Next Engine Generation: Materials, Surface Technology, Manufacturing Processes

What comes after 2000?

Dr. Klaus Steffens / Dr. Hans Wilhelm

MTU Aero Engines
Dachauer Str. 665, 80995 München

1. Introduction

Modern aero-engines have to fulfil extreme requirements concerning reliability, minimum weight, high performance, economy and long durability. During the past 40 years especially commercial engines fulfilled these requirements completely and have achieved a high degree of functional perfection. At the same time noise and pollutant emissions were markedly reduced.

As compared to car- engines fuel consumption of modern aero engines (per passenger–mile) is distinctly lower. Reliability was improved by a factor of 10 since the first generation of commercial turbo-jets. Today's third generation turbojets (PW 4000, Trent, GE 90) are characterised by less than 3 inflight shut downs per million flight hours. Therefore since about 20 years twin-jets are certified for long - distance transocean flights.

Big progress was also made in extending inspection and maintenance intervals. For modern turbofans TBO (Time Between Overhaul) is usually between 10.000 and over 20.000 flight hours depending on the individual flight missions.

Milestones for achieving this progress have been

- designing two- or three-shaft engines with a bypass-ratio exceeding 5
- increasing the total pressure ratio to more than 40
- increasing combustion temperature to about 1850 K .

Based on today‘s knowledge further significant improvements towards enhancing both thermal efficiency and propulsion efficiency need the following major modifications in basic design :

- Increase of the bypass-ratio from actual about 8 to values between 12 and 15 , needing a slowly rotating fan being powered by a fast rotating transonic low pressure turbine with a gearbox in between.
- Recuperative heat exchangers for utilisation of the thermal energy of the exhaust gas.

The first measure may enter into service near the end of this decade, engines with recuperator heat exchangers will need even longer time. The current basic design, however, will dominate the next decade.

Today’s state of aero-engines was only possible due to considerable progress in **materials , manufacturing and surface technology** supporting and completing the improvements achieved in design, aero- and thermodynamics.

For example introduction of the titanium-alloys in the early 1960s enabled the design of large fan blades and of fast rotating HPC-rotors. Today’s turbine entry temperatures (exceeding the melting temperature of the blade materials) inevitably need airfoils cast in single crystal technology with sophisticated internal cooling systems , supported by coatings for enhanced oxidation resistance. Thermal barrier coatings on rotating airfoils are the latest innovation introduced so far.

Due to the mature design of the engines, competition between the engine manufacturers will be mainly in the field of cost. The OEMs are striving for new ways of reducing the cost of ownership and in parallel improve the engine performance. These goals may be achieved by improved design, better materials and optimised manufacturing processes. At present, new engines are being designed with focus on minimised manufacturing costs e.g. by reducing the number of components. This means challenging tasks for both materials and manufacturing technology .

2. Materials Technology

General :
Typical engine materials are characterised by high specific strength values and excellent reproducibility of mechanical properties. Any material must be approved by aviation authorities. Both materials manufacturers and forging companies need special approvals by aviation authorities and are subject to stringent controls.

2.1 Traditional Engine Materials

Today’s relevant materials are Ti-alloys, Ni-alloys (superalloys) and high strength steels, see Fig.1. Others play only a minor role. Steels are mainly applied for shafts and gear parts, to some extent also for compressor and turbine casings. They shall not be regarded here since they are similar or identical to the corresponding materials in machinery or automotive parts.

2.1.1 Titanium Alloys

Titanium alloys are typical for compressor parts. They are attractive due to their low specific weight, however, their temperature capability is limited, see Table 1.
Most technical relevant Ti-alloys are ($\alpha+\beta$) - alloys containing both α-stabilisers like Al enhancing the ß-transus and ß-stabilisers like Mo, V decreasing the ß-transus temperature. Forging, especially finish forging is carried out below ß-transus for generating a fine grained bimodal ($\alpha+\beta$) - microstructure with an optimum balance of static and dynamic strength properties.
Until today Ti 6Al 4V (Ti64) is still the most employed of all Ti-alloys both for engine and air-frame applications. Ti64 is characterised by an optimum combination of properties: Uncritical in processing, high strength at low temperatures, excellent machinability and good weldability. Ti64 is available as forging, sheet and since about 1975 as investment casting for stator components e.g. compressor casings.
Ti 6242 and Ti 6246 have higher strength and temperature capabilities. At present the most advanced Ti-alloy for disk applications (up to 550^0 C) is IMI 834. Above 450^0 C this alloy is superior to any other Ti-alloy. Its price, however, is about twice the price of Ti64 with respect to its complex metallurgy and the thermomechanical processing parameters needed for optimum microstructure and mechanical properties.

2. 1. 2 Nickel Base Alloys (Superalloys)

Nickel base alloys (Superalloys) are the typical materials for the hot parts of the engine, starting with the rear stages of the HPC being too hot for Ti-alloys.
For combustors special sheet alloys (e.g. Hastelloy X , C263) have been developed with relative low strength, high oxidation resistance, good formability and suitable weldability.
For turbine applications there are basically two groups of superalloys, one for wrought disks and rings and the other one for cast blades and vanes. Both owe their elevated temperature properties to two different strengthening mechanisms :

- Solid solution strengthening by cobalt, chromium and refractory metals such tungsten and molybdenum.
- Precipitation hardening by the intermetallic γ '- phase $Ni_3(Al,Ti)$ or γ''-phase Ni_3Nb. Therefore the most heat resistant superalloys contain up to 10 weight-% (Al+Ti) or some % Nb.

