i.e. excessive weight of aircraft) in many design situations.
- In practice it would mean that you are not able to fly/drive any more…

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2. Fail Safe Design

- **Fail safe design requires that if one part fails, the system does not fail**
- Fail safe design recognizes that fatigue cracks may occur, but that the structure is designed in such a way that cracks will not lead to failure of the total system *before they are detected and repaired*
- How to achieve fail safe design? E.g.:
  - Multiple load paths
  - Duplication of critical systems
  - load transfer between parts of the structure,
  - crack stoppers built at intervals into the structure, and
  - Inspection at regular intervals

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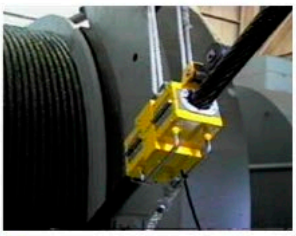
Cable cars

Fuse

Safety gear, elevator



Back-up disc

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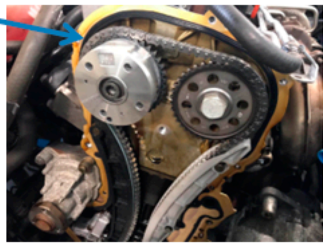
3. Safe Life Design

- Component is designed for a specific, finite life: e.g. 10,000 hrs, or 5000 cycles or 100,000 km's
- **All components are replaced at this safe life limit, irrespective of their condition**
- Used in many industries: automotive (distribution chain), pressure vessel design, aircraft engine disks !
- Based on fatigue testing of components + statistical analysis
- Safe life must include a safety margin



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Safe life aspects: statistical analyses of fatigue data

- **Safe Life: the life at which 1 in 1000 disks will develop a crack of 0.8 mm (not yet critical)**
- **We calculate the safe life based on fatigue data of specimens under realistic loading conditions**

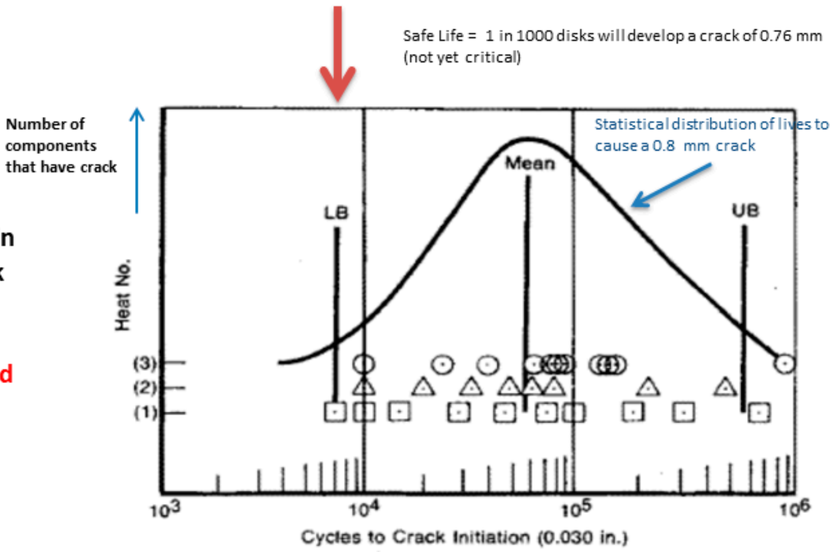

Fig. 2 Material data scatter results in conservative life prediction.

Fatigue tests of material under realistic loading conditions

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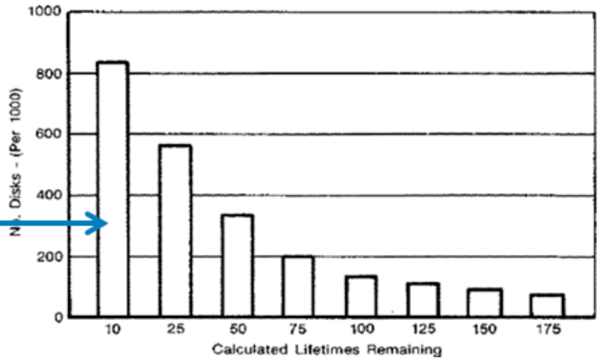
Safe Life Approach: pros and cons

- Used for critical systems which are either very difficult to inspect/repair or may cause severe damage to life and property. These parts are designed to work for years without requirement of any inspection/repairs.
- Drawback: products are in fact over-dimensioned
- Parts **must** be replaced after the design life has been reached.
- Most parts have many lifetimes remaining!
- Therefore: alternative design philosophies were developed: the damage tolerant design.



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Is Safe Life Design Approach

really safe?

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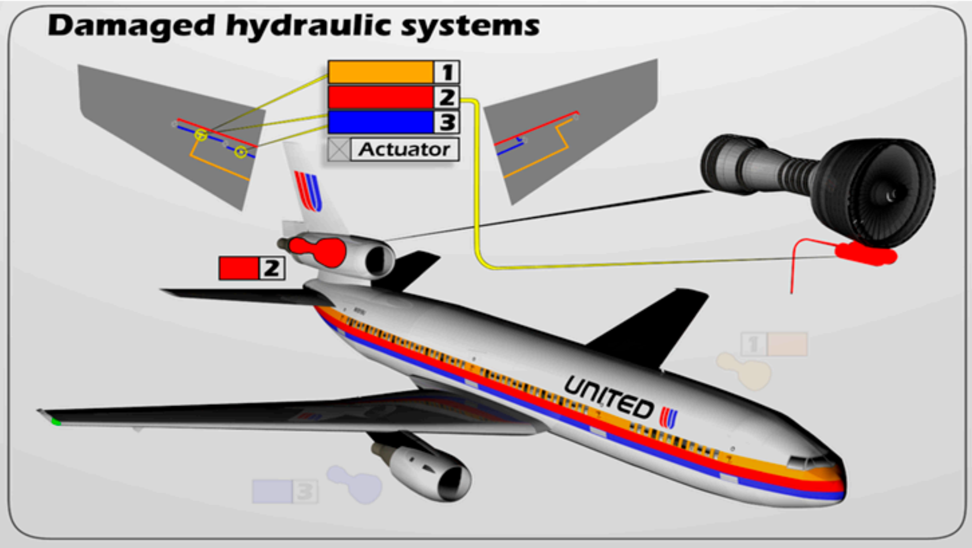
United Flight 232
crashed in Sioux City, 1989

uncontained fan disk failure



Uncontained –in flight- failure of the fan disk of tail engine of a DC 10.

Fan disk parts penetrated tail wing and all three hydraulic lines of the hydraulic system

This resulted in loss of flight control.

Crew tried to land on the airfield where it just had left.

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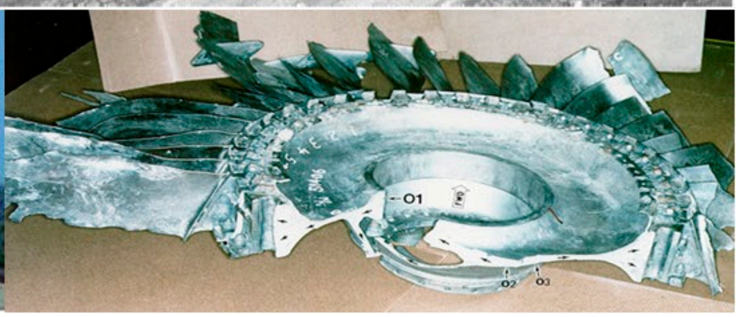
Crash of United Flight 232

The aircraft crash landed, 111 people died, 185 survived

A defect in the titanium fan disk initiated fatigue crack at bore of disk



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Fan disk had 16.899 cycles; safe life limit was 18.000 cycles

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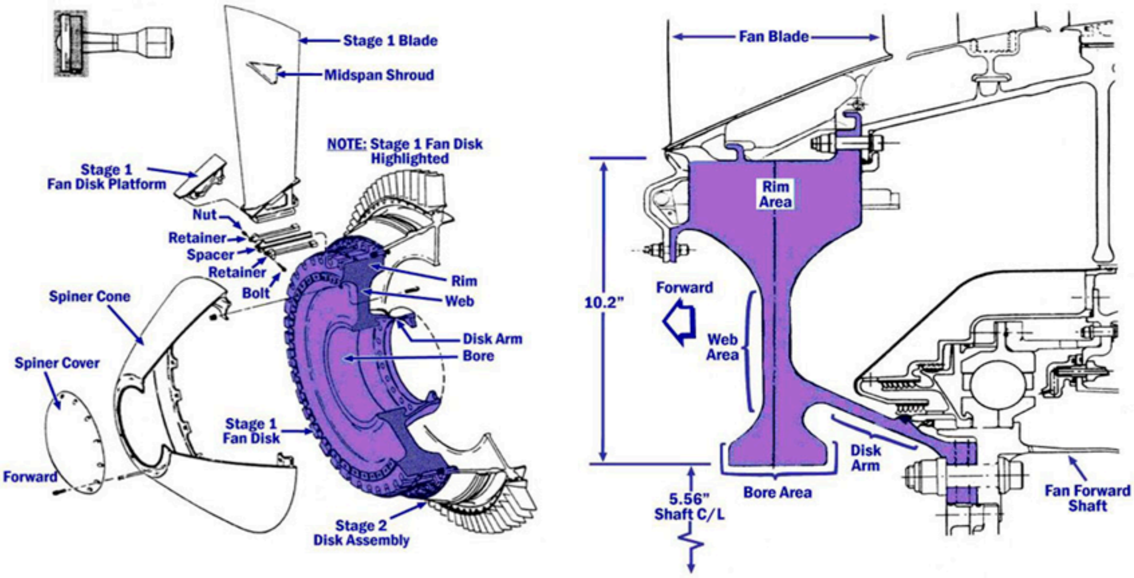
Crash of United Flight 232

CF-6 Fan Assembly Showing Fan Disk



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Fatigue crack originated at a hard α defect present after manufacture

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Safe Life Approach: pros and cons

- Used for critical systems which are either very difficult to inspect/repair or may cause severe damage to life and property. These parts are designed to work for years without requirement of any inspection/repairs.
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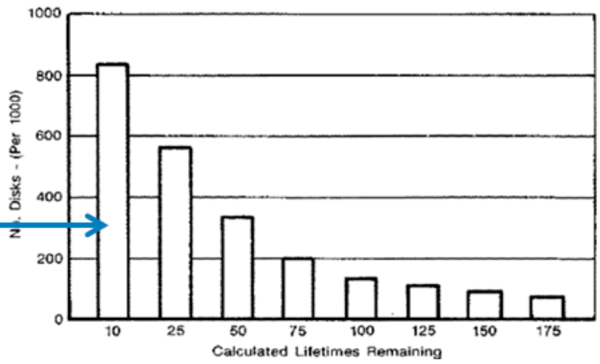

Safe Life → Damage Tolerant design

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4. Damage Tolerant Design (1)

- It assumes that cracks exist, either caused by processing or by fatigue
- **Fracture mechanics approach is used to predict crack growth**

Source: Bel Air Finishing

Source: KMWE/Dutch Aero

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4. Damage Tolerant Design (2)

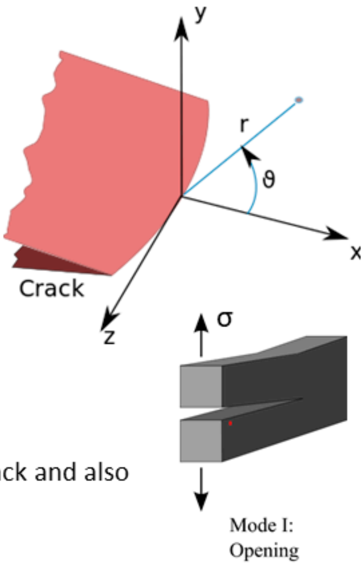
$K_I = \sigma \sqrt{\pi a}\ f(a/W)$, f (a/W) is a geometry dependent function of crack length a and specimen width W; σ is the applied stress.

Crack growth is given by:

$$\frac{da}{dN} = C(\Delta K)^n$$

At the critical stress intensity factor K_{IC} the part will fail:

$$K_{IC} = \sigma \sqrt{\pi a}\ f(a/W)$$



Stress intensity factor K predicts the stress state at the tip of a crack and also crack growth rate and failure.

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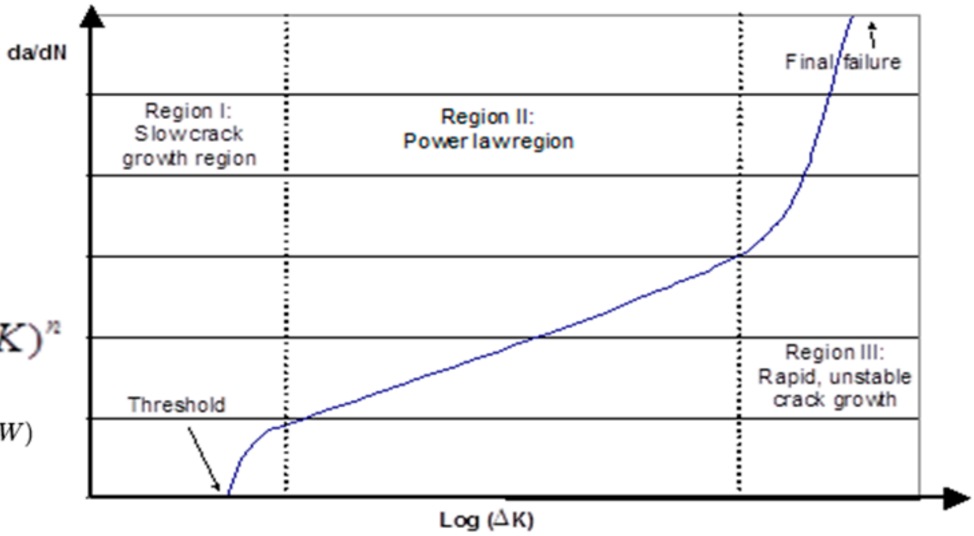
Typical (fatigue) crack growth curve (3)

We can predict crack growth by using the factor K !

$$\frac{da}{dN} = C(\Delta K)^n$$

$$K = \sigma\sqrt{\pi a}\, f(a/W)$$



The stress intensity factor, K , is used in fracture mechanics to predict the stress state ("stress intensity") near the tip of a crack caused by a remote load or by residual stresses. K is very useful to predict crack growth rate and failure. K = function of σ and a.

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4. Damage Tolerant Design (4)

- It assumes that cracks exist, either caused by processing or by fatigue
- **Fracture mechanics approach is used to predict crack growth**
- During the stable crack growth period we plan periodic inspections to detect the crack before it is becoming critical
- **Three key items** are needed for successful damage-tolerant design:
  1. fatigue crack growth behavior under realistic loading conditions
  2. maximum allowable crack length (residual strength of the structure)
  3. nondestructive inspection methods to detect the ‘smallest’ crack

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Phases in the fatigue life of a component (5)

Total fatigue life consists of:

- Early crack initiation phase, microscopic crack growth and microcrack linkup.
- The small crack will grow further. At some point in time this crack can be detected (detection limit).
- The crack will propagate until the combination of service load (stress) and crack size exceeds the material fracture toughness, at which fracture occurs.
- The fracture mechanics approach addresses the time between inspection limit and final fracture.

Crack initiation time varies very much (orders of magnitude); therefore safe life design results in throwing away many components with long remaining life

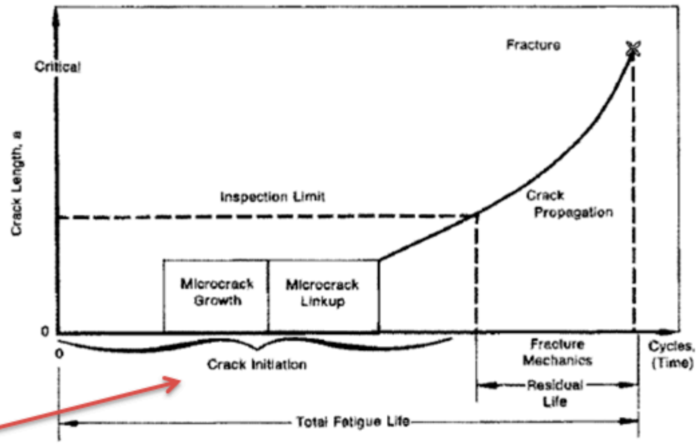

Fig. 1 Total fatigue life segmented into stages of crack development, sub-critical growth, and final fracture.

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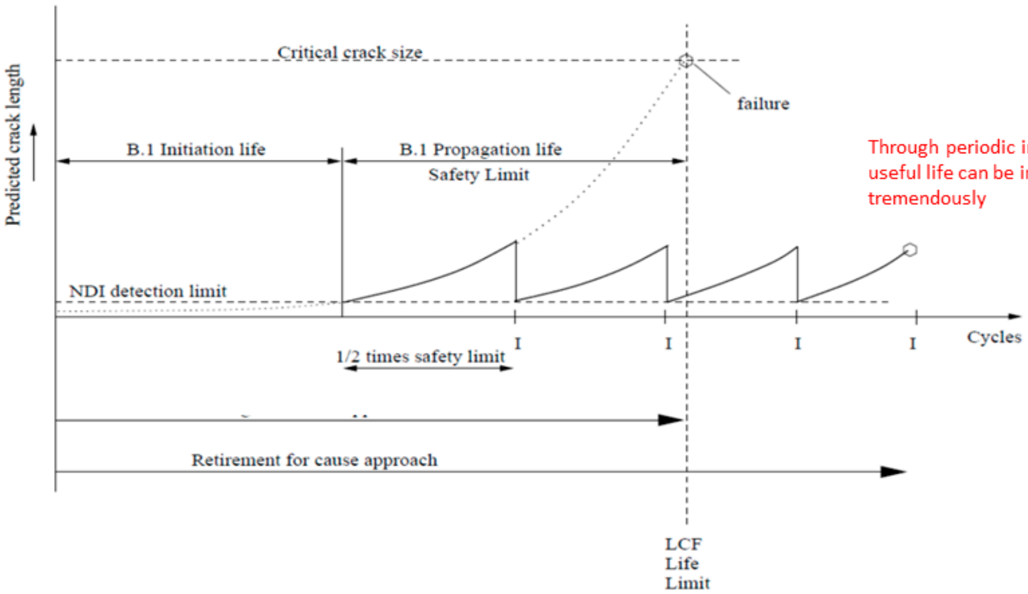
Pratt & Whitney Damage Tolerance and Retirement For Cause approach (6)



Through periodic inspections useful life can be increased tremendously

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Damage Tolerance – Summary (7)

Inspection schedule should result in continued safe operation; approach is based on:

- Assumed initial damaged condition of the structure
- Real operational stresses in the component
- Geometry of the material: that determines the stress intensity factor at the crack tip
- NDI crack detection limit (smallest crack visible by NDI inspection)
- Actual crack growth behaviour of the material
- Largest crack size before catastrophic failure
- Probability of crack detection
- Acceptable level of risk of complete failure

These factors determine how the structure can be operated safely: regular inspections are required to discover the crack before it becomes critical.

The interval between inspections must be selected with a certain minimum safety, and must balance the expense of the inspections,.

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Some parts have no hard life limit:

On condition maintenance/lifing

For example: compressor blades and vanes,
often also turbine blades and vanes.