Superalloys for disk applications are tailored for high static and dynamic strength properties at temperatures below 750 ^{0}C. Special emphasis is laid on optimum low-cycle fatigue (LCF)-properties being most important for disk design.
Table 2 shows some of the most important Ni-alloys for disks and rotating rings. The most widespread alloy is IN 718. It covers a wide range of applications both in the rear section of the HP-compressor and in the turbine.
Waspaloy has a higher temperature capability as compared to IN 718. Waspaloy , however , is very critical concerning metallurgical behaviour. It is difficult to achieve a uniform fine grained structure in forging. Therefore both machining and welding of Waspaloy is critical.
For many years disk alloys with higher temperature properties than Waspaloy could be manufactured only via powder metallurgy, e.g. Udimet 700, Rene 95 or IN 100. Some of them have very high strength even at high temperatures, however, fracture mechanical properties are critical. Since about one decade it is possible to produce similar alloys like Gatorized Waspaloy or Udimet 720 LI (LI = low interstitial) via the conventional route „casting plus forging„ in a quality level being sufficient for disk applications. This progress was possible by higher purity ingot material with better homogeneity and reduced segregations achieved by optimised melting parameters and by thermomechanical treatment. From today's point of view Udimet 720 LI is the most advanced alloy for disks that can be processed by non-PM technique. Its maximum service temperature is near 730^0 C. Compared to IN 718 the alloy Udimet 720 LI has a temperature capability of +80^0 C, however, the price of the billet material is much higher. At this moment no alloy with higher temperature capability than U720 LI is available at a price being acceptable for commercial engines.

In today's engines all blades and vanes in the **turbine** are **cast** (and **not forged**) for getting optimum creep, stress rupture and thermomechanical properties, since the airfoils are exposed to very high gas temperatures. Many alloys, depending on the individual service temperatures of different components, have been developed within the last decades. Some important ones are shown in Table 3. The Alloy IN 713 is still in service although it is a very old one. Today the main applications of IN 713 are blades and vanes in the rear stages of the LP-turbine where temperature is relative low. Castings from IN 713 have a polycrystalline, equiaxed microstructure.
IN100 has a higher temperature potential (+ 30^0 C vs. IN713) and is characterised by a low density (ρ = 7,75 g /cm^3). This alloy was among the first ones to be available not only with polycrystal structure, but also in DS (directionally solidified) and SX (single crystal) version. The basic idea of DS is to eliminate the grain boundaries orthogonal to the direction of centrifugal forces, since they have a negative influence creep. Single crystal (SX) structures have no grain boundaries at all. Therefore they have optimum creep properties. Both DS - and SX - structures are generated by special solidification techniques during casting. As shown in Table 3 today's advanced SX-alloys like PWA 1484 or CMSX 10 have a potential in service temperature versus IN 100 of about +100^0 C. This benefit, however, is achieved by a high density ($\rho \approx$ 9,0) and a high price of the component.

It is evident that the traditional materials for aero-engines, both Ti-alloys and superalloys, have achieved a high degree of perfection within the last decades.
Their potential for future improvement is limited. Any further progress is associated to a high increase of cost. Therefore time is ripe to look for new materials and /or structures with a potential for performance improvement at reasonable costs.
In Fig.2 specific strength (i.e. UTS / ρ) is plotted against temperature for the traditional materials like Ti-alloys and superalloys and also for other advanced materials, mainly composites and intermetallic phases. It is obvious that these new materials look promising concerning their temperature and strength potential. Fig.3 gives an impression on potential applications of these new materials.

2. 2 Advanced Materials / Structures

There are two promising groups of advanced materials for future generations of engines: Fibre reinforced composites and monolithic intermetallic materials. Advanced composites are either with polymer- , metal- or ceramic matrix. Among the intermetallic materials the TiAl- type looks favourable.
ODS-superalloys (oxide dispersion strengthened) will not play a major role in the next decade.
It shall not be concealed that among the engine manufacturers (and even inside the companies) there are some differences in judgement of the potential of these advanced materials. Even for those new materials which will come, it is not quite clear at which exact time they will be ripe for entry into service, and to which extent they will replace the traditional materials. It is evident, however, that even in the future the conventional cast or wrought Ti- and Ni-alloys will still be the dominating materials.

2. 2.1 Polymer Matrix Composites (PMC)

PMCs are attractive due to their low weight, high strength and low costs for complex shaped components, see Fig. 4. Service temperature, however, should not exceed 150^0 C, advanced materials go up to 200^0 C.
Common fibre materials are carbon, glass or aramid ($\varnothing \approx 8 \div 15\ \mu$m), the matrix is from epoxy-resin.
The traditional method to make PMC-parts is as follows: Lay up or stack multiple plies of preimpregnated fabrics (prepregs) in moulds then cure the sealed mould assembly in an autoclave. This process is time consuming and labour-intensive i.e. relative expensive.
Since about 1975 PMCs are used in jet-engines starting with simple panels in the fan and bypass duct. During the 80s the number of PMC-parts increased gradually, mainly for spacer rings, acoustic liners, bleed nozzles, LPC inner shrouds and nose cones. Today the fan exit guide vanes of the CF6 - 80 and CFM 56 are PMC-parts. Since they are sensitive to particles erosion, the leading edges are protected by sheet metal strips or other methods.
Due to improved quality of the fibres, today three-dimensional preforms (**not** pre-impregnated, cheap) can be made by stitch bonding. A new process for making high quality PMC-components is RTM (RTM = resin transfer moulding), comprising the following steps: Cut fibre, form fibre preform by stitch bonding, close mould, inject resin, cure part.
A milestone in PMC-technology was set by series production of the fan blades for the GE 90 engine with an airfoil length of about 1000 mm.
It’s assumed that in future the number of PMC parts will further increase for both cost and weight reduction. Special interest is on PMCs with higher temperature capability.

2. 2. 2 Metal Matrix Composites (MMC)

High strength Ti-based MMCs offer a potential for weight reduction of up to 50 % relative to conventional Ti-alloys by using high strength, high modulus fibres as continuous reinforcement. The route for making Ti-MMC disks or rings comprises the following main steps:

- fibres (usually SiC, ∅ ≈ 0.1 mm) are coated with a carbon layer to prevent extensive reactions between fibre and matrix during processing (HIP)
- fibres are coated with Ti-alloy using plasma or PVD- techniques
- wind coated fibres around mandrel.
- Consolidate fibre ring by HIP
- Insert fibre reinforced ring into a disk or ring and join together by HIP.

This method looks promising for making so-called blings (bladed rings) that offer distinct benefits concerning weight and rotor dynamics versus conventional disks and even versus today's blisks (integral bladed rotors), see Fig. 5.

In the USA blings (dia ≈ 400 mm) and other MMC-parts like shafts, fan blades and vanes have been successfully tested in demonstrator engines in the IPHTET-program. An connecting rod for actuating the exhaust-flaps of the F 414 recently went into series production.

At MTU cyclic spinning tests with Ti-MMC rings are in operation and look promising.