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F16 crash
Training mission, North Sea, 1981

Engine failure occurred: no power. Pilot evacuated and landed safely; aircraft was recovered; engine, relatively undamaged, was investigated

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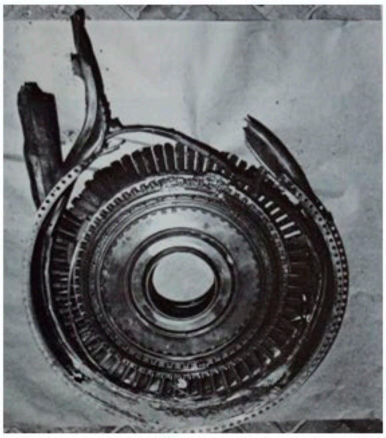
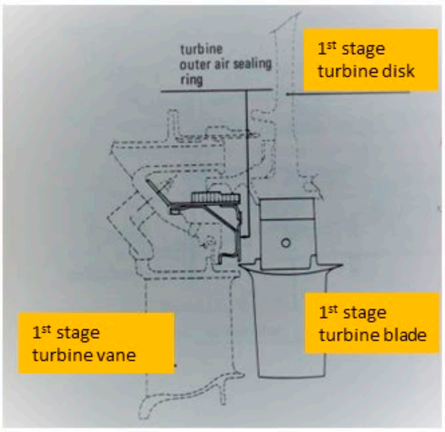
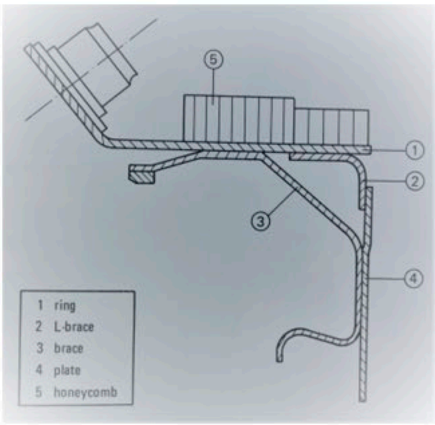
Braze joint failure







Turbine sealing ring failed by braze joint failure between ring 1 and part 2 and 3.
Cause: oxide layer build up during Ni-plating prior to brazing (NLR MP 87037, presented at BVM symposium, Wageningen, 1986)

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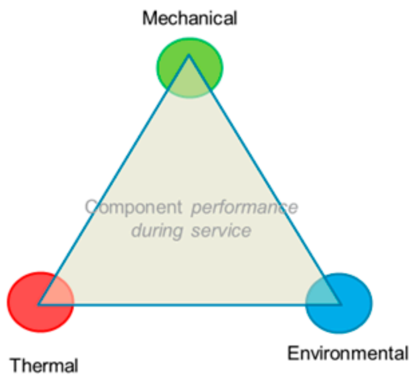
Which Loads?

Loads:

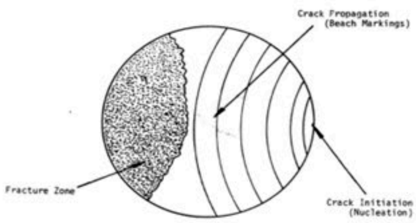
- Mechanical loads (always cyclic)
  - Centrifugal loads
  - Aerodynamic loads (pressure differences)
  - Vibrational loads
- Thermal loads
  - Difference in heating up
  - Difference in thermal expansion coefficient
- Environmental loads
  - Sand, dust, rain causes erosion
  - Corrosion (cold and hot section), oxidation
  - Fretting/contact wear



Cyclic loads are causing Fatigue

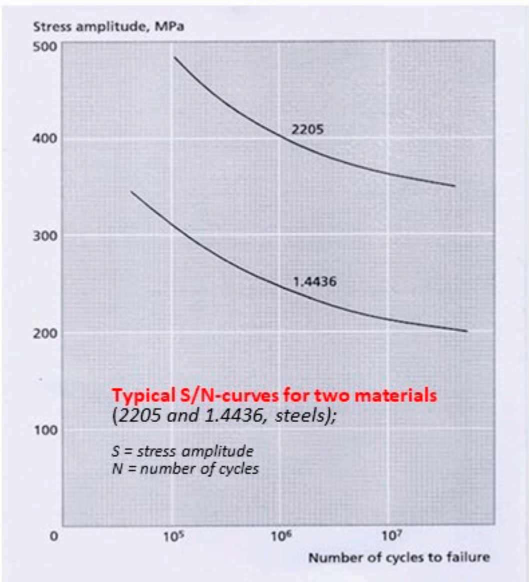
'Fatigue' is the weakening of a material caused by repeatedly applied loads

Fatigue data of materials are gathered by extensive fatigue testing

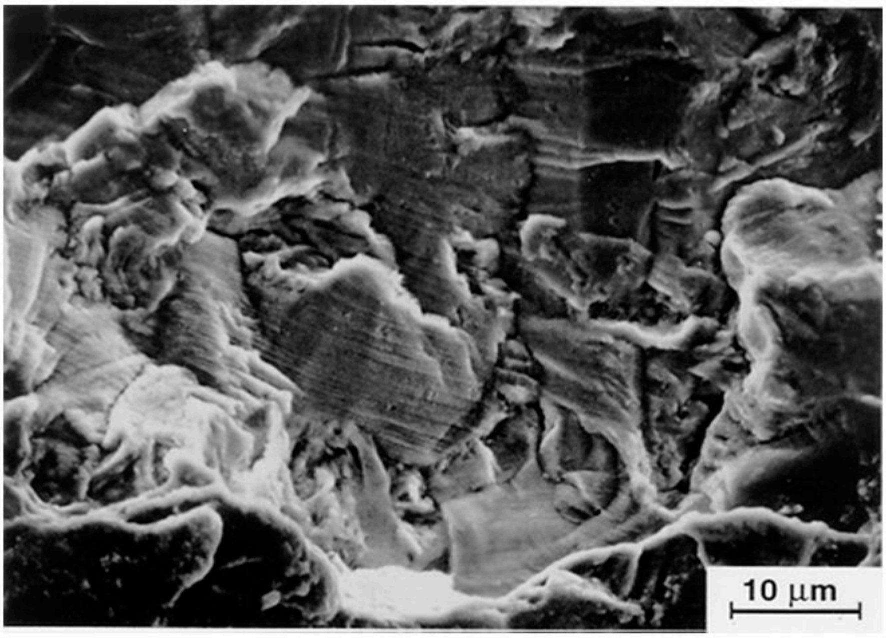


Schematic representation of fatigue fracture surface

Difference between high cycle fatigue (HCF) and low cycle fatigue (LCF)



Typical fatigue fracture surface



Striations (the parallel lines) are visible.
Each striation was caused by one load cycle.

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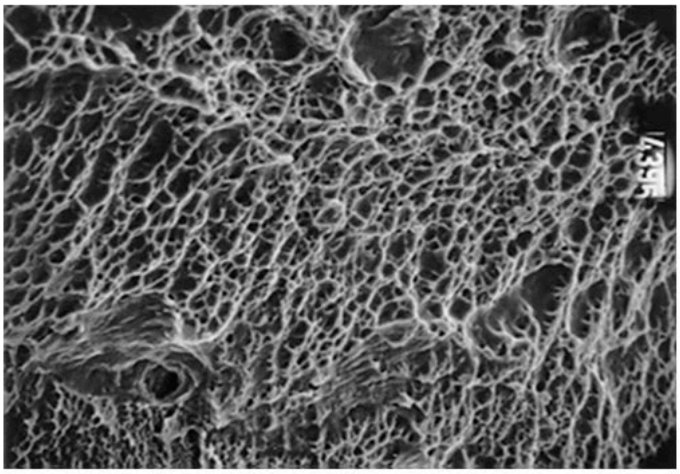
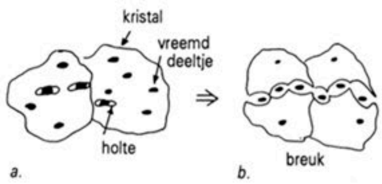
Typical overload fracture surface



Failure through void generation
Void generation is typical for overload fracture



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Difference between Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF)

- LCF often defined as: cracking of metals in less than 50,000 cycles
- A more fundamental distinction is:
  - LCF : high plastic strain in component
  - HCF: strain in component is predominantly elastic
- HCF occurs e.g. in blades due to vibration: elastic regime, very many cycles
- LCF occurs e.g. in disks due to cyclic loading: very high stresses, plastic regime, (1 start-stop cycle per flight/engine start-stop)
- Measures to increase HCF life:
  - Improved material cleanliness
  - Avoidance of surface defects
  - Introduction of residual compressive stress at surface

But: they do not have similar beneficial effects in the LCF range

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Which Loads?

❑ **Mechanical loads** 10 MPa ≈ 1 kg/mm^2

- Centrifugal loads; caused by high rotational speeds.The centrifugal force is equal to $mv^2/r = m\omega^2 r$ (m = mass, v = velocity, ω = angular velocity = v/r, r is radius); **these can be quite high**, typically e.g. 550 MPa in the blade roots. For turbine disks: 750 MPa (tangential stress at the bore, and 400 MPa in outer rim.
- Aerodynamic loads (pressure differences) causing airfoils to bend. To prevent bending, airfoils are designed such that pressure loads are compensated by centrifugal loads (it is important that airfoils are situated during operation in their best aerodynamic position). Typical loads can be 110 MPa (stators) up to 400 MPa (blades).
- Vibrational loads occur when an object is excited by an exciting frequency close to its natural frequency. Therefore components need to be designed such that their natural frequency is not close to a frequency generated by the gas turbine: difficult because a blade has many bending modes and during acceleration those frequencies are often passed ! Typical stress levels e.g. 70 MPa up to 140 MPa might occur!
- Static loading (e.g. casings due to internal pressure)

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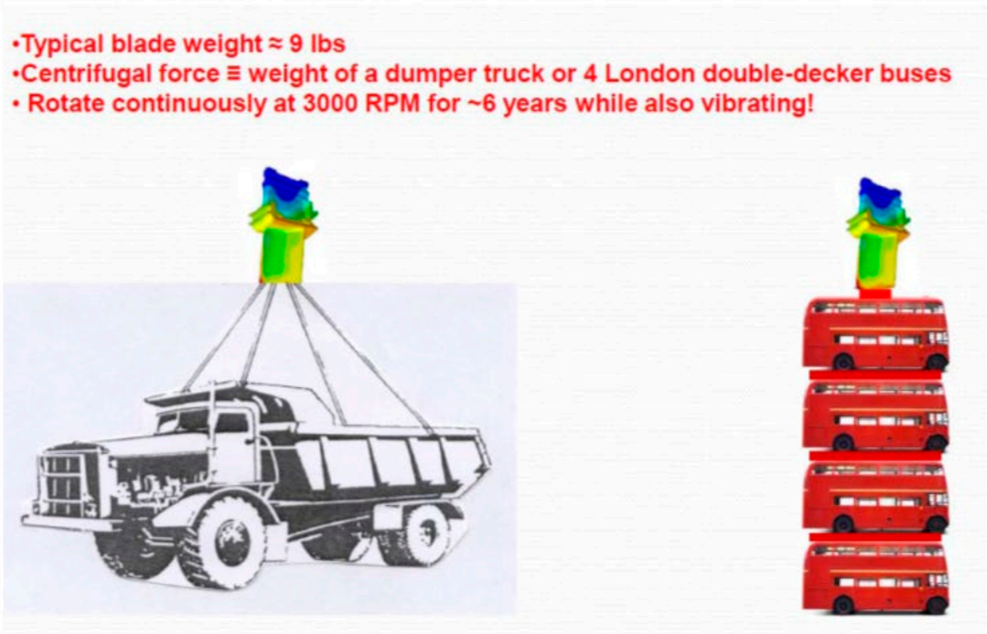
Food for thought ....



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Which Loads?

❑ Mechanical loads

10 MPa ≈ 1 kg/mm²

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- Vibrational loads: occur when an object is excited by a exciting frequency close to its natural frequency. To prevent vibrational loading components need to be designed such that their natural frequency is not close to a frequency generated by the gas turbine. This is difficult because a blade has several bending modes and during acceleration those frequencies are often passed ! Typical stress levels e.g. 70 MPa up to 140 MPa might occur!

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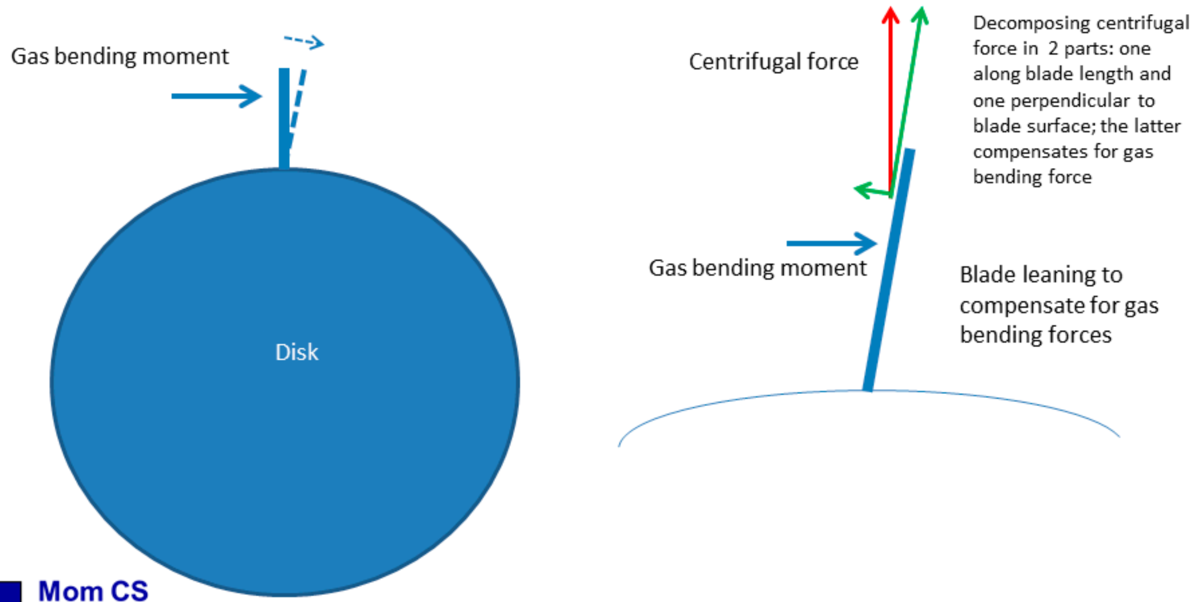
Principle of blade leaning to compensate for pressure loads



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Which Loads?

❑ Mechanical loads

10 MPa ≈ 1 kg/mm²

- Centrifugal loads; caused by high rotational speeds.The centrifugal force is equal to $mv^2/r = m\omega^2 r$ (m = mass, v = velocity, ω = angular velocity = v/r, r is radius); these can be quite high, typically e.g. 550 MPa in the blade roots. For turbine disks: 750 MPa (tangential stress at the bore, and 400 MPa in outer rim.
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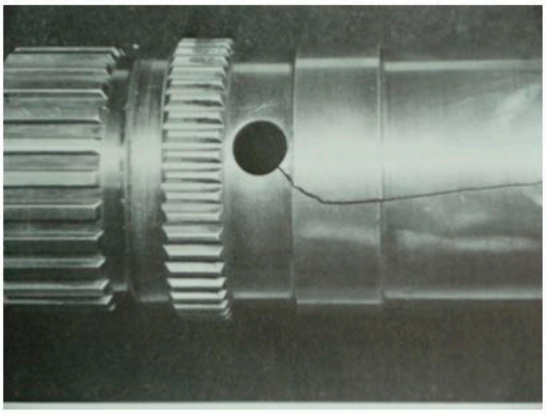
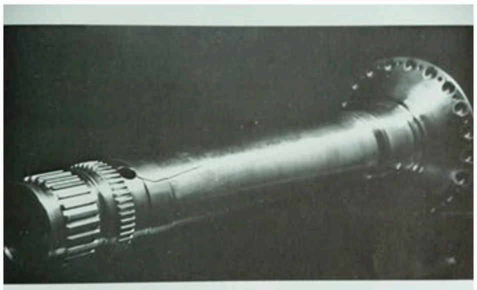
Fatigue failure in drive shaft
J85 engine – F5 aircraft





Drive shaft before final failure could occur

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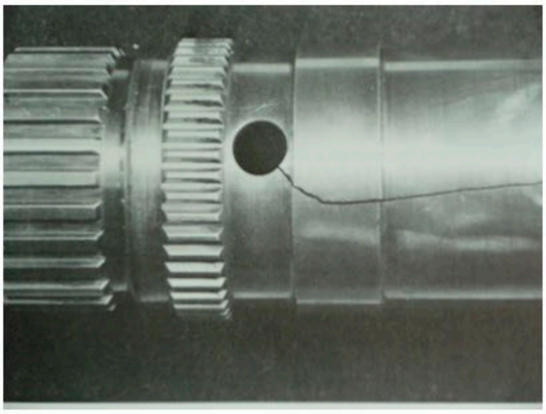
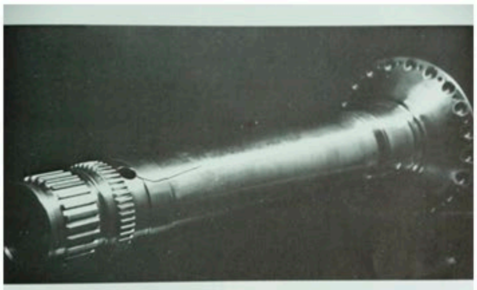
Fatigue failure in drive shaft

Rumble in afterburner (with same frequency as torsion frequency of shaft) caused high torsional stresses





Drive shaft before final failure could occur

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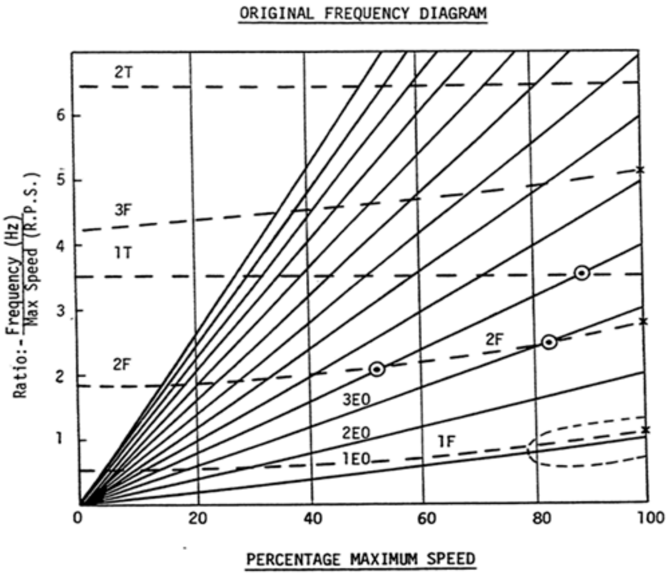
Campbell or 'spoke' diagram



A **Campbell diagram** plot represents a system's response spectrum as a function of its oscillation regime. It is named for Wilfred Campbell, who introduced the concept., also called interference diagram. The 'eigenfrequencies' often depend on the rotation rates

Which Loads?

❑ Thermal loads

These are caused when parts can not expand freely:

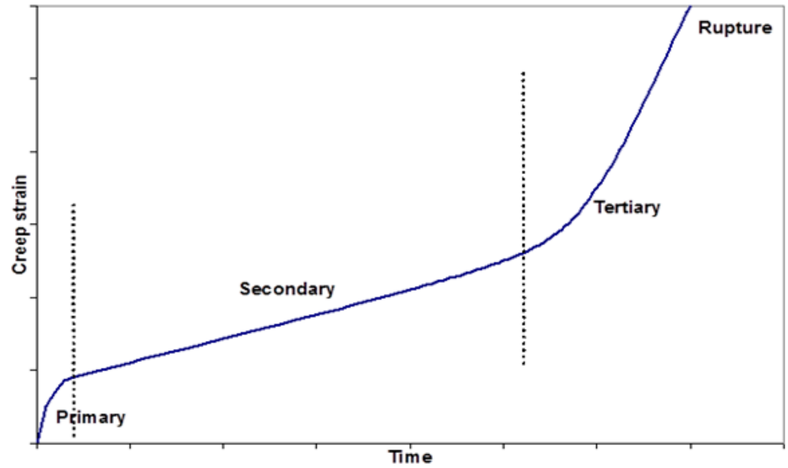
- Differences in heating up when the engine is accelerating: e.g. the outer part of a turbine blade is heated up faster than the inner part. This causes compressive stresses of the outer part and tensile stresses at the internal part. This situation is reversed during cooling down (from max thrust to cruise, or from cruise to idle).
- Differences in thermal expansion. If individual parts in one component have a different coefficient of thermal expansion (CTE) then stresses will occur.
- Note: Hot gas flow at turbine inlet up to 1600 C during take off; metal surface temperature ≈ 1100 C

Thermal loads are important for the life of the blade: they cause huge stresses often resulting in Low Cycle Fatigue (LCF).

Creep

Creep is the tendency of a solid material to deform permanently under the influence of a mechanical stress, especially at higher temperatures.

Typical creep curve at a certain temperature and stress level



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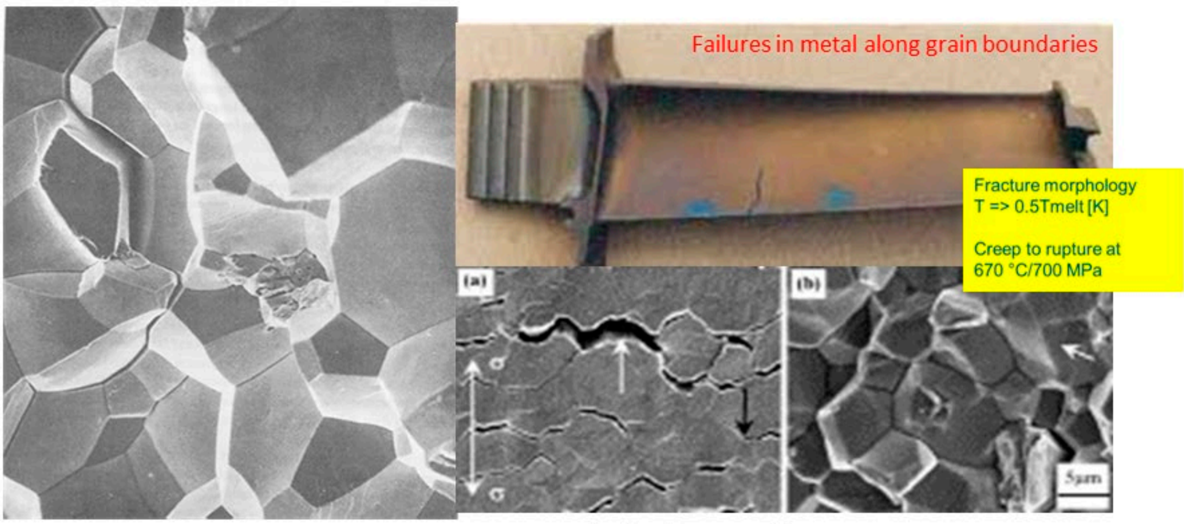
Creep



Fracture is often intergranular

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Outer casing combustor Inconel 718
pressure vessel 25 bars/550C

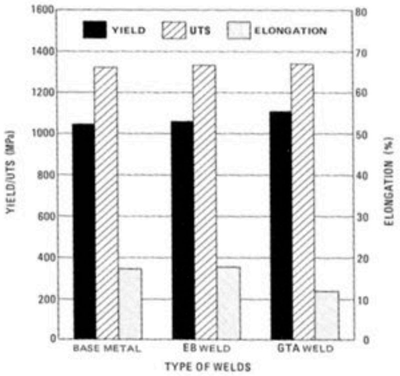

Fig. 9 Mechanical properties of fully heat treated Inconel 718 welds in O.D. skirt material

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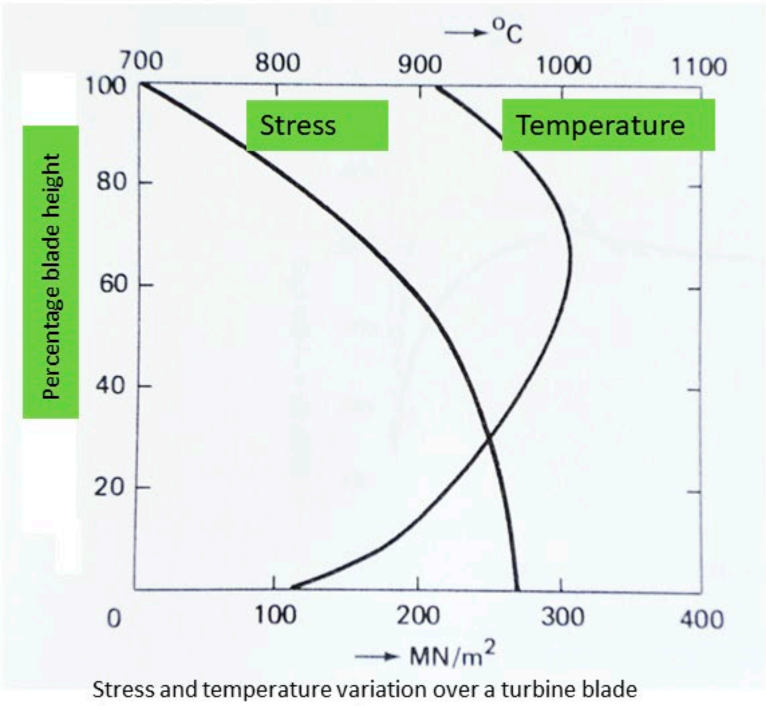
Stress and T variation over turbine blade length



Stress and temperature variation over a turbine blade (B. Rogues, AGARD CP120).

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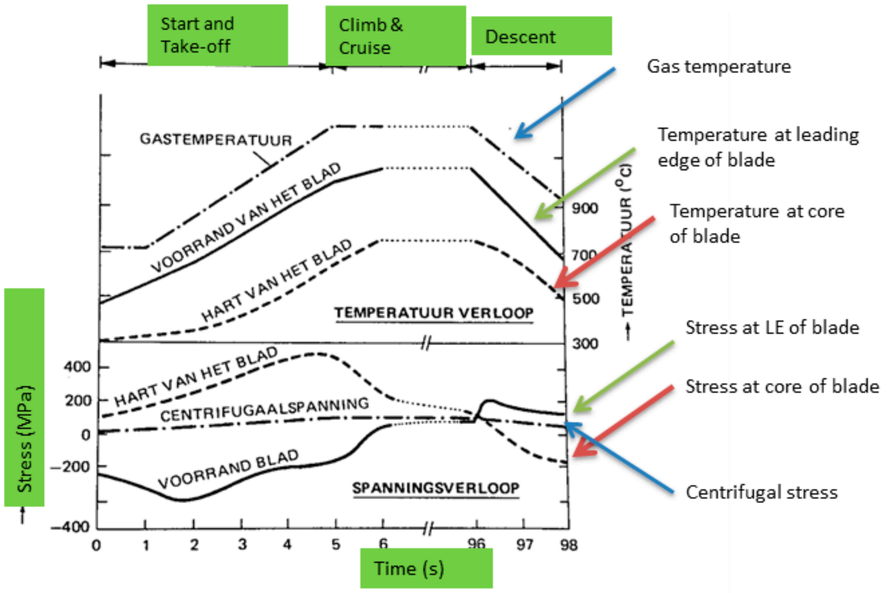
Stress and T variations in turbine blade



Temperature and stress in rotor blade during an operational cycle (J.E. Restall, AGARD CP120)

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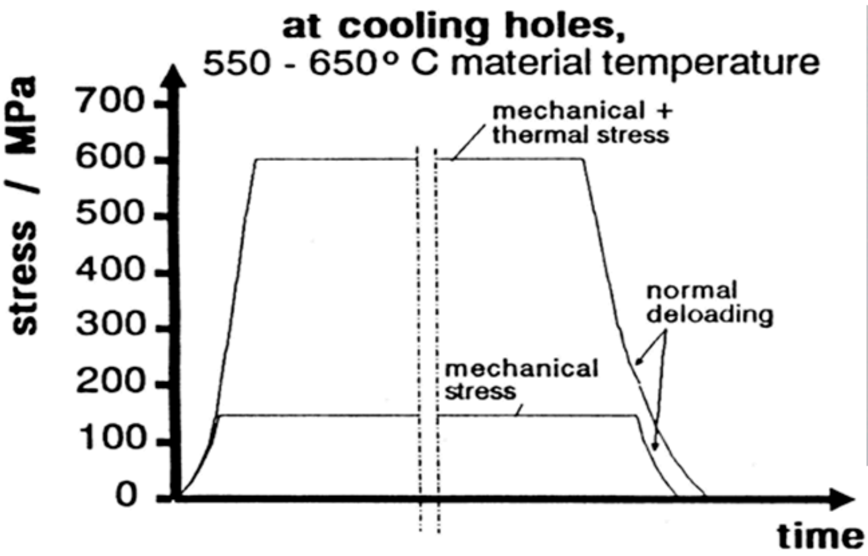
Stress variation at relatively cool regions in a turbine blade *(inside wall)*



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Which Loads?

- **Environmental loads**
  - Erosion, by
    - Sand (e.g. helicopters, Middle East)
    - Dust
    - Rain
  - Corrosion;
    - influence of H_2O, SO_2, seasalt (low T) or
    - S, Na, V in low grade fuels (hot corrosion)
  - Oxidation (high T)
    - Especially combustor and turbine
  - Fretting/contact wear

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Conclusions

The components/materials have to fulfil their tasks in an extremely harsh environment for thousands of hours. The 80 years of gas turbine development very much concentrated on the development of (light weight) alloys for these severe environments.

And: we are not at the end yet...

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In Summary

- Loading in gas turbines is very complex:
  - Mechanical
  - Thermal
  - Environmental
  - And combinations of these
- Loading schemes are quite different for different components in the gas turbine
- Each component requires a different set of properties to withstand the particular loading
- Materials behave quite differently at different temperatures; damage mechanisms vary
- The various design philosophies have been explained; dependent upon the component in the gas turbine different design philosophies are applied
- Damage tolerance concepts are increasingly used for a combination of safety and economic reasons (durability)
- Fail safe is used for the complete engine: if the engine fails the aircraft should be able to land safely

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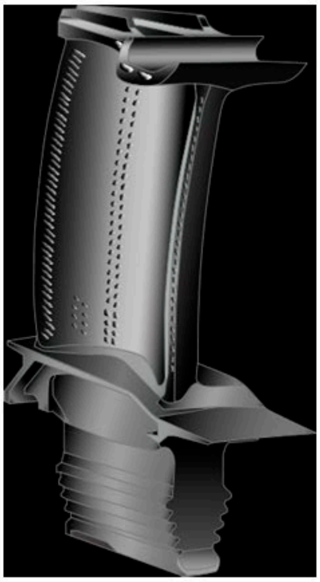
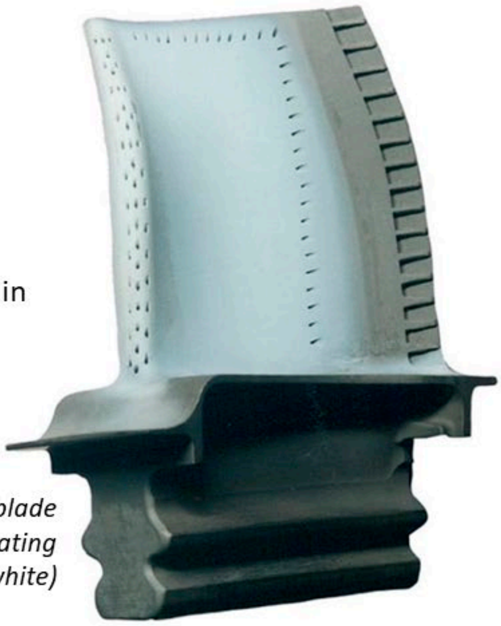
Examples of shrouded and unshrouded turbine blades



Shrouded turbine blade with cooling holes for film cooling

How does a shrouded tip influence the stress level in an airfoil of a turbine blade?



Unshrouded turbine blade with thermal barrier coating TBC (white)

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Overview of degradation mechanisms for different parts

Component	Degradation mechanism(s)
Compressor blades	Fatigue, erosion, low T corrosion (water, salt, SO_2)
Discs	Fatigue, corrosion
Drive Shaft	Fatigue
Combustor	Thermal degradation, (thermal) fatigue
Turbine stator vanes	Oxidation, hot corrosion, thermal degradation, (thermal) fatigue
Turbine rotor blades	Oxidation, thermal degradation, (thermal) fatigue, creep

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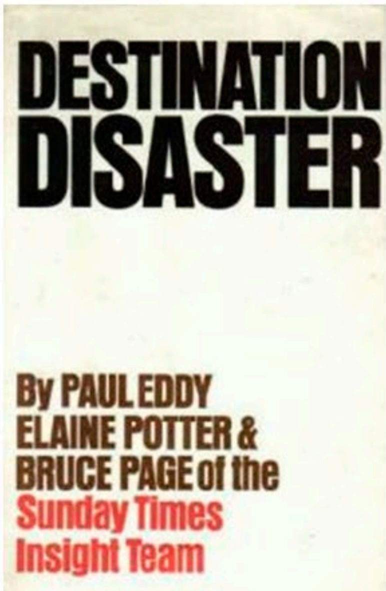
Literature: absolutely required

Authors: Eddy, Page and Potter, Sunday Times



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About the DC10 crash north of Paris. March 1977. Strong competition between competitors Boeing, MDD, Lockheed

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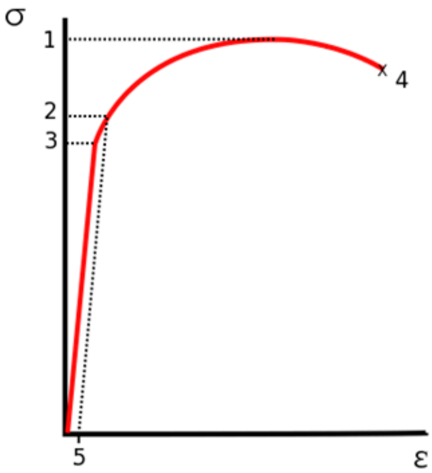
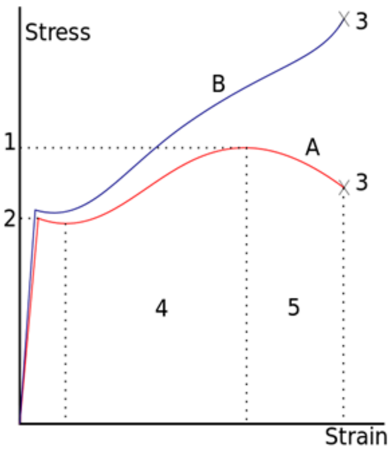
Stress vs. strain curve



Typical of aluminum
1. Ultimate strength
2. Yield strength
3. Proportional limit stress
4. Fracture
5. Offset strain (typically 0.2%)



Typical of structural steel
1. Ultimate strength
2. Yield strength
3. Fracture
4. Strain hardening region
5. Necking region
A: Engineering stress
B: True stress

Round bar tensile specimen after testing

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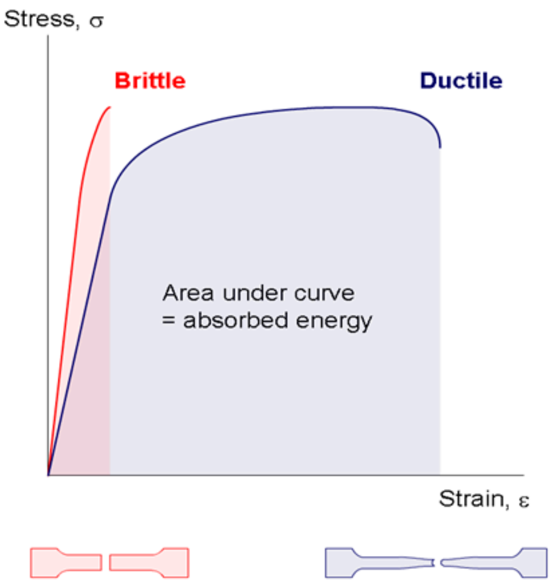
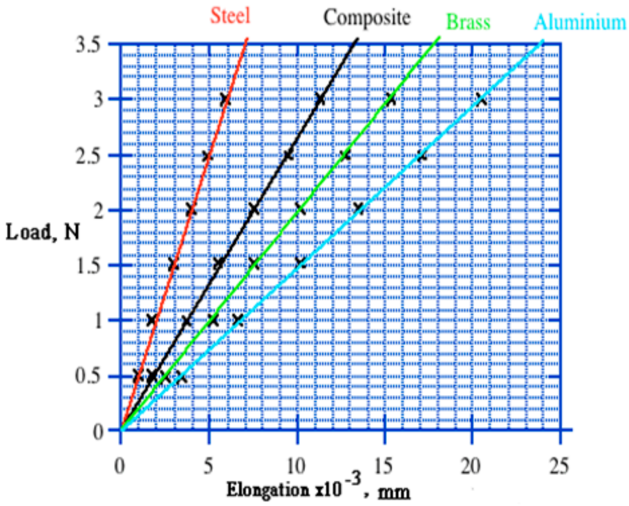
Stress - strain curve





Youngs modulus is measure for stiffness of the material

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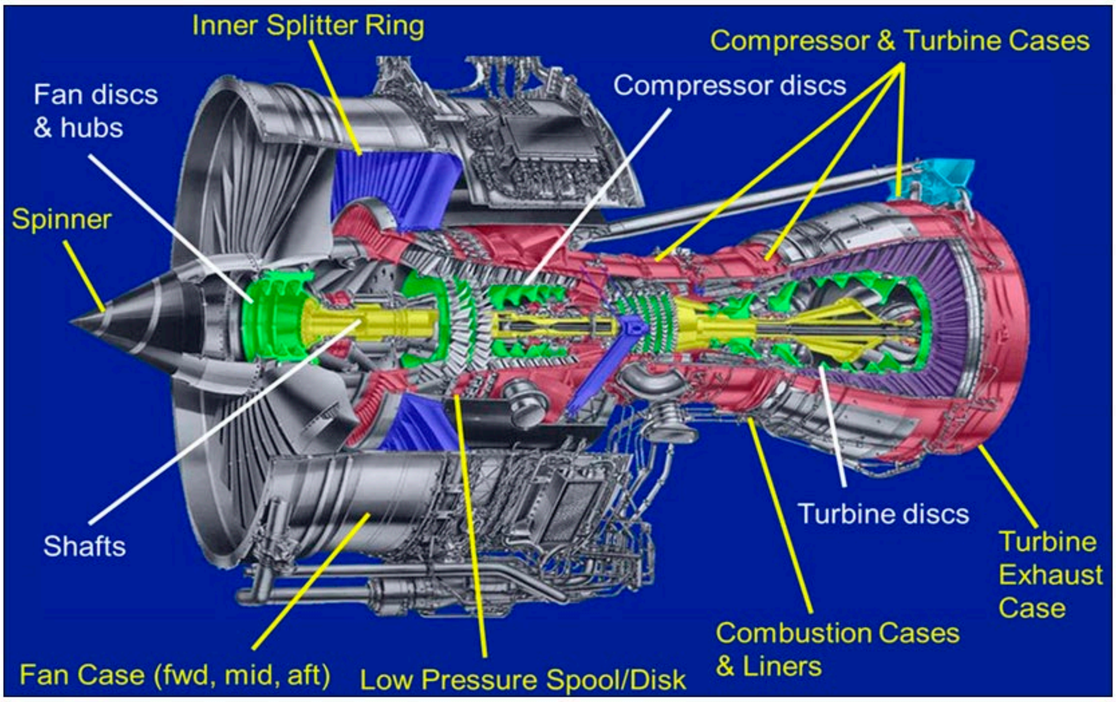
2 Manufacturing processes, phase diagrams & superalloy strengthening mechanisms, protective coatings