It is evident that Ti-MMC technology is sophisticated. Since the possibilities of non destructive testing methods (NDT) for detecting internal defects in composites are limited, the quality of the parts must be assured mainly by an optimised process stability of each step and by strict process control. With respect to the long chain of process steps such parts cannot be cheap. A realistic cost estimation shows that under series conditions the price for a Ti-MMC-bling could be about twice of a "normal " blisk machined from a conventional forged pancake.

For this reason potential applications in forseeable future will be mainly in military engines.

2. 2. 3 Ceramic Matrix Composites (CMC)

Ceramic materials are attractive for aero-engines due to their high temperature strength and low density ($\rho \approx 1{,}5 - 3{,}0$ g /cm^3). The low ductility, however, proved to be a severe obstacle for engine-applications of monolithic ceramics. This refers to SiC, Al_2O_3 and Si_3N_4 grades. Therefore the focus of interest is now on fibre reinforced ceramic matrix composites (CMC). Fibre materials are mainly SiC, carbon and Al_2O_3. Matrix materials are usually either SiC, Al_2O_3 or mixtures ($Al_2O_3 + SiO_2$).

Exposing today's CMCs to more than 1000^0 C for several hundred hours may result in two kinds of problems, depending on stress and fibre material:

Oxide fibres like Al_2O_3 are thermodynamic stable, but their creep properties are not optimum. On the other hand non-oxide fibres like SiC have suitable creep–properties, however, chemical reactions of the fibre with the matrix material may happen (despite of protective coatings on the fibres) being harmful to the properties. Therefore there is some doubt about the potential of CMCs for temperatures above 1000^0 C . On the other hand, monolithic ceramics don't have these problems. Their handicap is a lack of ductility and fracture toughness.

There are only few applications for CMCs in near future. Potential applications could be stator parts of the LPT (e.g. exhaust cones, flaps etc.) but not in the HPT. At present only one series application of a CMC–part has been published: The exhaust flaps of the SNECMA M 88 engine.

Due to their excellent high temperature strength properties in case of short-term exposure, however, CMCs are most attractive for engines of space-rockets.

2. 2. 4 Intermetallics (TiAl)

Since some years there is growing interest in intermetallic materials like TiAl or Ti_3Al with respect to their low density and their enhanced temperature capability (in relation to conventional Ti-alloys). Their main drawback is brittleness especially at low temperatures. By minor modifications of the chemical composition and optimisation of the processing parameters ductility of TiAl could be improved up to 1.5 ÷2 % elongation at room temperature and about 3.5% at 750^0 C. So the ductility is approaching the requirements of “normal“ engineering materials. TiAl parts are usually made by investment casting. Typical series applications could be airfoils for the rear LPT- stages (see Fig. 6) or HPC-casings being too hot for conventional titanium. The weight benefit (compared to cast Ni-alloys) is attractive and the (weight related) strength values are not bad.
In the USA TiAl-blades and -vanes have been successfully tested in engines. Despite of the positive results still more experience is necessary before making a final decision for series production.
Ti_3Al offers no advantage in performance (in relation to TiAl) and is normally processed by forging. Its density is higher ($\rho \approx 4,5$ g/ cm^3) and processing is complicated. So there is only limited interest in this alloy.
Ni-intermetallics are no longer of interest since they offer neither benefits in performance nor in weight.

2. 2. 5 Metal Injection Moulding (MIM)

MIM is an established technology for manufacturing small precision parts from both ceramic and metal powder. The technology is associated to sintering.
Typical applications are fasteners, levers, actuators etc. for cameras, watches and electronic equipment. Component weight is between 0.1 g and about 100g. The typical process steps and some characteristic data can be seen in Fig.7. By using fine grained powder it’s possible to make complex net shaped parts with tight tolerances and good surface quality ($R_t \approx 1$ µm).
By optimum processing parameters nearly full density ($\rho_{rel} \approx 99.9$ %) and $>$ 95 % of the strength of forged material are achievable. The remaining lack ($\Delta < 5\%$) can be compensated by materials selection. For instance if the strength of forged IN 718 is needed then just make the part by MIM from Udimet 720 LI material.
These properties and the potential for substantial cost reductions are of growing interest for engine applications.
At MTU the parts shown in Fig.7 have been successfully tested in rigs or engines. Some of them will go into series production of the EJ200.

2. 2. 6 Spraycasting of Rings / Casings

Fig.8 is a schematic of the spraycast process. It consists of vacuum induction melting (VIM) of an alloy in a ceramic crucible, delivering this to a tundish and metering it through a controlled orifice. This metered alloy stream is then passed through an atomiser array, where the stream is broken up by high purity argon gas impingement, into a spray. This spray is deposited on a preheated steel mandrel representing the inner contour of the component including the envelope for machining to finish shape.
The as-sprayed material is (due to the rapid solidification) fine grained (ASTM 5 - 7) and very homogeneous. The resulting preform is then HIPed to close porosity and subsequently either forged or ring rolled.
The main advantages of the spraycasting being in advanced stage of development, is that both ingot weight and the number of process steps (compared to forging and ring rolling) are reduced which saves both cost and lead-time. According to the STI (Spray-form Technologies International, subsidiary of Howmet) mechanical properties (includ-ing LCF) of spraycast plus rolled rings of IN718 are equal or slightly better than those for conventional forged, pierced and rolled rings. Further benefits in machinability (cutting speed increase by >25 %) and in NDT-inspectability result from the fine grained structure.
Engine tests with a PW 4000 HPT-case (IN 718 , spraycast + HIP + ring roll) for nearly 1000 endurance cycles were successful.

It can be assumed that in few years spray formed components mainly turbine casings, will be introduced in commercial series engines.

3. Manufacturing

3.1 General Requirements / Trends

The competition between the engine manufacturers will go on and exert permanent pressure to reduce cost and delivery time and in parallel improve performance and reliability of the engines. Recently GE announced that for satisfying customers demands they will reduce the time for assembling the CFM 56 from actually 11 days to only 7 days. Reduction of lead- time for manufacturing the components will be similar.

Such goals can be reached only by an optimum shop organisation, by enhanced stability of the manufacturing processes (produce quality instead of selecting bad parts) and by motivated personnel. The key words for being successful are **manufacturing cells, optimised parts flow, team- work and team motivation.** This will be demonstrated by some examples.