Manufacturing & Machining



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Manufacturing routes

(Near) net shape vs intermediate products and machining

- Castings :
  - near net shape (turbine blades & vanes, some casings)
  - Raw castings; casings/housings
- Forgings
  - Requires in most cases intensive machining/manufacturing afterwards
  - Near net shape: HIPping (powders)
- Rolled products (hot and cold)
  - Sheet, plate : requires intensive machining/welding/brazing afterwards
  - Rolled product: requires extensive machining

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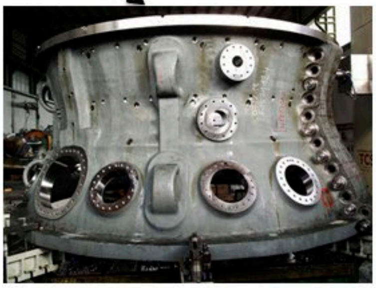
Manufacturing products – Examples (1)

Castings:

- High T turbine blades & vanes (hollow)
- Complex casings, gearbox housings
- Sometimes high T exhaust nozzle parts



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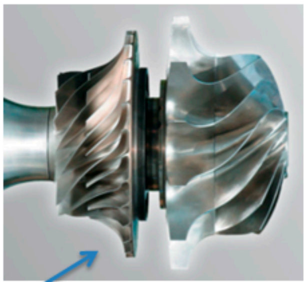
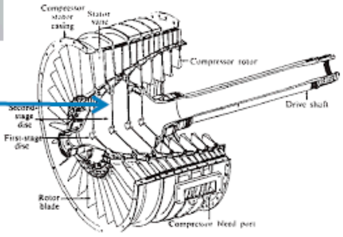
Manufacturing products – Examples (2)



Forgings:

- Compressor and turbine disks
- Compressor blades and vanes
- Turbine blades, lower (uncooled) stages
- Gear wheels
- Mounting pads, levers, etc



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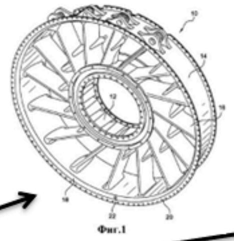
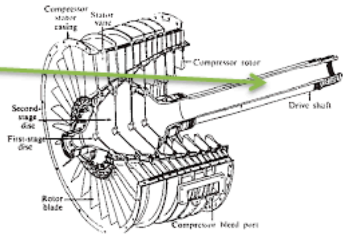
Manufacturing products – Examples (3)



Rolled Products:

- Casings
- Shafts
- Liners
- Tubing



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Manufacturing routes: castings

Castings

- Pros:
  - Complex geometries
  - Casting route standard for high T blades and vanes; 3 reasons:
    - Not possible to forge these very high strength turbine materials
    - The components are relatively small: less tendency for segregation
    - Casting provides opportunity to realise complex cooling channels
- Cons:
  - Process results in microstructural defects and segregation
  - Process is normally not used for rotating parts (**except for turbine blades**), mostly for stationary parts (less critical)
  - Large components: structural defects can limit application

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Manufacturing routes: Forgings

Forgings

- Pros:
  - Homogeneous structure with few inherent microstructural defects, so less tendency for crack initiation
  - Widely applied for highly demanding rotating applications
  - Large parts can be manufactured
  - Forgings are widely applied for blades, vanes, shafts, disks
  - In combination with powder material (PM) HIPping complex geometries is possible
- Cons:
  - Difficult to manufacture complex geometries
  - Process requires many additional machining/welding/brazing steps for manufacturing of complex components

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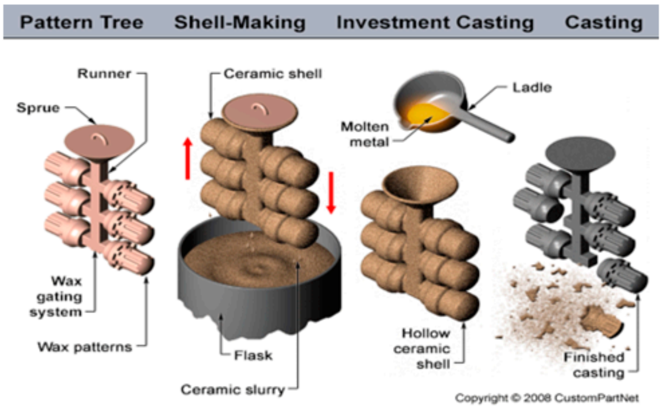
Manufacturing – Investment Casting

Example of wax replica



- Wax replicas of desired shape, produced by injection molding
- Assembly: the patters are attached to a central wax stick, to form a casting assembly
- The shell is built by immersing the assembly in a liquid ceramic and then into a bed of extremely fine sand; process is repeated several times
- Once the ceramic is dry, the wax is melted out, creating inside a negative impression of the assembly The shell is filled with molten metal creating one solid casting
- The ceramic shell is broken off
- The parts are cut away from the central feed line using a high speed friction saw
- After minor finishing operations, the metal castings – identical to the original wax patterns – are complete

Example of casted blade and ceramic insert

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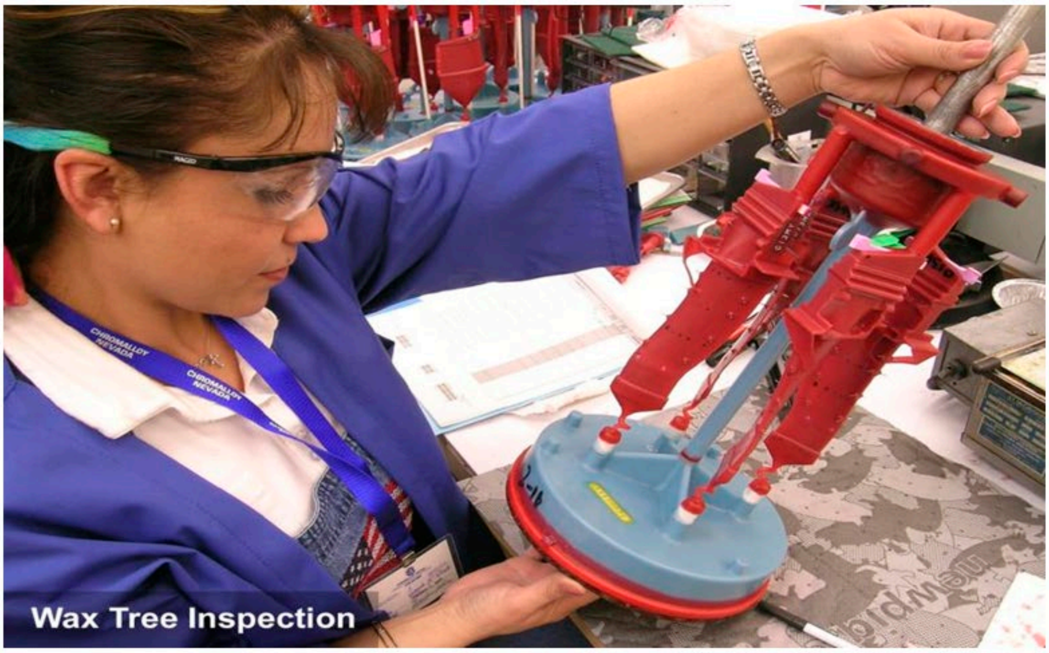
Pictures of lost wax process



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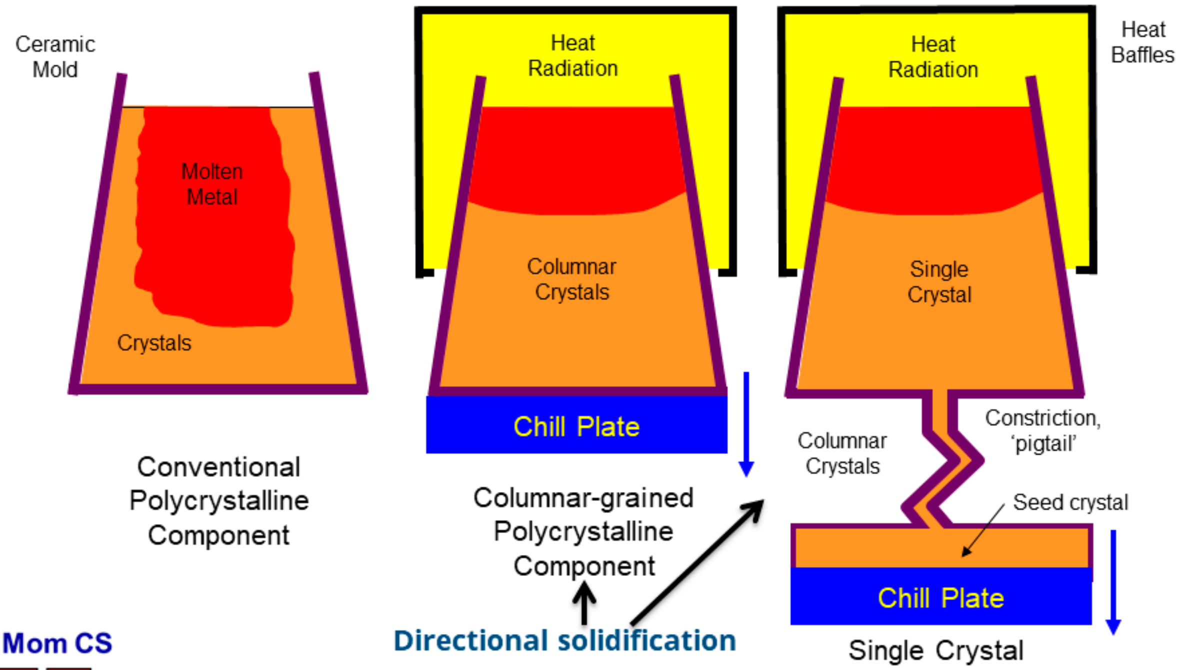
From polycrystalline to single crystal processing



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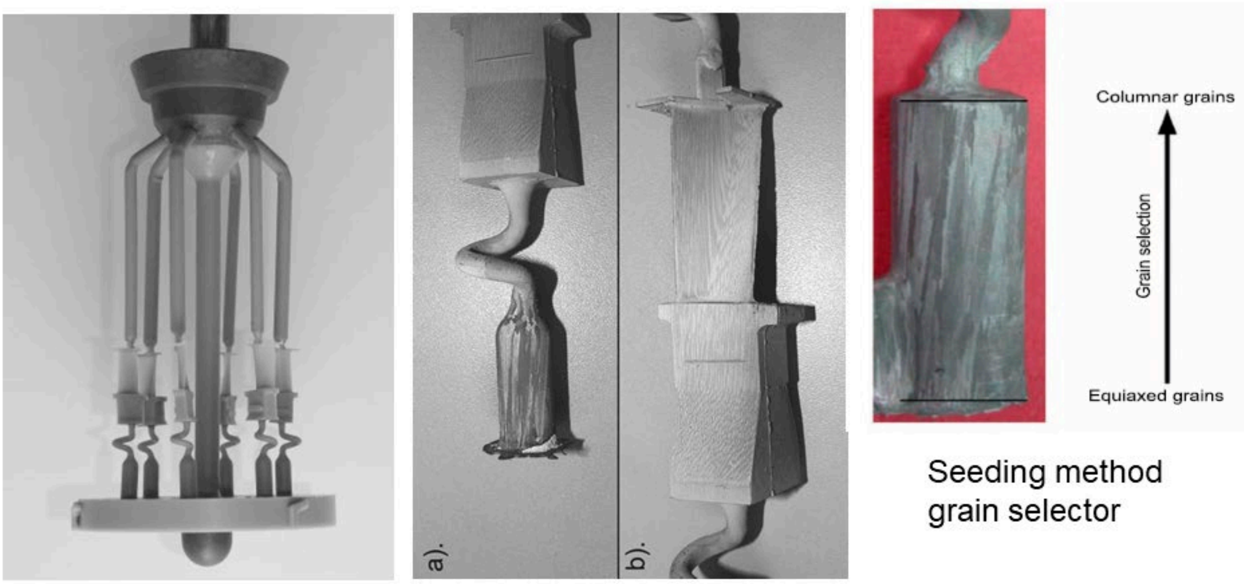
Single Crystal Casting



Seeding method
grain selector

$\sigma = E . \varepsilon$
E in {001} direction lower

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Forging processes (1)

Starting material : cast ingots

- Ingot can be forged – in various steps - into the product you want to have

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Forging processes (2)

Examples from processing starting from a cast billet

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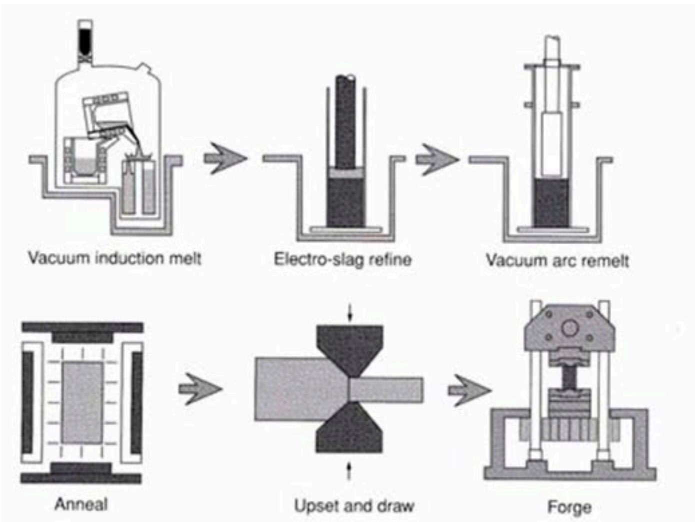
Forging processes – for turbine disc (3)



Sequence of processes used for the production of a turbine disc by **ingot metallurgy** [Benz MG].

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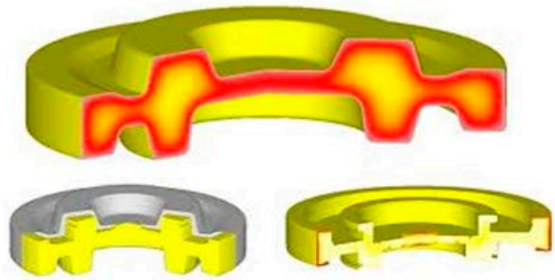
Manufacturing – Forging processes (4)

- Open die forging (to produce preforms)
- Closed die forging
- Upset forging (for producing preforms)
- Extrusion
- Roll forging
- Ring rolling
- Rotary forging
- HIPPING



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Forging processes (5)

Starting material : cast ingots

1. Ingot can be forged – in various steps - into the product you want to have

2. **Cast ingots can also be used for making metal powder:**
   - **Filling powder in preform**
   - **Hipping of preform (to make it a solid block)**
   - **Further forging processes**

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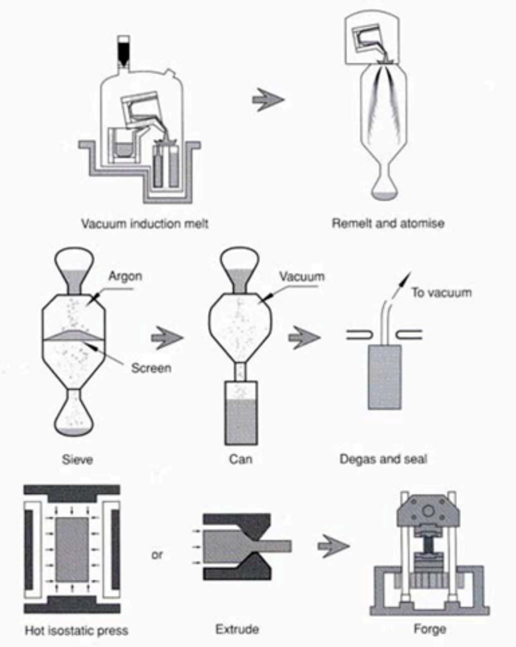
Forging process – for powder metallurgy route (6)



Sequence of processes used for the production of a turbine disc by conventional **powder metallurgy** [Benz MG].

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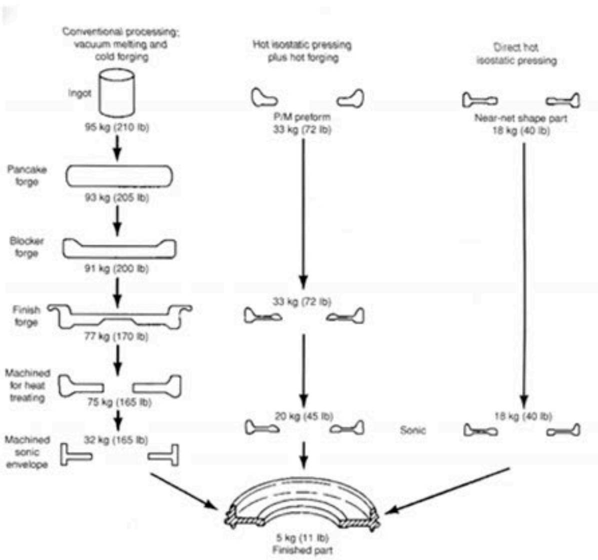
Forging processes (7)



Processing sequences for the production of F-101 compressor discs [Ferguson BL] used for B1 - aircraft

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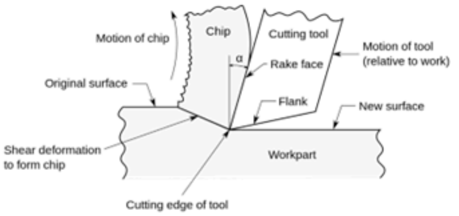
Machining after casting and forging

Traditional
- Cutting
- Milling
- Turning
- Grinding

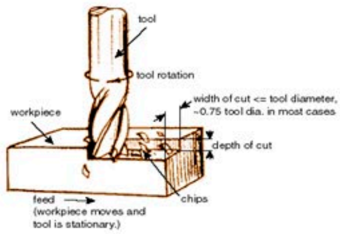
Non traditional
- Water jet machining
- Laser machining
- Chemical Machining
- Electrochemical machining ECM
- Electro discharge machining EDM



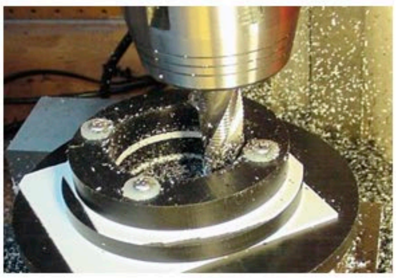
'Traditional' Machining Processes

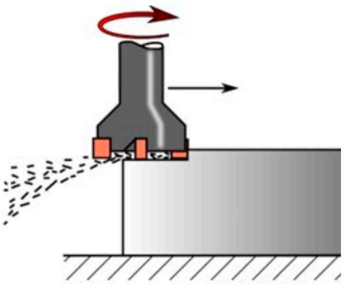
Drilling

Turning



Grinding

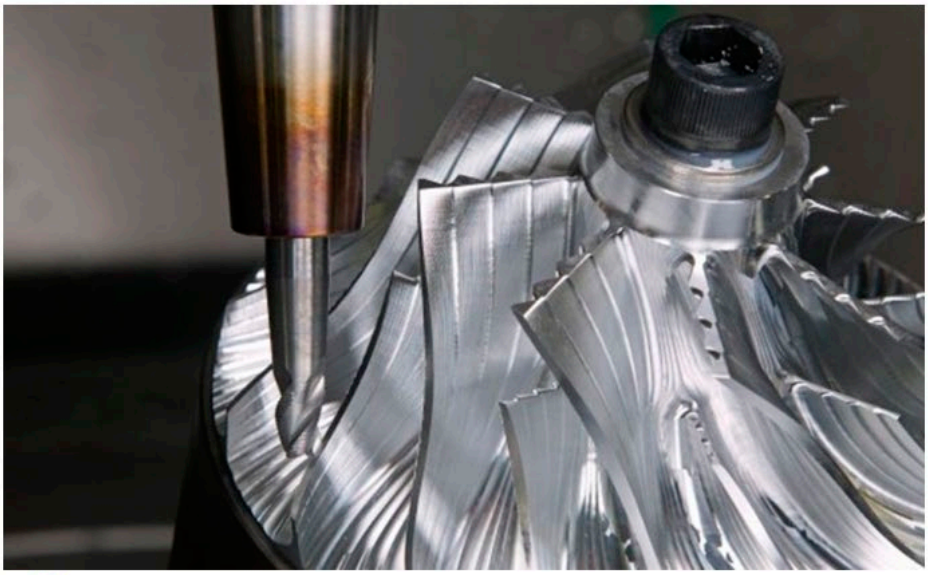




Milling

‘Traditional’ Machining can be quite advanced (1)

5-Axis machining https://www.youtube.com/watch?v=SNoj5XtpEa8



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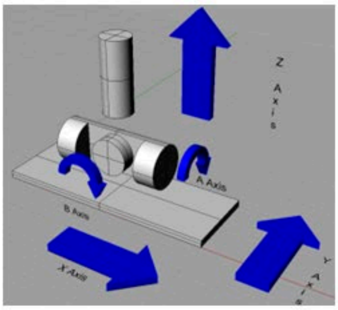
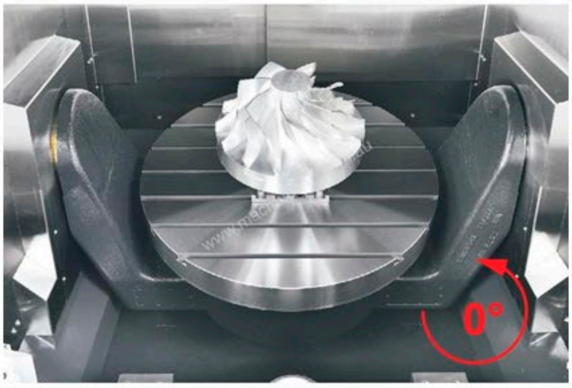
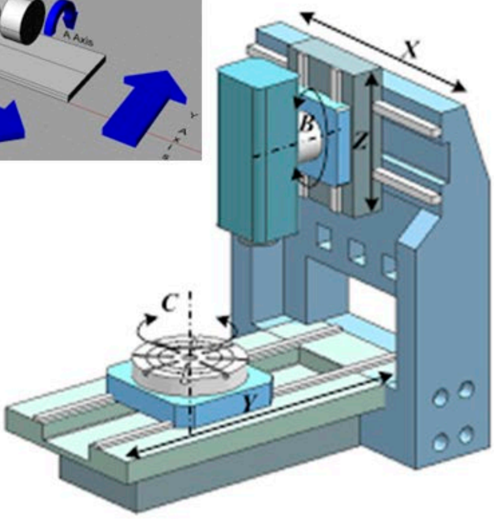
‘Traditional’ Machining can be quite advanced (2)

5-Axis machining







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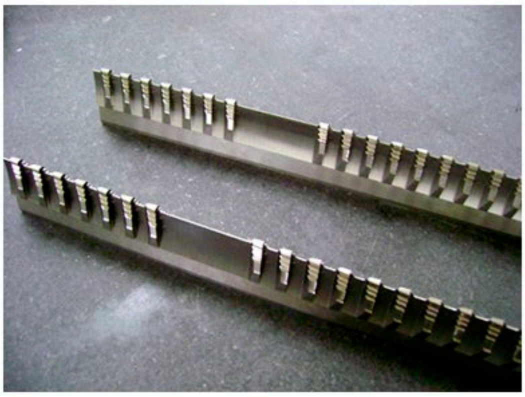
'Traditional' Machining can be quite advanced (3)

Broaching



Linear Broaching

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'Non traditional' Machining

- **Water jet machining**
- **Laser machining**
- **Electro discharge machining EDM**
- **Chemical Machining**
- **Electrochemical machining ECM**
- **Etc.**

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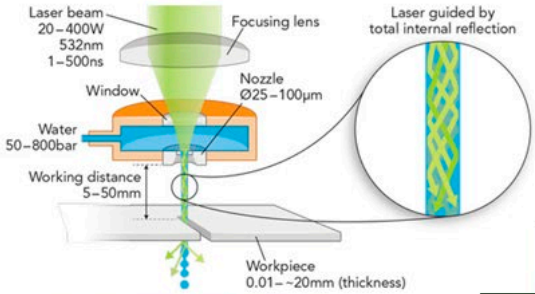
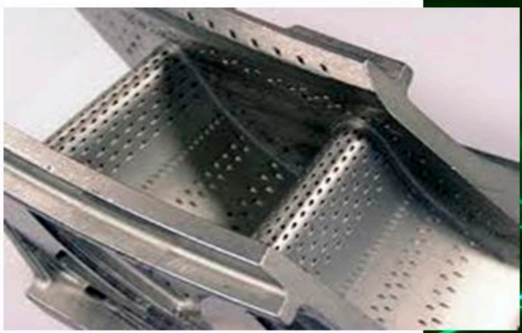
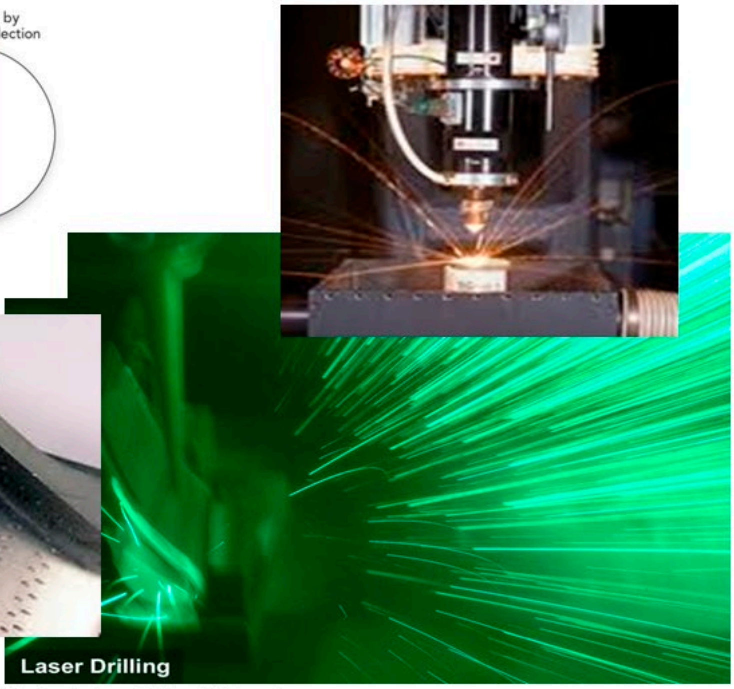
‘Non traditional’ Machining – Laser drilling







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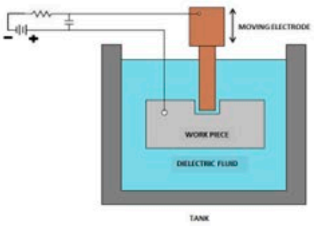
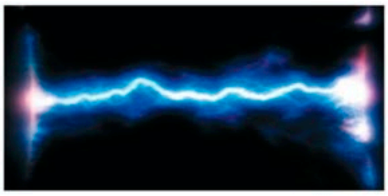
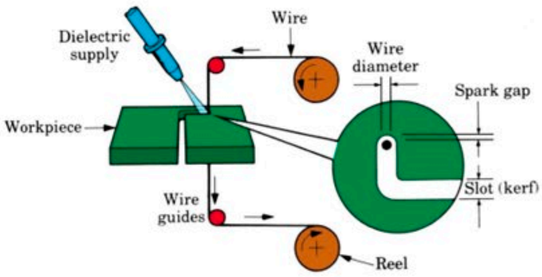
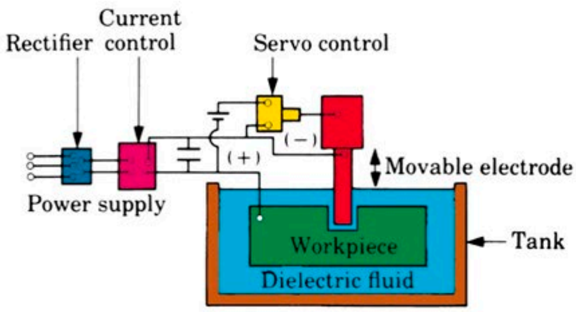
‘Non traditional’ Machining – Electro Discharge Machining EDM









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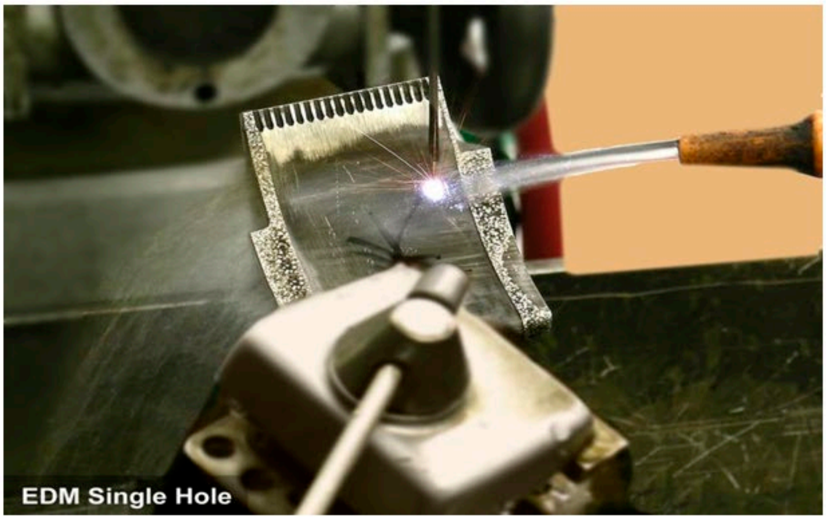
‘Non traditional’ Machining - EDM



‘Non traditional’ Machining – Chemical Machining

Chemical Milling

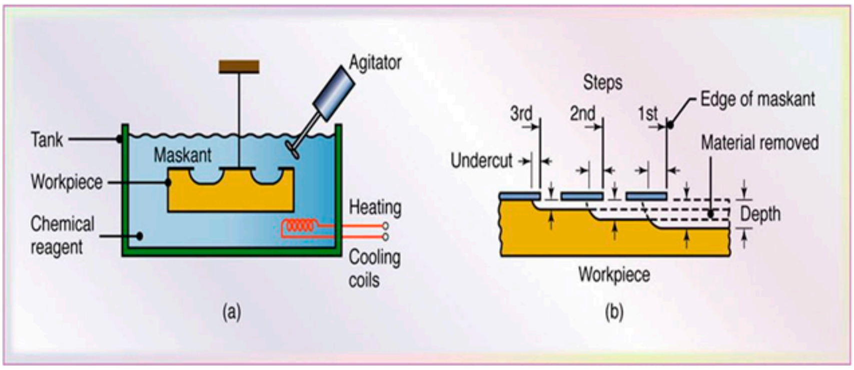
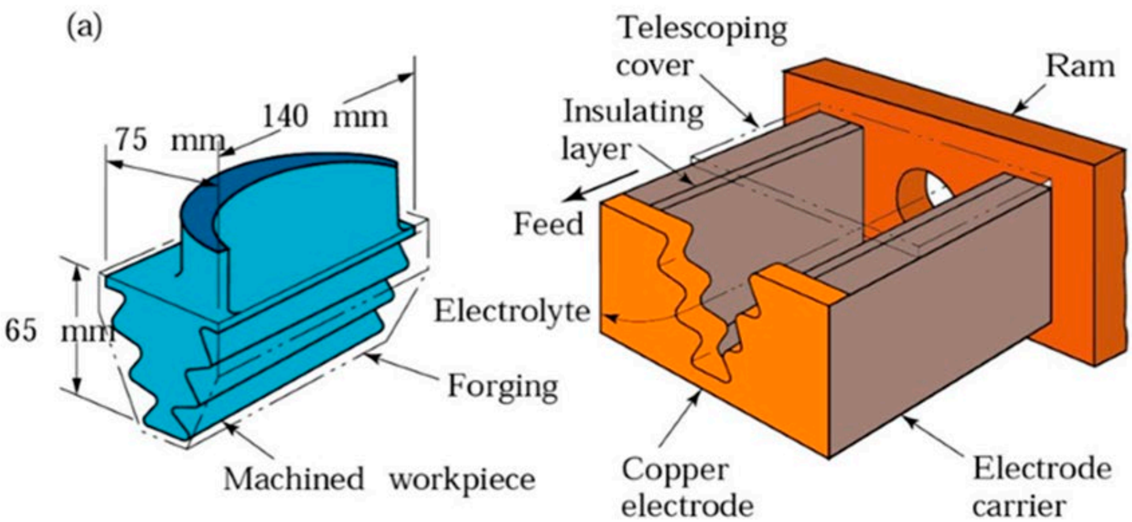


Figure 27.3 (a) Schematic illustration of the chemical-machining process. Note that no forces or machine tools are involved in this process. (b) Stages in producing a profiled cavity by chemical machining; note the undercut.

‘Non traditional’ Machining – Electrochemical Machining ECM



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‘Non traditional’ Machining – Electrochemical Machining ECM

Electrochemical Machining – Blisks produced by KMWE-Dutch Aero

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Literature

- ASM Handbook, Volume 14B, Metalworking: Sheet Forming, Published 2006, ASM International, pp. 405-418. High Velocity Metal Forming; Glenn S. Daehn
- The Jet Engine, Rolls Royce, 5th edition: http://airspot.ru/book/file/485/166837_EB161_rolls_royce_the_jet_engine_fifth_edition_gazoturbinnyy_dviga.pdf
- Many overviews at internet/Wikipedia

Nice video's:

- https://www.youtube.com/watch?v=hjSKJ6lHZIA
- https://www.youtube.com/watch?v=ZWXFhdeOjMY

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Study material

1. Understand/describe the casting process for turbine blades
   - what is core shift, and which detrimental effects might occur?
2. How to manufacture cooling holes?
3. What is non-conventional machining and give examples
4. Gas turbine parts are manufactured in different ways. Give examples of parts that are:
   - Castings/casted
   - Forgings/forged
   - Sheet and plate/formed, shaped and joined
5. What are basic differences between casted and forged parts; what would you prefer to use for static and for rotating parts and is this always done in the real world?
6. Do you know examples of Dutch companies that manufacture gas turbine parts?

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Superalloy Strengthening Mechanisms

- Phase diagrams
- Crystallography
- Dislocations
- Strengthening mechanisms

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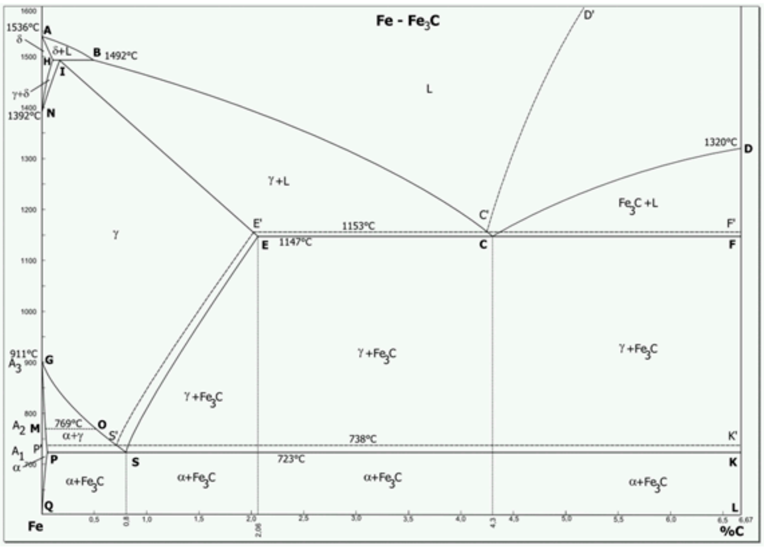
The Fe-C phase diagram



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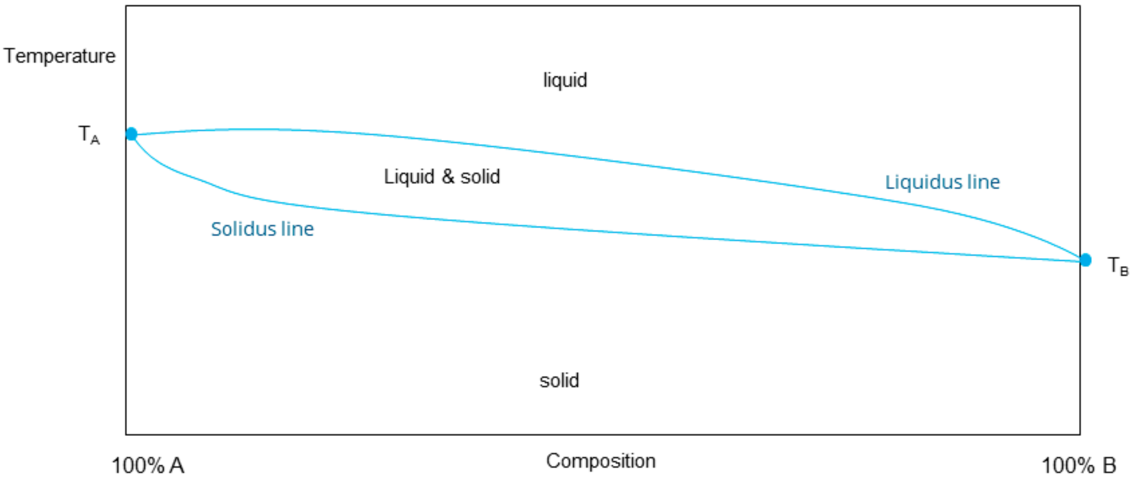
Binary phase diagram

Complete solubility of 2 metals A and B: e.g. Cu + Ni
One solid solution exists at all temperatures (isomorphous)



Liquidus – line at which solidification begins
Solidus – line at which solidification is completed

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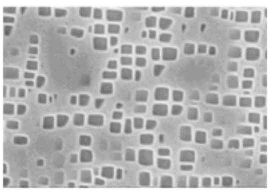
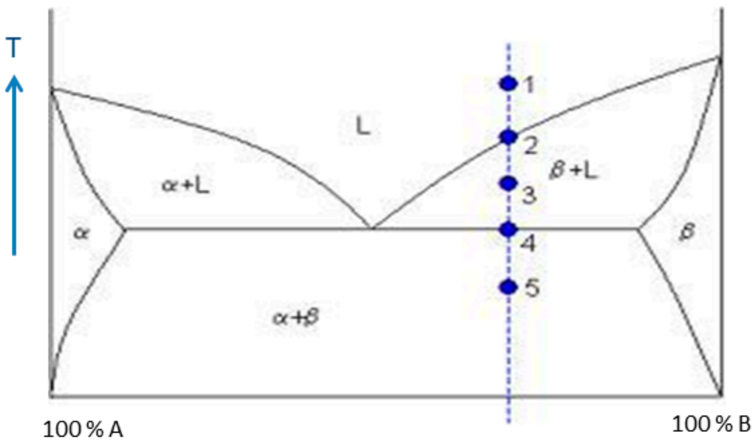
Binary phase diagram

- Limited solubility of A in B and B in A
- At solidification: two different phases will develop, an α-rich solution and a β-rich solution





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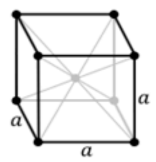
Crystallography- what kind of crystallographic phases

Body centred cubic (BCC): Fe (at low T), Cr, W

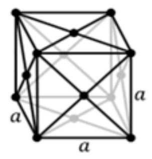
Face centred cubic (FCC): Al, Ni, and Co (at high T)

Hexagonal close packed (HCP): Ti, Co

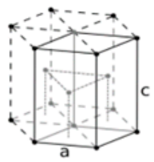
Which phase forms depends on size of atoms and inter atomic forces



body-centred cubic (bcc)



face-centred cubic (fcc)



hexagonal close packed (hcp)

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Dislocations

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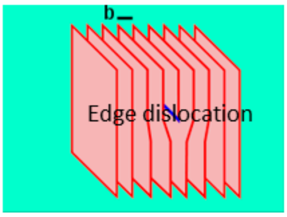
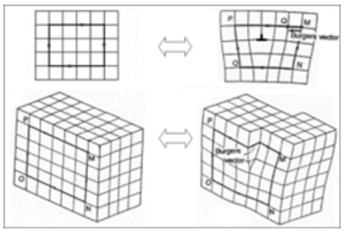
How do materials deform: dislocations

Deformation of materials is caused by dislocations: a dislocation is a crystallographic defect/irregularity within the crystal structure.