Furthermore in case of new engine programs basic technology must be available at program start and not be developed during the program.

3. 2 Forging and Investment Casting / Semifinished Products

All highly stressed disks / rings in the engine and all **compressor** airfoils are made by **forging**, all blades and vanes in the **turbine** section are investment **castings** (with respect to creep properties). Although some engine makers still have their own forging and casting facilities, most “advanced“ parts are made by few highly specialised forging shops and foundries operating worldwide.

Forging :

Cost reductions in current production may be achieved by reduction of the billet weight (see Fig. 9) being enabled by process simulation (ALPID or DEFORM System e.g.). Simulation is a proven method for analysis and optimisation of material flow, stresses, strains, temperatures etc. The existing tools are improved to include metallurgical and physical phenomena like recrystallisation and grain size distribution. For advanced disk materials from Ti- and Ni-alloys this is necessary since the “parameter window“ for optimum material flow and mechanical properties of the component is small. It can hardly be found by the “try and error method “at reasonable time and costs.

Also in future conventional forging will remain the dominating process. With respect to costs isothermal forging will be limited to high strength PM-Superalloys.

Investment Casting :

Very complex shaped parts like turbine vane rings are integral cast with equiaxed polycrystal structure. On the other hand optimum material properties are achieved in SX-technology. Fig 10 gives a schematic today’s state of the art and expected future developments. In single crystal HPT-airfoils efforts focus on tightening geometrical tolerances and improving cooling efficiency by more complex inner shape of the airfoils. Advanced vane rings will be cast in near future with DS or even SX airfoils. Process simulation has become a valuable tool to optimise the casting process.

The foundries make efforts to cast flanges, platforms, shrouds etc. on blades and vanes close to net shape so that value add in the machining shop decreases. Some foundries quote completely finished blades (including advanced coatings) to the customers.

3.3 Manufacturing Technology / for finished components

3.3.1 Shop Structures

Key missions in future will be cut down of lead time and costs with simultaneous improvement of quality and flexibility. These goals require new ways of organising labour both in the office and in the shop. Main tasks in this process are optimisation of the parts flow and minimising of interfaces.

Fig.11 shows the layout for manufacturing a disk prior and after reorganising the shop. The most significant differences of the **new manufacturing cell** related to the old structure are a unidirectional parts flow, physical integration of (former external) functions like quality assurance, non–machining processes like shot peening etc. into the cell and installation of team structures delegating to the team both responsibility and freedom how to organise the job. After training the team concerning quality consciousness, safety aspects, shop cleanliness and personal identification with the produced disk there was an immediate increase in quality (- 55% defects) and a reduction in lead time by more than 25%. Further improvements can be expected by Kaizen and improved maintenance concepts for the machinery.

3.3.2 Machining and Joining Technology

General :

Since many years there is a (nearly) continuous decrease of machining costs due to improved cutter materials, process improvement and / or substitution of processes by more efficient ones. This trend will go on.

Regarding cutters a new generation of ultra-fine grain carbide cutters is emerging with the capability of a significant increase of the cutting speed in milling Ti- and Ni-alloys. For Ti-alloys there is still no cutter material available enabling high speed turning with respect to tribological problems.

Whisker reinforced alumina cutters can soon be replaced to a certain extent by Si_3N_4 inserts with the same performance at lower cost.

Machining without or with minimised coolant is very critical for both Ti- and Ni-alloys since it's nearly impossible to achieve process stability.

The actual state and trends in making high tech engine components shall be demonstrated by the following examples :

Blisk-Technology:

Blisks (= bladed disks) have been applied to aero-engines since many years, mainly for APUs, Helicopter engines and business jets with small, simple shaped airfoils. Since the early eighties there is a growing number of blisk in larg military and civil engines. The EJ 200 (for Eurofighter) will have six blisk stages including a fan-blisk with heavy twisted wide-chord airfoils. Also the BRR 700 series has several blisk stages.

There are three different ways for manufacturing blisks :

- Milling from a solid pancake,
- ECM (= electrochemical machining) ,
- attaching finish forged airfoils by LFW (= linear friction welding).

Each method has it's specific advantages and drawbacks, depending on material, size and complexity of the airfoil.

Blisk Milling:

This is the traditional manufacturing route. In any case it's the fastest way for making prototypes and test hardware.

In series production milling may be very cost effective in case of relatively small Ti-airfoils especially if the profile is suitable for flank milling.

The blisk shown in Fig.12 (Ti-alloy, ∅ 500 mm, 85 airfoils, chord 33 mm) needs about 15 minutes for machining one airfoil by high speed milling. Cutting speed for roughing is about 100 m /min and near 350 m /min for finishing. Milling strategy and parameters for high speed cutting have to be optimised carefully to achieve the required process stability. There was a reduction of the machining time by more than 50 % related to conventional milling.

Due to the optimised milling process there is no manual radiusing of the profile edges prior to surface finishing (by vibropolishing) to meet the drawing requirements of $R_z = 1.2\ \mu m$.

In some cases Water Jet Cutting for generating slots between the airfoils is economic for creating space around the airfoils to insert the milling cutters. Material up to 100 mm thick can be cut, even some 3D-contours are possible.
Milling of blisks from Ni-alloys (for HPC- stages) is difficult with respect to the poor machinability and the very thin,small airfoils. ECM may be suitable for making such parts.

ECM - Blisk :
ECM is suitable (i.e. cost effective) for series - production of medium size airfoils (i.e. chord length above 70 mm) from Ti-blisks.
The reproducibility of the ECM-process is excellent. There is no wear on the electrodes generating the shape.The process parameters have to be controlled carefully, particularly concentration, temperature and conductivity of the electrolyte. Optimisation of the shape of the electrodes is empirical and needs usually several iteration steps. ECM requires experienced and skilled personnel. Optimisation is consuming time and money.
After the ECM-process is established it's productivity is high. A finished airfoil including radii on leading and trailing edge may be generated from a rough preform (made by ECM, milling or Water Jet Cutting) within 5 minutes. The size of the airfoil is unimportant (if the installed electrical power is sufficient) just as the mechanical strength of the material.
MTU will soon start series production of an EJ200 LPC-blisk (∅ 650 mm, 40 airfoils) from Ti on a 5-axis machine with a capacity of 20.000 Amps.
Fig. 13 shows an ECM - blisk in the flow-box (top cap removed) and the electrode set retracted from the flow box.

LFW – Blisk :
Linear friction welding (LFW) was originally developed as a method for replacing severe damaged airfoils that cannot be repaired by fusion welding.
LFW proved to be not only suitable for repair but also as cost effective for manufacturing new blisks with big size airfoils.
The basic principle of LFW is simple: One of the parts to be joined is static, the other one makes a linear oscillation. By pressing the matching surfaces of the parts together friction heat is generated bringing the joint area to forging temperature. Simultaneously the length of the parts is reduced by forming a flash in the joint area just like in circular friction welding. Then the oscillation is stopped within about 0.2 seconds in a predetermined position. The weld zone is characterised by an extremely fine grained microstructure with excellent strength.
Fig.14 shows MTU's LFW - machine and part of a LFW-blisk. The blades to be welded have finish forged airfoils (except a clamp shoulder near the weld zone). After welding only the clamp shoulder and the flash have to be removed by adaptive milling. Adaptive milling is necessary with respect to the tolerances of the airfoil. Milling merely to nominal contour could cause a step in the airfoil.
For large airfoils LFW is cheaper than machining the airfoils from a solid block. In addition precision forged airfoils have better metallurgical and mechanical properties.
MTU has started series production of LFW-blisks for the EJ 200, after all tests including bird strike ingestion and over 400 hours flight testing were successful.
So far more than 100 LFW-blisks have been manufactured without problems.
LFW as a repair method for replacing damaged airfoils is more sophisticated than LFW of new blisks, since in repair the disk is finish machined, thin walled and sensitive to distortion. By using a suitable fixture all associated problems could be solved. It was demonstrated that any damaged airfoil can be cut off and be replaced twice. Certification of LFW as an approved repair method is in progress.

Machining of Lifetime-critical Holes :
Flange holes on disks and rotating rings are critical locations on these parts. Wrong machining parameters may cause a catastrophic failure of the disk. Therefore such holes are machined according to very stringent specifications.

There is a strict process control and monitoring system.The following data are permanently controlled and monitored:

- Electrical power consumption of the spindle drive
- cutting forces
- coolant flow.

The systems sets alarm (= yellow limit) before the tolerance limit is reached. Then special measures are to be taken, e.g. change of cutters and visual inspection of the regarded hole. In case of exceeding the tolerance limit (= red limit) special inspection methods are applied. Depending on its results rework may be necessary or even scrapping the part.

Making critical holes is expensive. Nevertheless or even therefore it's necessary to cut costs. Fig.15 gives an impressive example. By modifying operation sequence and optimising the parameters, both quality and process stability could be improved and machining time was reduced substantially.

Millturning :

Millturning is a new method for manufacturing of axially symmetric parts (disks). Machinery is similar to a lathe, however, a rotating mill-cutter is used instead of a turning tool, see Fig. 16. The interrupted cut generates short chips (instead of continuous ones in turning) and enables efficient cooling of the cutting edges. This is beneficial for machining Ti-alloys: With respect to tribological problems cutter inserts from ceramics or CBN cannot be applied for turning of Ti. Therefore cutting speed in turning Ti with carbide cutters is limited to 50 m / min in roughing. In milling, however, due to better cooling of the cutting edge the cutting speed may be much higher.

Therefore by using the millturning process for Ti the cutting speed may be increased versus normal turning of Ti thus doubling the metal removal rate and reducing costs and lead time. Since most millturn machines have 5 or even 6 axis and large tool magazines a lot of operations can be made on one machine in one set up including holemaking and milling. This gives benefits concerning quality, lead time and costs.

MTU has started series production of EJ 200 parts by millturning.

Machining of Turbine Blades and Vanes :

Mechanical machining goes only via grinding, in a conventional shop on single machines or for large batch sizes on automated grinding centers with integrated measuring systems for dimensional control. These grinding centers are expensive (5 to 10 Mio $) and not very flexible. Therefore new machine concepts become attractive. Fig.17 shows the principle of a new manufacturing cell for LPT–blades with emphasis on maximum flexibility, low cost and minimum lead time. At MTU this manufacturing started production in autumn 1999:

Five small and cheap grinding machines plus equipment for measuring, deburring etc. form a cell with unidirectional parts flow. The cell is operated by a team of only 3 skilled workers. Each machine is equipped with two different low cost fixtures for manual hard clamping the blades. So up to 10 grinding operations can be carried out in the cell without tool change. Alumina wheels are employed with dressing between the grinding operations. All operations in the cell including computer assisted measuring, marking, deburring and cleaning of the blades are carried out by the team.

Lead time is now only one day versus 10 days in a conventional shop. Due to higher motivation of the team and less transportation damages the quality increased.

Machining costs dropped by more than 50 % (vs. conventional shop). Based on the very positive experience it can be assumed that more such grinding cells will be installed in near future.

4. Surface Technology

4.1 General

The performance of modern aero-engines is strongly dependent on a top-level surface technology. Most materials are designed for special requirements of the **base material** concerning mechanical strength, high temperature capability etc. If there are requirements with regard to **special properties of the surface of a component, then surface technologies like coatings, shot peening etc. are applied**.

The importance of the surface technology will even grow in the future for the following reasons: On one hand the traditional engine materials have only a limited potential for further improvements. On the other hand the efficiency, performance and durability of the engines will be further improved by better aerodynamics, by enhanced combustion temperatures and higher mechanical stressing of the components. This requires better surface quality mainly of the compressor airfoils, improved air seals, thermal barrier coatings on rotating parts, improved wear resistant coatings etc. That means a lot of challenges for the surface technologies in the future.

4.2 Mechanical Surface Finish

Many components like blisk airfoils need optimum HCF-properties and a low surface roughness. So after finish machining there is in many cases a shot peening followed by automated surface finishing for removal of feed marks and roughness caused by machining or peening. Usually no manual polishing or radiusing is allowed. Fig.18 shows surface finish of large blisk airfoils by abrasive flow machining (AFM) . In AFM a viscous, rheological paste containing abrasive particles is moved along the airfoil and removes the roughness peaks and generates the radii on the leading and trailing edge. Since the removal rate on the edges is different from the concave and convex side of the airfoil, machining prior to AFM must be optimised in such a way that after AFM the airfoil matches the drawing. In the shown example the time for AFM one airfoil is about 15 minutes. For smaller airfoils it is usual to AFM all airfoils simultaneously.