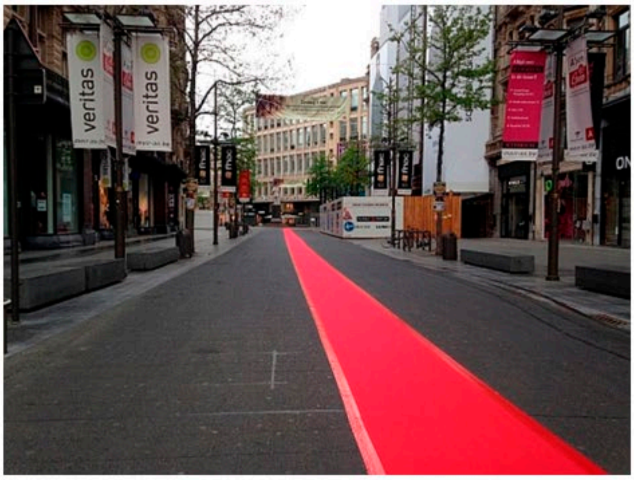
The presence of dislocations strongly affect the plastic behaviour: stresses will easily result in deformations.





How do materials deform: dislocations

Example of an edge dislocation; how does it work?



How to move a long carpet?

How do materials deform: dislocations

Example of an edge dislocation; how does it work?

How to move a long carpet

Make a small pleat in the carpet and push it forward

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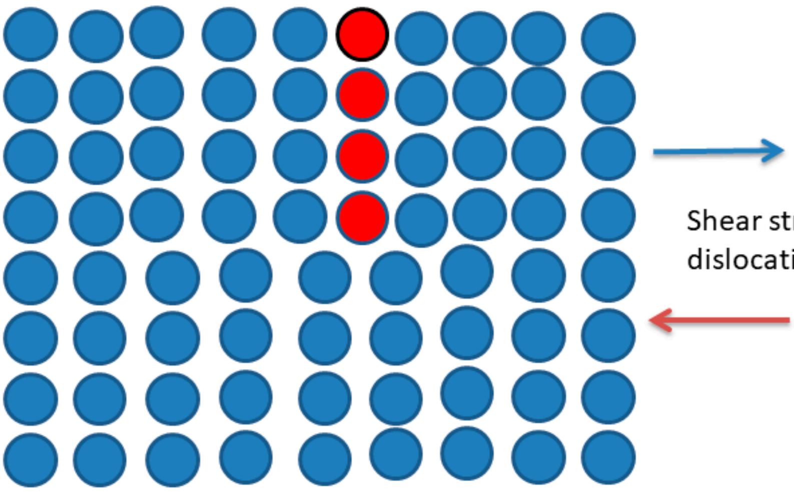
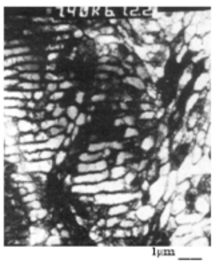
How do materials deform: dislocations



Shear stress will move dislocation to the right



Edge dislocation; material will easily deform in a plastic way

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Mechanical + physical properties of some 'pure' metals

Element/ Metal	Ultimate tensile strength [MPa]	Yield strength [MPa]	Young's modulus [GPa]	Density [kg/dm³]	Melting point [°C]	Coefficient of linear expansion [um/(m K)]	Crystal structure
Al	70	10	70	2.7	660	23.6	Face-centered cubic
Ti (grade 1)	345	220	110	4.5	1668	8.41	Hexagonal close packed
Fe	180	120	200	7.9	1538	11.8	Body-centered cubic; Face-centered cubic between 912–1394 °C
Ni	450	150	210	8.9	1455	13.4	Face-centered cubic

Pure metals: dislocations will easily move; they are not strong
Stresses in GT-components are often 600 – 1000 MPa !

So: for use in practice they should be strengthened!

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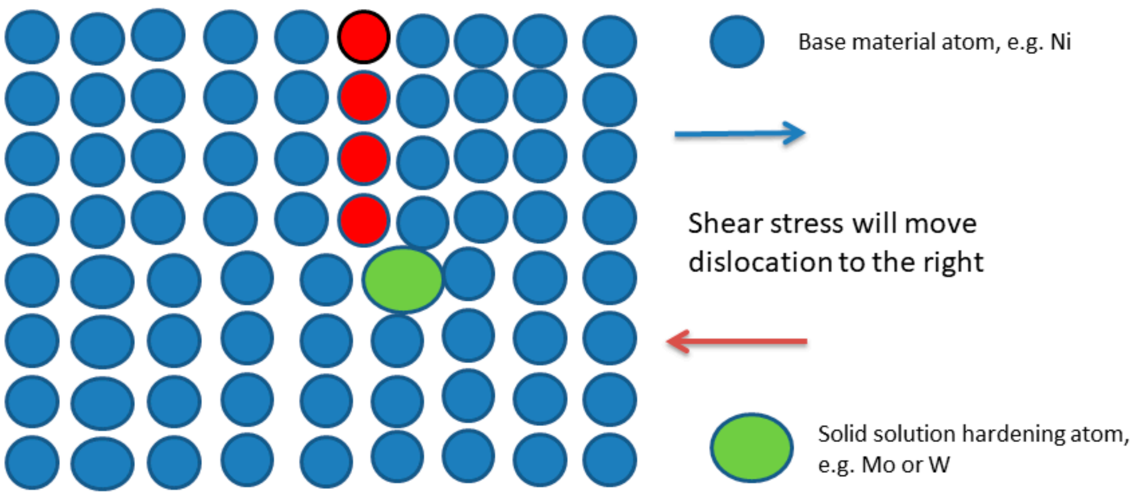
How to strengthen metals?
Deformation will be more difficult with disturbing atoms



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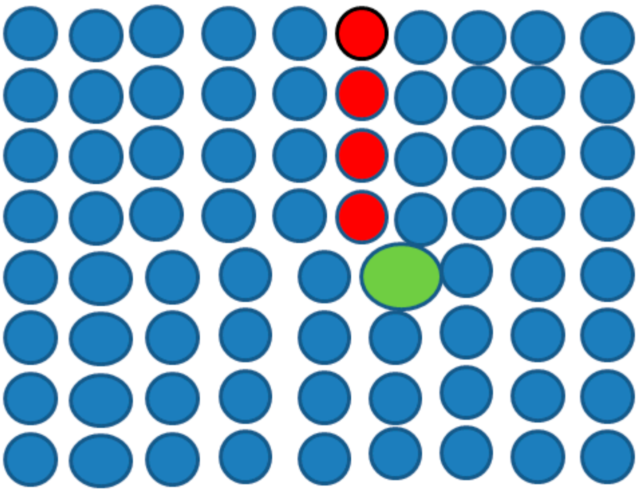
How to hinder the movement of dislocations?



1. Solid solution strengthening elements (W, Mo,..)
2. Precipitates (other phases): precipitation hardening
3. Grain boundaries (difficult for dislocations to pass grain boundary)
4. Fix movement by intertwining with other dislocations

Dislocation has more difficulty in moving under stress when other atoms, precipitates, grain boundaries, interlocking dislocations are present

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Superalloys - requirements

- High temperature strength in the service range; good creep resistance
- Fatigue properties fulfilling design requirements, incl. low crack growth rates (da/dN)
- Sufficient ductility and toughness, particularly in rotating parts
- Retention of properties, even after prolonged service
- Excellent resistance to high T oxidation and corrosion.
- Sufficient weldability, formability and castability, to allow cost effective manufacture and repair

This is a very demanding set of requirements!

Superalloys are austenitic (FCC) alloys based on Nickel, Cobalt or Iron-Nickel

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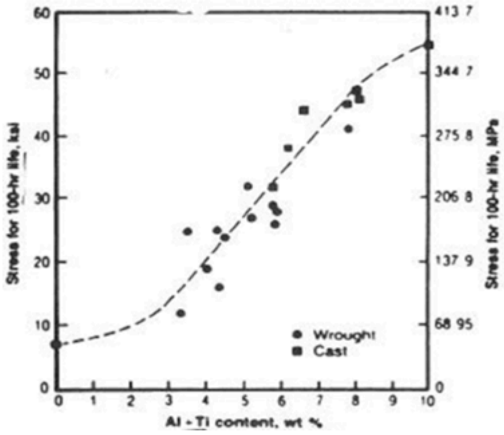
Nickel Alloys are the most popular

Why?

- Melting point
- Microstructural stability at high temperature
- Adding Al + Ti results in γ' formation
- Adding Cr: superior corrosion resistance
- Adding elements for solid solution hardening

Effect of Al & Ti content on strength of Ni-based superalloys at 870°C



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How to strengthen metals/alloys

Typical composition of superalloy
IN100 in %: 60Ni, 10Cr, 15Co, 3Mo, 4.7Ti, 5.5Al, 0.6 Fe, 0.15 C, 0.06Zr, 1.0V

Alchemy

or Science?

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How to strengthen a Ni superalloy?

1. Add Cr, because of **corrosion/oxidation resistance** (10 – 20% Cr);
2. Add also other atoms: crystal structure will be deformed, this causes strengthening: **solid solution strengthening** (Co, W, Mo, Fe, Re, Cr, Mn)
3. **Precipitation hardening** by adding Ti and Al: Ni_3Ti, Ni_3Al, $Ni_3(Ti,Al)$ will precipitate, causing superior characteristics
4. Al will further enhance oxidation performance
5. **Strengthen the grain boundaries** (for improving creep resistance)

Or:

1. Avoid grain boundaries in transverse direction:
    - Directional Solidification & Single Crystal
2. Single crystals allow for more alloying elements, further strengthening effect

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How to strengthen a Ni superalloy

- γ matrix, stable, high tolerance for alloying with solid solution hardening elements, owing to nearly filled 3rd electron shell
- γ' formation = precipitate of $Ni_3(Ti,Al)$
- Grain boundary strengthening
- Carbide formers: Chromium, molybdenum, tungsten, niobium, tantalum, and titanium
- Oxide formers for the surface: chromium and aluminum (low vacancy content, restricting diffusion)
- **Some of these alloys can be utilized up to 0.9 Tm** (Melting point) and for times up to 100,000h at somewhat lower temperatures

Most of the nickel alloys contain 10-20% chromium, up to about 8% aluminum and titanium, 5-10% cobalt, and small amounts of boron, zirconium, and carbon.
Optimal common additions are molybdenum, tungsten, niobium, tantalum, and hafnium.

Matrix elements	Ni, Co, Fe
Solid solution strengtheners (Ni)	W, Mo, Co, Re, Cr, Fe, Mn, V
Gamma prime (γ') formers	Al, Ti, Nb, Ta
Grain boundary strengtheners	B, C, Zr, Hf, La
Surface protection	Al, Cr (but also Hf and Y)
Carbide formers	Ta, W, Cr, Hf

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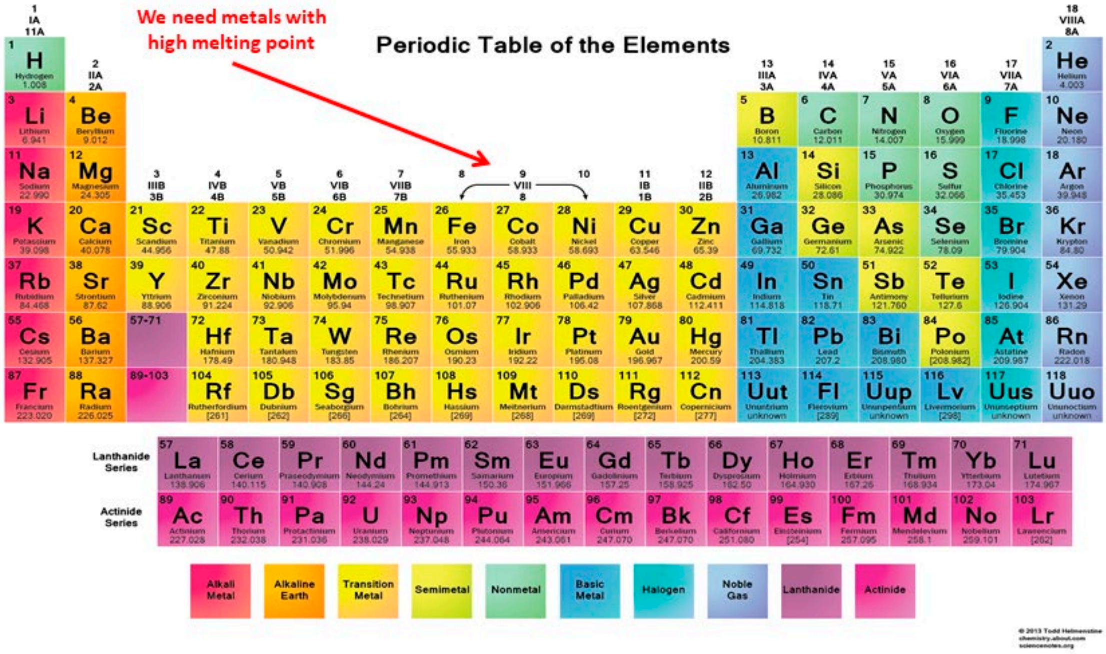
Periodic table of elements



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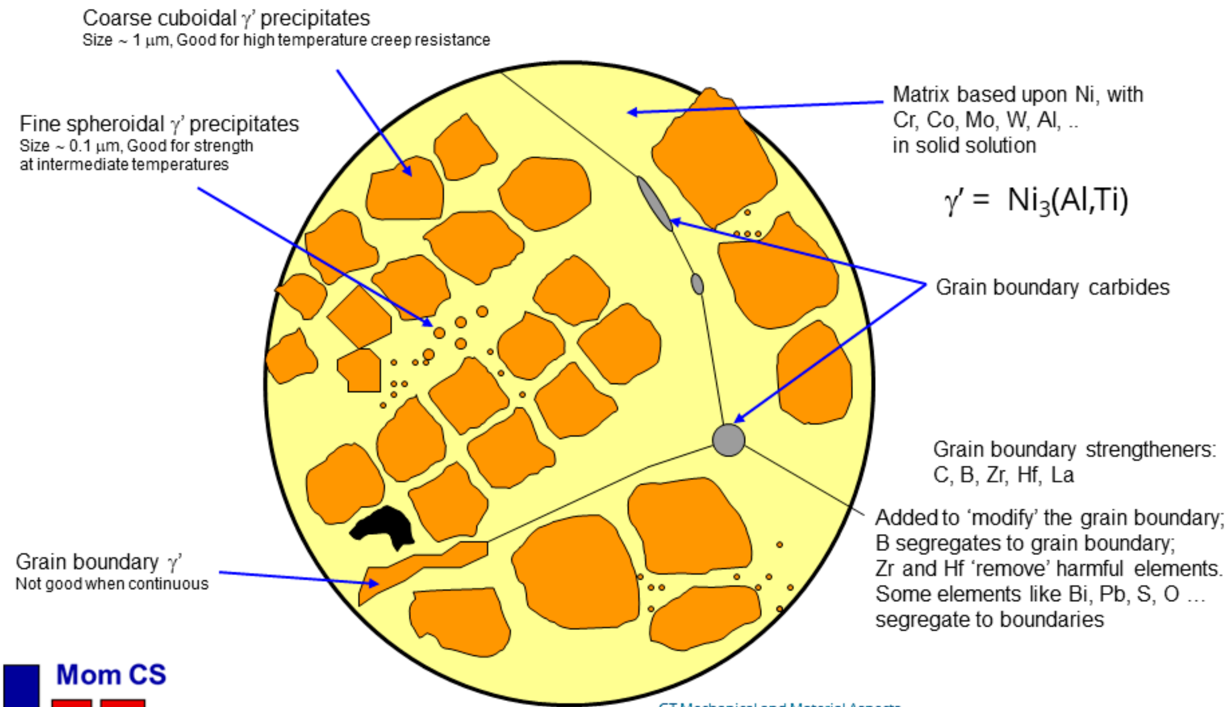
Microstructure of Nickel based superalloy