Other processes for surface finish of blisks are barreling or vibropolishing, sometimes assisted by chemical processes. They usually need much longer processing time, machines and fixtures, however, are cheaper and no permanent operator is necessary.

Therefore it’s likely that their range of applications will grow.

4.3 Coatings

General:

The general requirements for minimising costs and lead time, and improvement of process stability and quality have high priority in coating technology, since many coatings are expensive and stability of some processes is not optimum. So substitution of processes will continue to save costs and / or improve quality.

Example: LPPS–MCrAlYs can be replaced sometimes by the ”low cost“ processes aluminising plus air plasma spraying (APS) MCrAlY.

Some APS-MCrAlYs will be replaced in near future by slurry techniques.

Also optimising process chains can save costs as shown by the following example:

HPT-blades are usually first ground and then diffusion coated. Prior to coating some of the finish machined areas must be masked, thus causing costs. By changing the operation sequence and start with diffusion coating and then do grinding there is no more need for masking.

Thermal Spraying :

Thermal spraying processes are very important for aero-engines since there are many thermal sprayed coatings, e.g. air seals, thermal barrier coatings, corrosion / oxidation resistant coatings, wear resistant coatings etc.

Nevertheless process stability doesn’t fulfil today’s demands. Additionally until today there is no satisfying understanding of the very complex phenomena that happen in the torch during

injection and melting of the powder and on the component during deposition. The first step to improve this situation will be the introduction of an online monitoring system for both the plasma jet and the coating :
Diagnostics of the plasma jet is focussed on measuring velocity, temperature of the particles, optical analysis of the jet (by digital process imaging) and spectroscopic analysis of the plasma and the powder.
On the component temperature and thickness (thickness increase respectively) of the coating are continuously measured.

- The immediate effect of online monitoring is that irregularities are recognised immediately and the affected parts can be checked for defects without delay. Further measures can be taken to bring the affected parameters back into the tolerance band.
- Medium term it is expected to find correlations between parameter deviations and the resulting deviations in the coating's properties. Once these correlations are known, then specific measures against these parameter deviations can be developed.

It is expected that after finishing these actions the process stability and quality of the coatings can be improved, thus saving costs and reduce rework and lead time.
Then the number of test samples (for checking hardness , bond strength etc.) can be substantially reduced. Until now such samples have to be sprayed before and after every shop order, causing high costs.
Another benefit will be a better understanding of the complex physical phenomena in plasma spraying and doing first steps towards process simulation as a tool of process optimisation.

Blade Tip Hardfacing :
Air seals (abradables and tip coatings) are important for the efficiency of both compressor and turbine. They shall minimise tip clearance losses and wear on the rotating part in case of rub in. Hardfacing of turbine blade tips with abrasive particles deposited by electro-plating is common practice in many engines. For compressor blade tips, however, it is relatively new and not so wide spread.
Compressor abradables are usually made by thermal spraying. For increasing the resistance against particle erosion (by particles in the flow path) the abradables of the newest engines are specified for higher hardness and lower porosity. Accordingly the blade tips have to be hardfaced to prevent wear (or even titanium fire) in case of heavy rub in. Therefore if rub in occurs the blade tip shall **cut** into the abradable rather than **rub** against it. This is achieved by coating the tip with abrasive particles see Fig.19. In this process CBN particles with $\varnothing \approx 100$ – 150 µm are brazed onto the blade tip along the chord of the very thin profile. The relevant process steps are listed in Fig.19. Regarding the small dimensions it is clear that every operation is carried out very carefully. This refers especially to the robot assisted deposition of the CBN particles and for the inductive brazing process. Brazing takes only few seconds.Temperature is controlled by a thermography camera since one hand it must be above the liquidus temperature of the applied TiCuNi brazing filler , on the other hand it must be below β-transus of the Ti-alloy of the blade, otherwise there is a dramatic worsening of its dynamic strength properties. After all engine tests have been completed successfully, preparation of serial hardfacing of EJ 200 HPC blades is progressing.
Future efforts will focus on improvement of the process stability and on cost reduction .
As an alternative the application of special hardfacing brazing fillers containing abrasive particles is being tested and looks promising. This new kind of brazing filler is easy to handle and needs no separate deposition of the particles on the blade tip.
Also slurry technique looks promising for this kind of hardfacing and will be investigated.

Thermal Barrier Coatings (TBC) :
Plasma sprayed TBCs are applied to stator parts of aero-engines since about two decades, e.g. for for combustion chambers and for platforms and /or airfoils of HPT–vanes. Fig.20 (top side) shows an APS (air plasma sprayed) TBC from yttria stabilised zirconia. The bond coat is LPPS (low pressure plasma sprayed) MCrAlY. The structure of the TBC is characterised by horizontal

layers with a homogeneous porosity. TBCs with such microstructure fail in service through spalling off due to macrocracks caused by thermal fatigue in the zirconia coating itself. Failure mechanisms are complicated in detail and cannot be discussed here. Plasma sprayed coatings are not suitable for TBCs on rotating parts.

Fig.20 (bottom side) shows a TBC made by EB-PVD (electron beam physical vapour deposition). It is characterised by a columnar structure perpendicular to the surface without any visible defects. Such coatings are successfully applied to rotating airfoils of HPT blades and also for vanes since several years due to their good thermal fatigue properties.

If failure occurs, then it is usually caused by oxidation at the interface between bond and top coat.

One drawback of EB- PVD coatings, however, is the high price caused by the investment of at least 10 Mio $ needed for a series production machine.

With respect to the increasing combustion temperatures this kind of TBC will be applied to the HPT - airfoils and even the first LPT stage of most newly designed engines.

SNECMA and MTU founded a joint venture last year for making EB-PVD TBCs mainly for HPT blades and vanes of their own engines and for customers from the world market.

5 Concluding Remarks

Although no changes in the basic design of the aero-engines are expected for the next years, their performance will be improved by better design, materials and progress in manufacturing and surface technology.

The competition between the engine manufacturers exerts strong pressure to reduce costs and lead time and in parallel improve quality. This means a great challenge for production technology

The traditional monolithic Ti- and Ni-alloys have only a limited potential for further improvements. Nevertheless they will keep their great importance.

Materials with improved strength / weight ratio are either intermetallics or fibre reinforced polymer, metal or ceramic matrix composites. Among these only the polymer matrix composites are already “established”. In spite of successful engine tests the other “candidate materials“ still have to prove that they can be produced at reasonable costs by stable processes being strictly controlled. Process control is absolutely necessary for cost reasons since there are hardly any NDT-methods for detecting defects in composites , Ti- MMCs e.g.

In manufacturing and surface technology focal points of interest are reduction of costs and lead time and quality improvement. This goals can only be satisfied with stable processes.

Improvement of process stability is a top issue. Process stability of sensitive processes shall be proven by continuous monitoring of all relevant parameters.

In the shop new structures (parts related manufacturing cells, operated by effective teams) were installed with focus on optimised parts flow and integration of quality assurance and other “external“ functions in the cell. In doing this substantial costs and lead time reductions can be achieved.

Blisk manufacturing technology is well established, either by high speed milling, ECM or LFW.

Efficiency of machining processes will be further improved by better cutting materials and new machine designs (millturning, cheap grinding machines etc.).

It is not yet clear if machines based on Hexapod kinematics are mature for series fabrication of engine components.

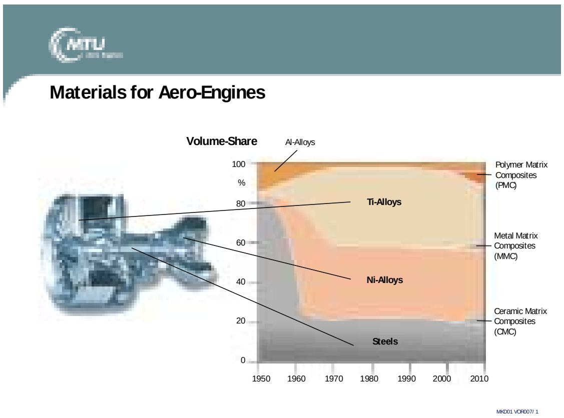
Laser assisted machining and machining without coolant are not suitable for engine materials.

Thermal spraying is applied for coatings on many engine components. The stability of thermal spraying processes, however, must be substantially improved. Work for achieving this goal by process monitoring, beam diagnostics, thermography etc. is progressing.

Thermal barrier coatings on rotating airfoils are of growing interest.

New engines need better air seals including hard facing of the blade tips.

Altogether there are many challenges for the surface technology in the next years.



Materials for Aero-Engines

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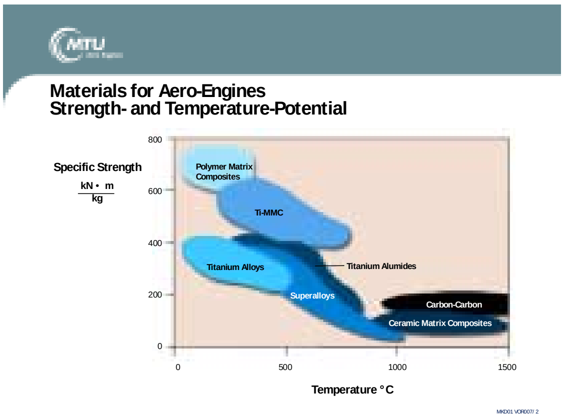
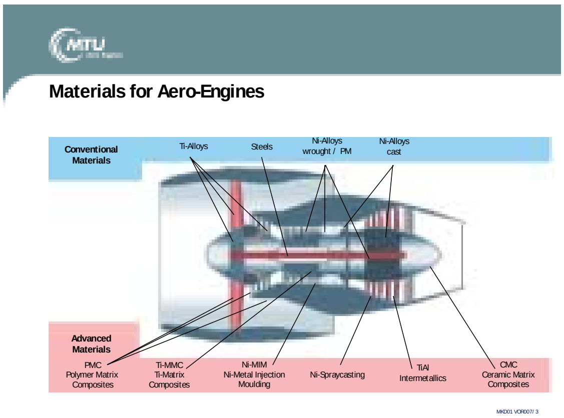
Figure 1



Materials for Aero-Engines
Strength- and Temperature-Potential

MKD01 VOR007/ 2

Figure 2



Materials for Aero-Engines

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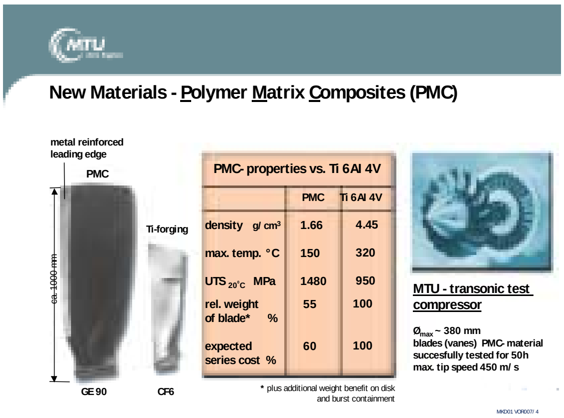
Figure 3



New Materials - Polymer Matrix Composites (PMC)

PMC- properties vs. Ti 6Al 4V

	PMC	Ti 6Al 4V
density g/ cm³	1.66	4.45
max. temp. °C	150	320
UTS $_{20°C}$ MPa	1480	950
rel. weight of blade* %	55	100
expected series cost %	60	100

* plus additional weight benefit on disk and burst containment

MTU - transonic test compressor

$Ø_{max}$ ~ 380 mm
blades (vanes) PMC- material succesfully tested for 50h
max. tip speed 450 m/ s

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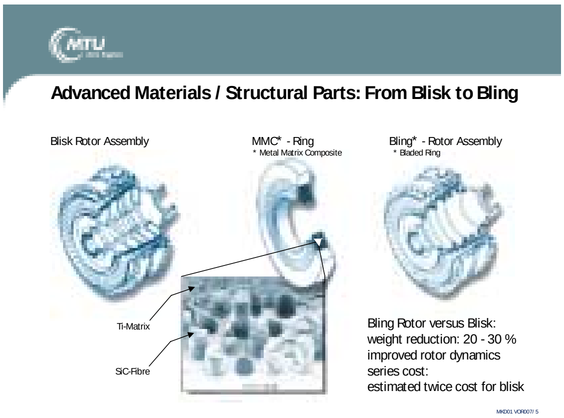
Figure 4