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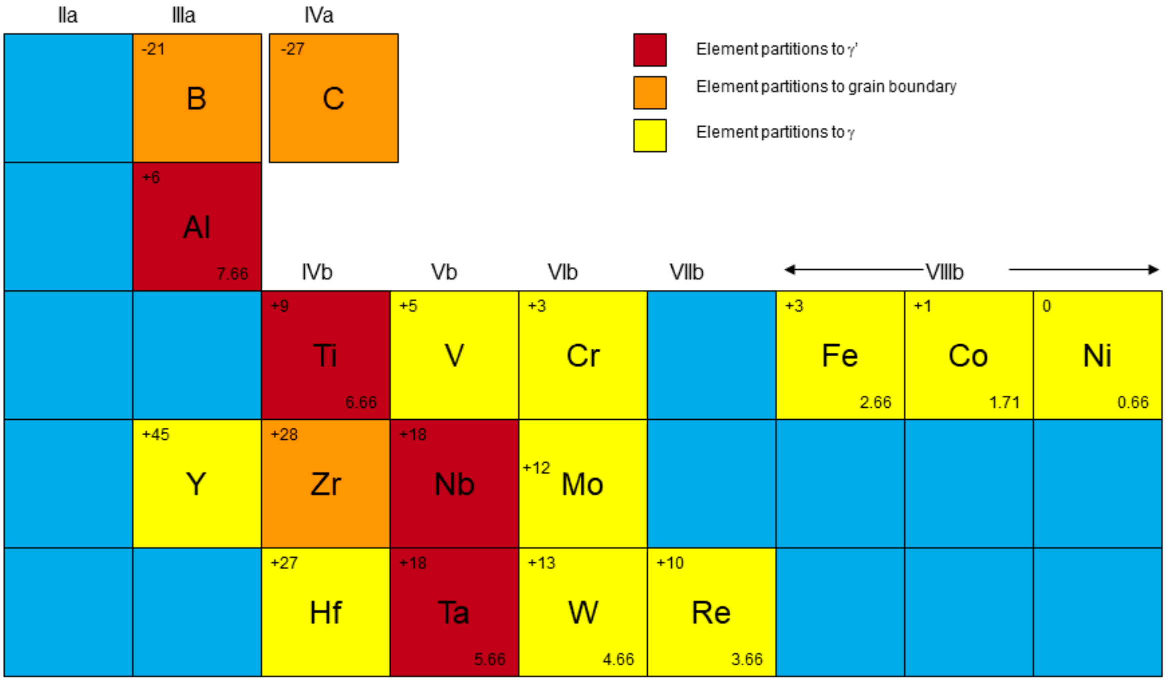
Superalloy – important elements



Source:
Superalloys II, High-temperature materials for aerospace and industrial power

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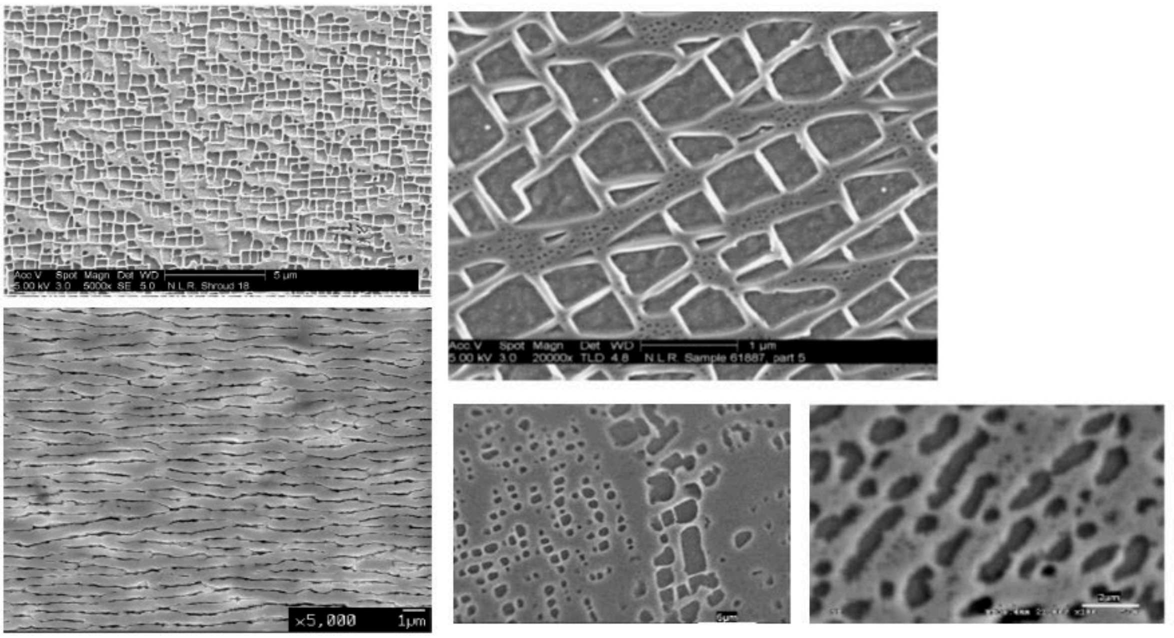
Microstructure from Ni-base alloys

cubes and spheres are γ' precipitates giving strength even at high temperatures



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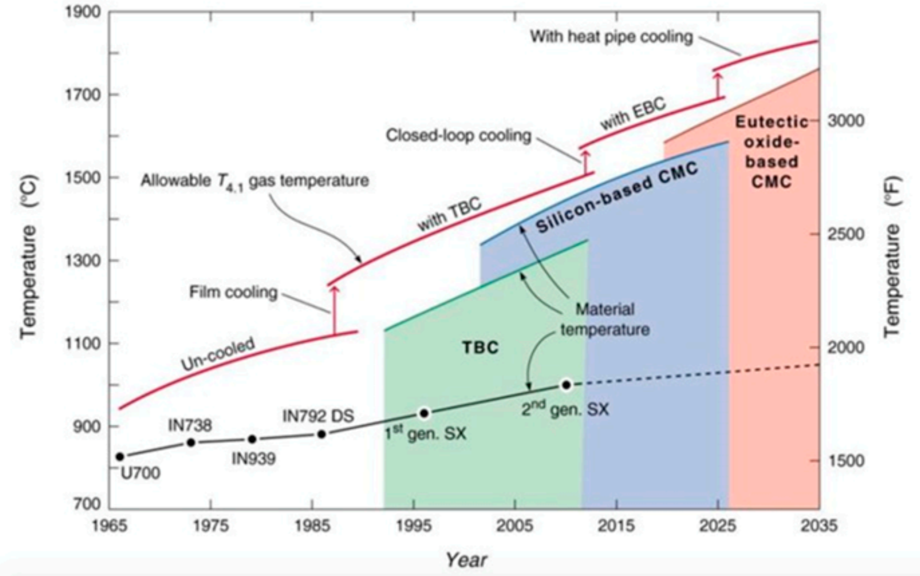
Materials in the turbine section
Rotating & Stationary



Evolution of materials, coatings and cooling system used in gas turbines and the capabilities of CMCs for the future (Alejandro Simó Vesperinas, August 2018)

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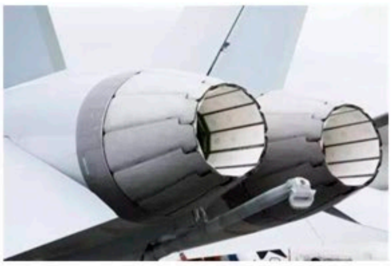
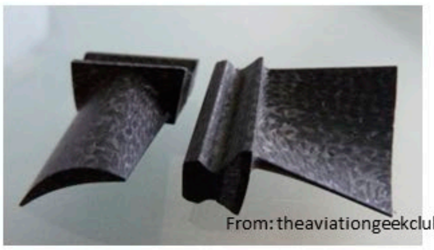
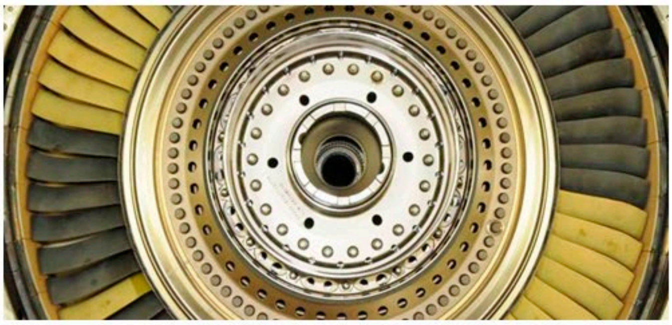
Examples of CMC parts





From: theaviationgeekclub.com



AltaSim Technologies

GE Aviation tested the world's first rotating ceramic matrix composite (CMC) parts in the low-pressure turbine of a F414 turbofan demonstrator engine

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Coatings

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Coatings – general applications

- Decorative
- Functional
- Both

Examples

- Decoration / Aesthetic
- Printability, gloss (papier)
- Conductivity
- Fire resistance
- Barrier for substances (oil, fat)
- Waterproofing

- Cleaning properties (graffiti)
- Wettability
- Antifouling
- Optical
- Shock absorbing
- Chemical resistant

- Adhesion
- Non-stick coatings
- Corrosion/oxidation resistance
- Wear resistance
- Thermal barriers

For Gas Turbines

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Types of coatings in gas turbines (1)

Do we need coatings? – Where?

- Compressor section: to withstand:
  - Aqueous corrosion
  - Erosion (incoming particles)
  - Wear (of tips against shrouds)
- Combustor section:
  - Oxidation resistance
  - Thermal barrier function
- Turbine section:
  - Oxidation resistance
  - Hot corrosion resistance
  - Thermal barrier function
  - Wear resistance
- Other sections (shafts/bearings/..):
  - Wear resistance
  - Lubrication

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Oxidation and Hot Corrosion

- Oxidation
  - Oxidation of base metal under the presence of oxygen (air)
  - Relatively slow process
  - Oxidation rate increases with temperature
  - To prevent oxidation: we need a dense oxide layer with good adherence and low diffusion characteristics (especially Al and further Cr)
- Hot Corrosion
  - Attack of the base metal (accelerated oxidation including sulfidation) under the influence of hot molten salts (alkali sulphates)
  - A good/dense and closed oxide layer is not formed
  - Process is extremely fast
  - Process is supported by presence of S in fuel or S in air (SO2)
  - Process is seriously aggravated by presence of Na, K and V in fuel (crude oil)
  - Temperature at which Hot Corrosion occurs is lower than T at which oxidation occurs (700 – 900C)
  - To prevent hot corrosion: clean fuels, clean air, higher Co and Cr content in coating

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Types of coatings in gas turbines (2)
Do we need coatings? – Why?

- We need coatings,
  - otherwise insufficient life
  - risk for failure (Starfighter, Breguet Atlantic, Lockheed P3 Orion)
- We need coatings for
  - Lowering metal temperature and temperature variations
  - Increasing turbine inlet temperature, and hence efficiency/power
- However:
  - For each location in the gas turbine we need specific coatings (location and T)
  - Different coatings for specific function:
    - Oxidation / Corrosion / Wear, Thermal barrier
- Coatings should allow for repair at overhaul !

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Types of coatings in gas turbines (3)
Do we need coatings? – Approach in past and presence

- Original approach:
  - Base material itself was able to withstand mechanical/ thermal loads
  - Coatings were needed because the base material could not withstand corrosion, oxidation and wear; so to improve life
- New approach:
  - Coatings are an integral part of design, and have specific functions, e.g.:
    - Thermal barrier will substantially lower the substrate temperature: **only because of the coating the substrate can do its work**
    - Coatings for counteracting rub and wear; better clearance control

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New approach: Coatings are an integral part of design
Example: Thermal Barrier Coatings

Turbine Inlet Temperature of current, modern gas turbines is much higher than melting point of alloys used for turbine components!

How is that possible?

1. Component is internally cooled by relatively low T cooling air
2. Component is externally cooled by thin film cooling layer
   - But T of outer part of component will still be close to gas temperature
3. Apply a ceramic layer on top of component to reduce metal temperature
   - This type of solution will only work if component is cooled !
4. Temperature difference over coating might be more than 100 C !

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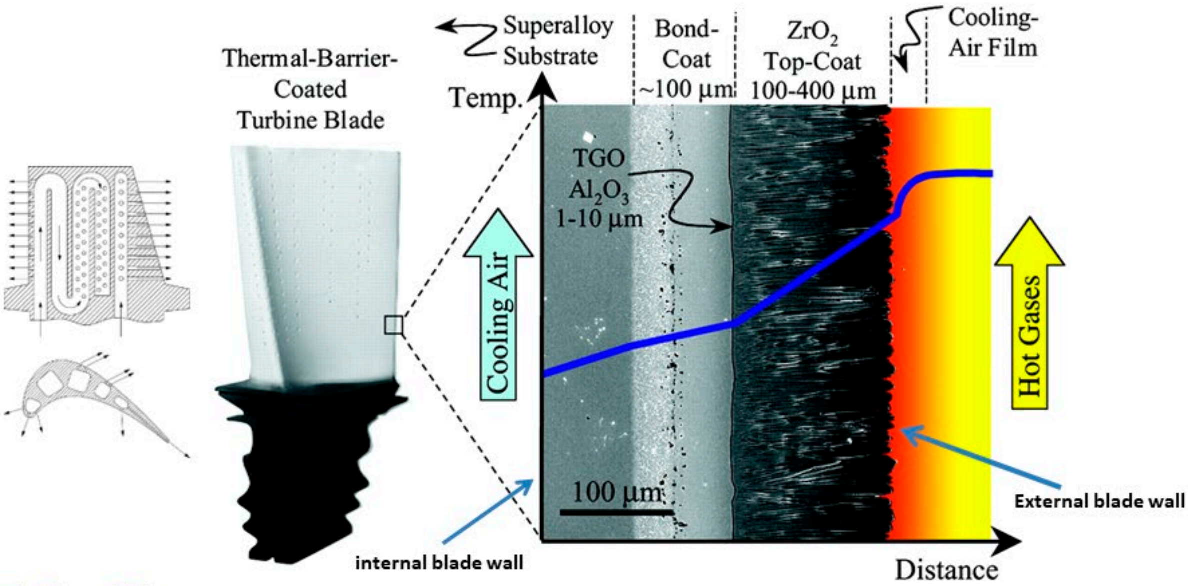
Thermal Barrier Coatings

High temperature gradient over thermal barrier coating allows for safe operation of component



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Types of coating application processes In general (1)

- Hot dip plating (e.g. hot dip galvanizing (Zn) of steel (guardrails), also e.g. Sn, Al
- Electroplating – in electrolyte (Zn, Cr, Sn, etc)
- Chemical (electroless) plating - reduction in electrolyte; e.g. Cu on steel
- Slurry spraying of paint (thermal treatment required)
- Electrophoresis of paint (movement of electrically loaded particles in an external electrical field); used e.g. for paints; requires additional heat treatment
- Barrel plating (in rotating barrel with coating powder)
- Hardfacing (e.g. WC; can be done by welding or metal spraying)

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Types of coating application processes - general (2)

- Metal * (thermal) spraying
  - Flame spraying
  - Wire arc spraying
  - Plasma spraying
  - Detonation gun spraying
  - High velocity oxy-fuel (HVOF) or air fuel (HVAF) application
- Plating by rolling/explosive plating
- CVD (chemical vapour deposition)
- PVD (physical vapour deposition)
- Ion implantation

- * Instead of metals also ceramic material can be sprayed

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Some types of lower temperature coatings

Examples

- Steel components in stationary turbines can be coated with a
  - Al diffusion coating, to prevent corrosion
  - Al type paint, which is heat treated, to prevent corrosion
- Titanium alloy components can be nitrided, to improve wear resistance
- Tips of rotor blades can be coated with WC to improve wear resistance

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Principal types of high temperature coatings *for gas turbines*

- Diffusion coatings
  - Metal is applied on surface, followed by diffusion of metal into substrate
  - Mostly done with Al and Cr to improve oxidation/corrosion resistance
- Overlay (metallic) coatings
  - Metal is applied on surface, no or few diffusion into substrate
  - All kind of compositions possible; done for corrosion/oxidation improvement
- Overlay (ceramic) coatings
  - Ceramic layer is applied on substrate, no diffusion into substrate
  - Done because of thermal barrier behaviour of ceramic material

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Diffusion coatings

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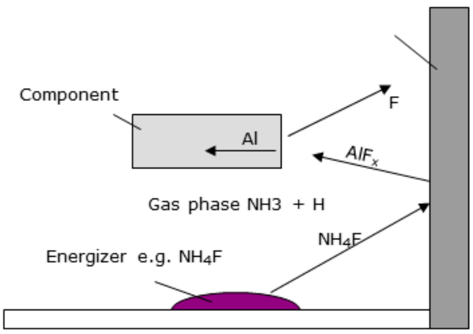
Diffusion coatings (1)

The Process (CVD type process)

- Coating Metal (Al) + Halide vapour (HCl) → Metal-halide ($AlCl_x$) vapour
- Metal-halide ($AlCl_x$) + Substrate (Ni) → Coating (NiAl) + Halide vapour (HCl)

CVD Processes

- Pack cementation
- Out-of-pack (above-the-pack)
- Total gas phase CVD - process



Consumables

- Energizer: NH_4F or HCl (a halide gas)
- Donor: Al-containing material (e.g. NiAl)
- Atmosphere: inert (Argon)

Variables for CVD

- T ⇒ 1080 - 1100 °C
- t ⇒ 4 - 12 h

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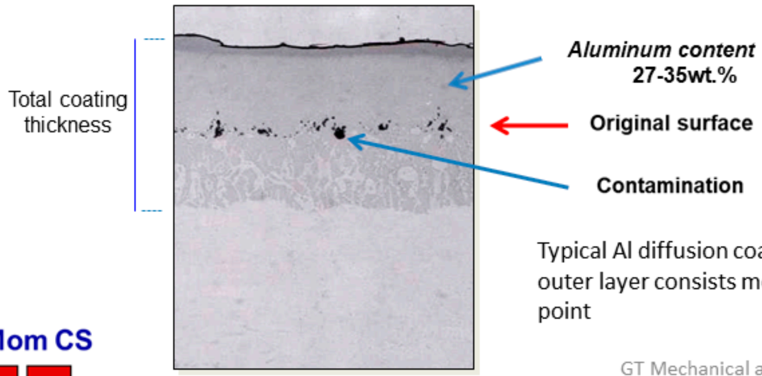
Diffusion coatings (2)

- Components are brought in a coating chamber, containing gases
- Al is present in the gas phase in the coating chamber (e.g. AlF_x); high T
- AlF_x reacts with the substrate, decomposes, and Al diffuses inward
- Al diffuses inward; substrate element Ni diffuses outward
- The balance of diffusion process is dependent on temperature of application:
  - Low T: Al diffuses inwardly ; at higher T Ni diffuses outwardly
- Coating thickness is limited by diffusion process (normally 50 µm)
- Typical type coatings: Al (aluminizing), B (boronizing), Cr (chromizing); Si (siliciding)



Typical Al diffusion coating, outward type; outer layer consists mostly of NiAl with high melting point

Diffusion coatings (3)

- CVD: Generic term for a family of processes used for the deposition of coatings out of the gaseous state (so this includes Pack Cementation and Above the pack processes)
- These relatively simple aluminide diffusion coating can be modified
  - add Cr for better hot corrosion resistance
  - Pt plating beforehand improves oxidation resistance (better Al_2O_3 adherence) and less inward diffusion of Al

Disadvantages:

- A zone 'under the coating' is negatively affected
- When a coating is removed (repair), part of substrate is also removed!
- Diffusion coatings are based on intermetallic phases:
  - Brittle at low temperature

Internal coating of cooling passages requires CVD type of application process

Damages related to manufacturing and coating

Many KLM engine failures CF6-50, Boeing 747
End 70's – beginning 80's

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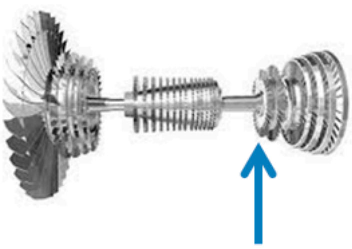
Damages related to manufacturing and coating

KLM experienced many engine failures CF6-50, Boeing 747, 1970's–80's.

After take-off one of engines failed; aircraft had to return, dump excess fuel in North Sea and land at Schiphol again.

Costs 1 – 2 M€ each time.



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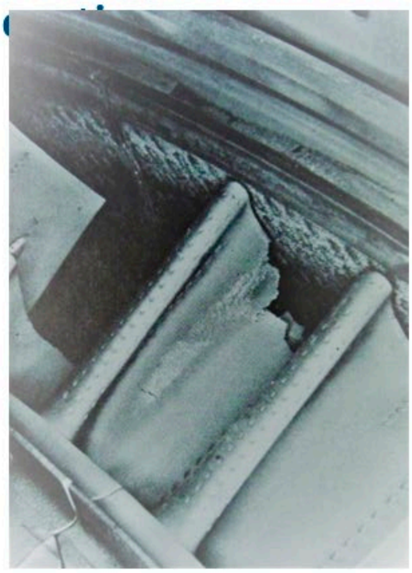
Damages related to manufacturing and coating



Broken and damaged 1st stage turbine blades in civil aircraft engine

Detail of crack formation in leading edge of 1st stage turbine blade

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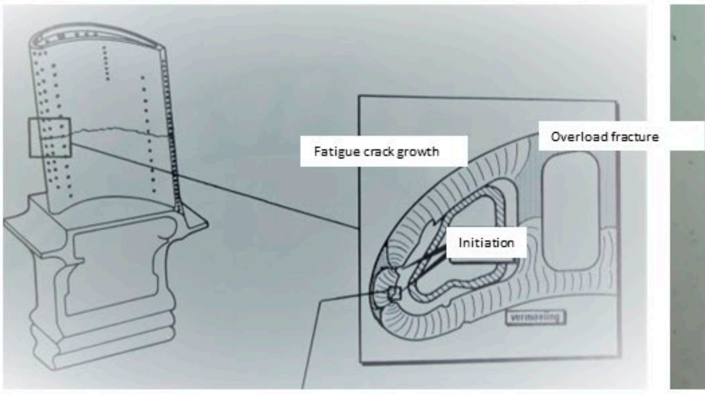
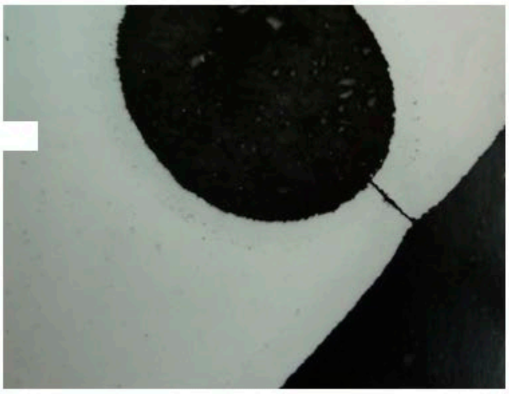
Damages related to manufacturing and coating



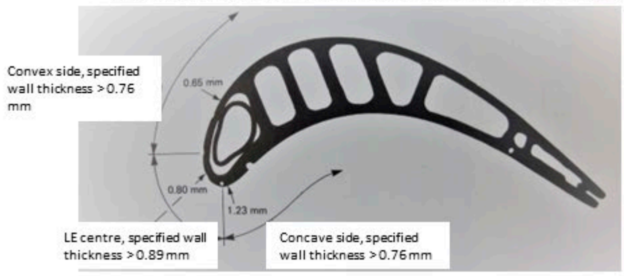
Crack initiation, fatigue crack growth and overload fracture



Crack initiation at location where film cooling hole intersects blade wall

Cracking occurred in:

- Repaired blades
- Fatigue cracks started at leading edge, at cooling holes intersecting the surface
- OEM: had instructed system for blade cooling measurements; also total set flow requirements
- Nevertheless still failures



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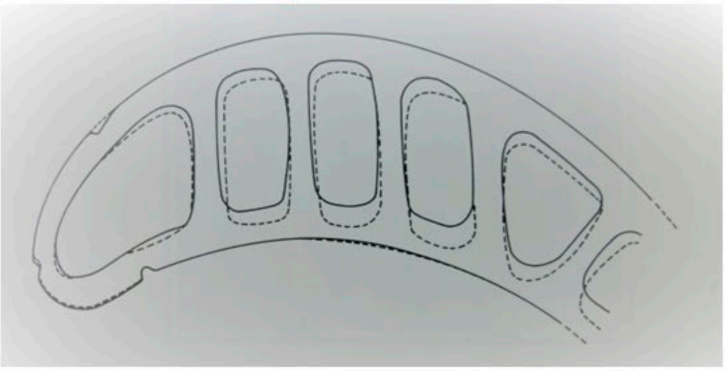
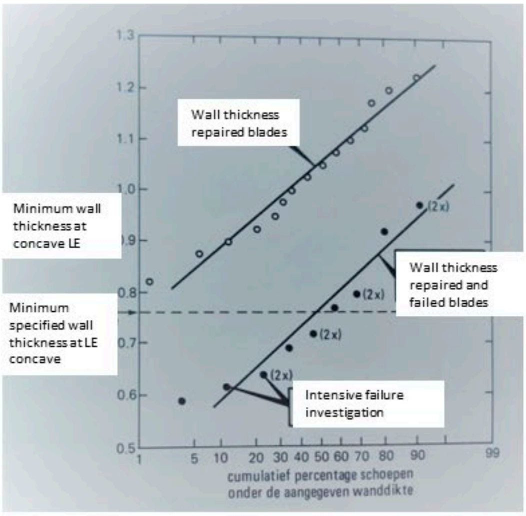
Damages related to manufacturing and coating



Shift in location of internal cooling circuit for 2 different blades



Probability curves wall thickness for repaired blades

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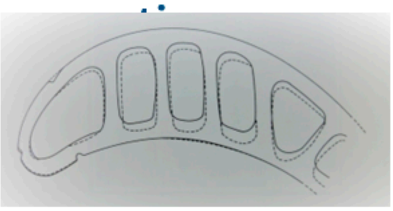
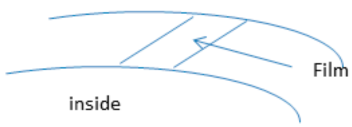
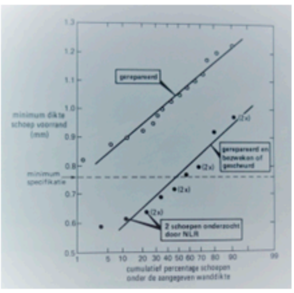
Damages related to manufacturing and coating







Causes for failure: a combination of 3 different mechanisms:

- Core shift during casting process
- Repair leads to additional wall thickness decrease; below spec
- Coating removal leads to widening up cooling holes and changing film cooling hole exit geometry
- Cooling flow in blades will therefore (theoretically) increase
- However: total cooling flow restricted, resulting in lower internal pressure

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Overlay Coatings

Overlay coatings (1)

Application via:

- Physical Vapor Deposition (PVD)
- Thermal spraying

Types:

- Metallic coatings (often of MCrAlY type) M = Ni, Co or both
- Ceramic coatings (often of ZrO_2-Y_2O_3 type)

Difference with respect to diffusion coating

- Nearly no interdiffusion of coating layer and substrate
- The structure/composition of the substrate is relatively unaffected
- The chemical composition of the coating layer can be designed for optimal performance: structure and composition is produced in-situ
- Often much higher thicknesses (e.g. >100 µm)
- Nearly any composition of coating can be applied, also ceramic coatings!

Overlay coatings - application process (1)

Physical Vapour Deposition PVD (1)

1. Process is carried out in vacuum or inert gas
2. Coating metal is evaporated from a source
3. Metal vapour transport to substrate: line of sight process
4. Deposition of metal vapour onto substrate
5. So: transport of metal vapour takes place without the need for a carrier gas, as with CVD

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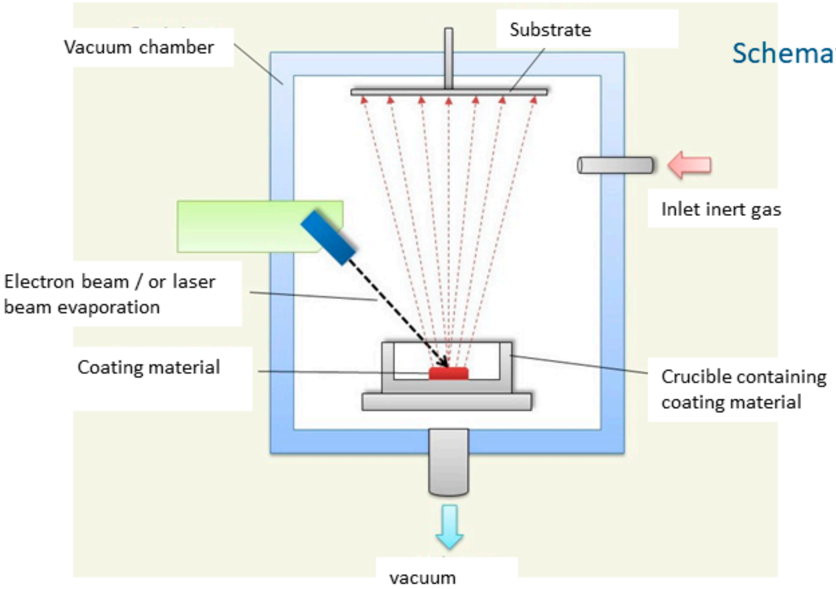
Overlay coatings - application (2)

Physical Vapour Deposition PVD (2)



Schematic of process

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Overlay coatings - application (3)

Physical Vapour Deposition PVD (3)

Coating vapours are being produced by:

- Evaporation: heating of source by:
  - Resistance heating
  - radiation
  - eddy current
  - electron beam
  - laser beam
  - arc discharge
- Sputtering
  - material is removed from the source by energetic particles bombardment (by Argon ions)

Coating formation itself can be supported by:

- Ion (assisted) plating: Coating is densified by the simultaneous bombardment of the substrate surface by ions. An electric arc between source and substrate will ionize inert Argon: these positive Argon-ions bombard the negatively loaded substrate.
- Coating composition can be varied by using sources with different source metals

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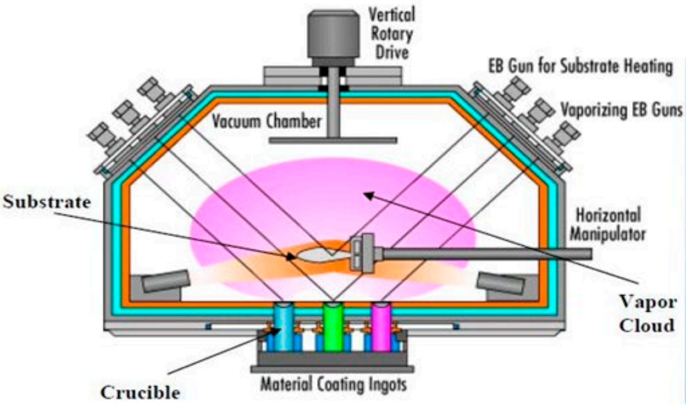
Overlay coatings - application (4)

Physical Vapour Deposition PVD (4)

EB-PVD coatings

Electron beam – physical vapour deposition



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Overlay coatings - application (5)

Thermal Spray Processes (1)

- Thermal spraying techniques: the melted coating materials are sprayed onto a surface using a spray torch/gun
- The "feedstock" (coating material) is heated by:
  - electrical means (plasma or arc), or
  - chemical means (combustion flame)
- Line of sight process
- High coating rates
- Wide compositional variation
- Cheap

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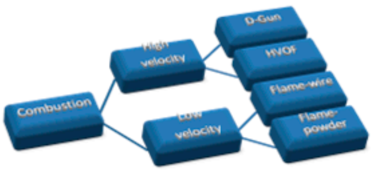
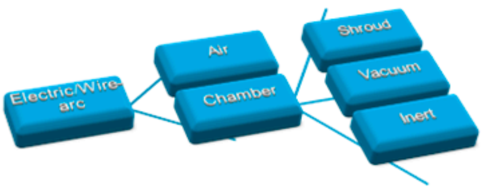
Overlay coatings - application (6)

Thermal Spray Processes (2)

- Combustion
  - High Velocity
    - D-Gun
    - HVOF
  - Low velocity
    - Flame wire
    - Flame powder
- Electric Wire/Arc
  - Air
  - Chamber
- Plasma
  - APS
  - VPS





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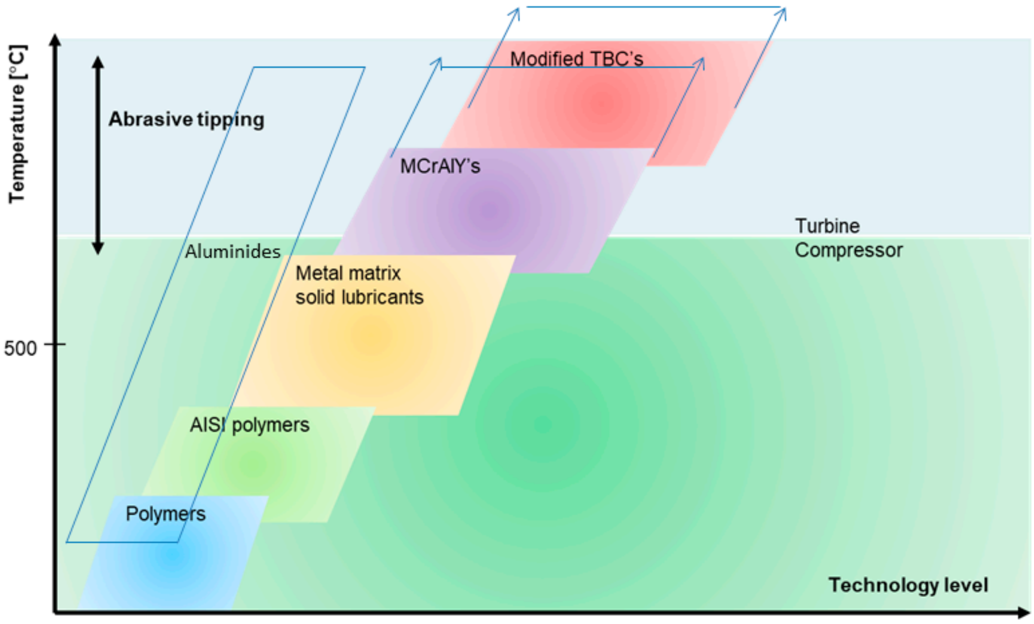
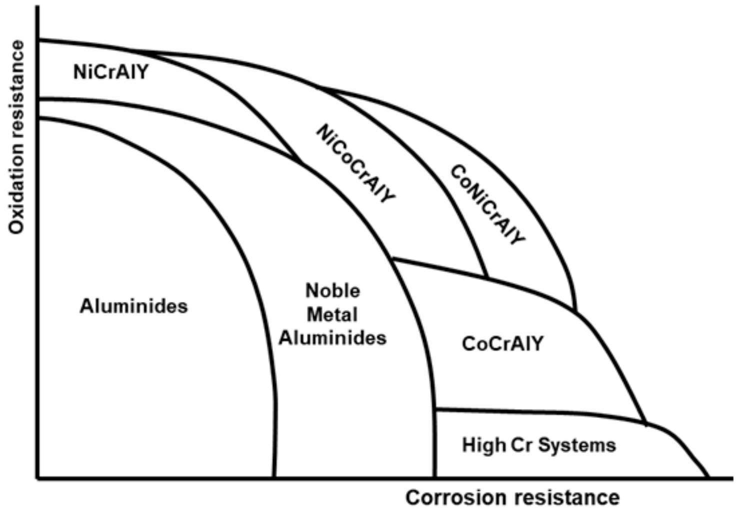
General characteristics major coating methods

	Plating	Thermal Spray	CVD	PVD
Equipment costs	low	low to moderate	moderate	moderate to high
Operating costs	low	low to moderate	low to moderate	moderate to high
Process environment	aqueous solution	atmospheric to soft vacuum	atmospheric to medium vacuum	hard vacuum/inert gas
Coating geometry	omnidirectional	line-of-sight	omnidirectional	line-of-sight
Coating thickness	moderate to thick, 10 µm - mm	thick, 50 µm - 0.5cm	Thin to thick, 0.1 µm – 100 µm	Very thin to moderate, 0,1 - 400 µm
Substrate temperature	low	Low to moderate	moderate to high	low
Adherence	moderate mechanical bond to very good chemical bond	good mechanical bond	very good chemical bond to excellent diffusion bond	moderate mechanical bond to good chemical bond
Surface finish	moderate coarse to glossy	coarse to smooth	smooth to glossy	smooth to high gloss
Coating materials	metals	powder/wire, polymers, metals/ceramics	metals	metals, ceramics, polymers

Overview of coatings (2)



Overview of coatings (3)



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In Summary Lecture Coatings

- Protective coatings are required in modern gas turbines
- Protective coatings allow for the achievement of a realistic TBO
- Protective coatings allow for subsequent repair after reaching the TBO
- Overhaul and repair (OHR) are often not considered in OEM design and manufacture
- Factors to be considered in coating selection/evaluation:
  - Effect on TBO
  - Effect on subsequent repair
  - Effect on heat treatment sequencing
  - Substrate affects performance of coating
  - Coating consumes substrate: affects dimensional features of component, and hence loading
  - Affects subsequent aerodynamic performance (after repair)

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Literature

Overview

Protective coatings – purpose, role, and design

G. W. Goward

A wide range of coatings and coating processes is now available for protecting components in gas turbines operating in a variety of conditions. Coated aerofoils are less likely to fragment, and they keep their original shape – and hence their aerodynamic efficiency – for longer. Aluminide diffusion coatings perform well in relatively clean environments, especially on alloy bases which have a moderate resistance to the many forms of hot corrosion, and with additions of chromium or platinum they provide resistance to sulphate-induced hot corrosion. In hotter or more aggressive corrosive environments, overlay coatings based on MCrAlY (M = Fe, Co, Ni), CoCr, and MCrSi(Al), applied by electron beam evaporation or plasma spraying, are suitable for a wide variety of applications. It is not yet possible to design coatings from first principles for particular applications. Development still proceeds by repeated selection and testing, but modern technology has made this approach more effective than it was in the 1960s. The future is likely to see the rate of progress slow down; advances are expected to take the form of more efficient and flexible processes rather than a broadening of the range of applications. MST/280

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NLR operates as an objective and independent research centre, working with its partners towards a better world tomorrow. As part of that, NLR offers innovative solutions and technical expertise, creating a strong competitive position for the commercial sector.

For over 100 years, NLR has been an ambitious applied research organisation, driven to keep innovating for the benefit of making aerospace more sustainable, safer, efficient and effective. Objectively and independently, we are now laying the foundation for a future meaningful, societal impact.

In a rapidly changing world, mobility and stability needs are constantly evolving. Aware of the social urgency, NLR helps pave the way for promising concepts to quickly see the light of day and transform into disruptive solutions or incremental improvements. We do this by combining a deep understanding of customer needs, multidisciplinary expertise and the use of our leading research facilities. In doing so, NLR plays a pivotal role between science, industry and government at home and abroad, bridging the gap between fundamental research and practical applications.

NLR is taking a leading role to achieve Dutch and European objectives. Together with our partners, we are working hard on a resilient and sustainable mobility system, and we support Dutch Defence in all military domains, with space and cyberspace playing an increasingly prominent role. From its headquarters in Amsterdam and Marknesse and our two satellite sites and in this way, NLR contributes to a safer and more sustainable society, strengthening the competitive position of Dutch industry.

For more information visit: **www.nlr.org**

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