Advanced Materials / Structural Parts: From Blisk to Bling

Bling Rotor versus Blisk:
weight reduction: 20 - 30 %
improved rotor dynamics
series cost:
estimated twice cost for blisk

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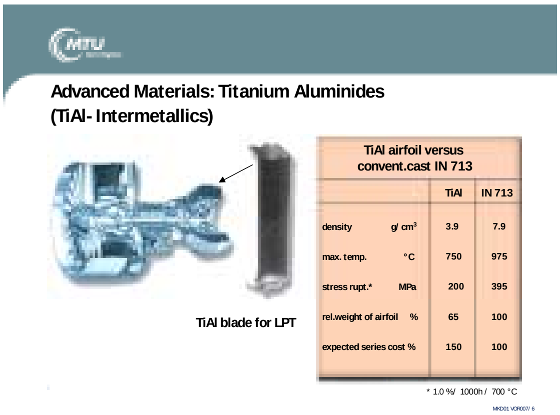
Figure 5



Advanced Materials: Titanium Aluminides
(TiAl- Intermetallics)

TiAl airfoil versus convent.cast IN 713

	TiAl	IN 713
density g/ cm³	3.9	7.9
max. temp. °C	750	975
stress rupt.* MPa	200	395
rel.weight of airfoil %	65	100
expected series cost %	150	100

* 1.0 %/ 1000h / 700 °C

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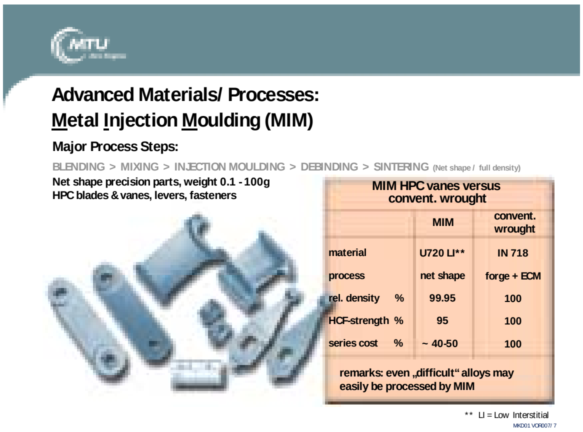
Figure 6



Advanced Materials/ Processes:
Metal Injection Moulding (MIM)

Major Process Steps:

BLENDING > MIXING > INJECTION MOULDING > DEBINDING > SINTERING (Net shape / full density)

Net shape precision parts, weight 0.1 - 100g
HPC blades & vanes, levers, fasteners

MIM HPC vanes versus convent. wrought

	MIM	convent. wrought
material	U720 LI**	IN 718
process	net shape	forge + ECM
rel. density %	99.95	100
HCF-strength %	95	100
series cost %	~ 40-50	100

remarks: even „difficult“ alloys may easily be processed by MIM

** LI = Low Interstitial

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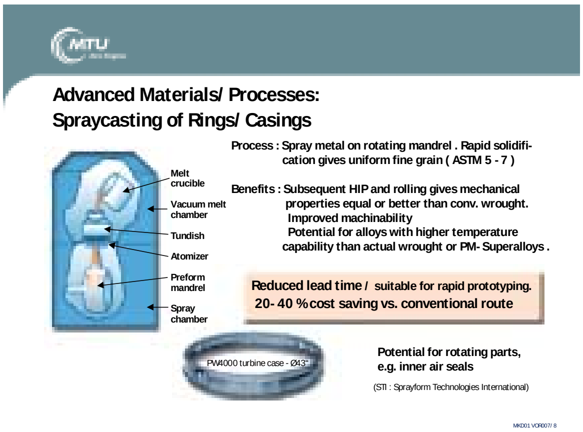
Figure 7



Advanced Materials/ Processes:
Spraycasting of Rings/ Casings

Process : Spray metal on rotating mandrel . Rapid solidification gives uniform fine grain (ASTM 5 - 7)

Benefits : Subsequent HIP and rolling gives mechanical properties equal or better than conv. wrought.
Improved machinability
Potential for alloys with higher temperature capability than actual wrought or PM- Superalloys .

Reduced lead time / suitable for rapid prototyping.
20- 40 % cost saving vs. conventional route

Potential for rotating parts, e.g. inner air seals

(STI : Sprayform Technologies International)

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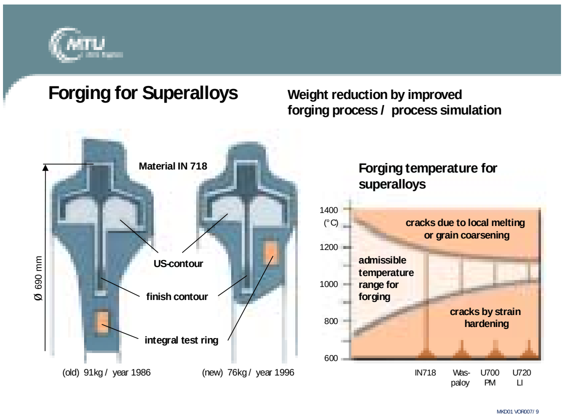
Figure 8



Forging for Superalloys

Weight reduction by improved forging process / process simulation

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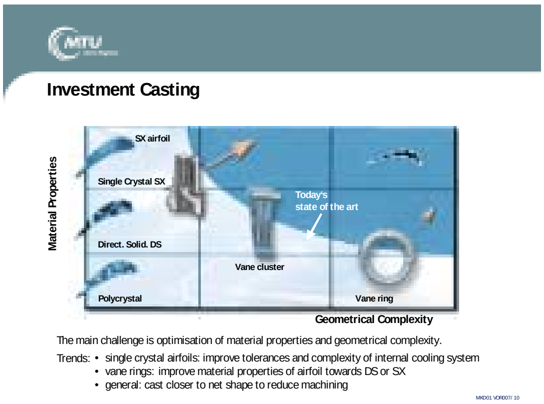
Figure 9



Investment Casting

The main challenge is optimisation of material properties and geometrical complexity.

Trends:
- single crystal airfoils: improve tolerances and complexity of internal cooling system
- vane rings: improve material properties of airfoil towards DS or SX
- general: cast closer to net shape to reduce machining

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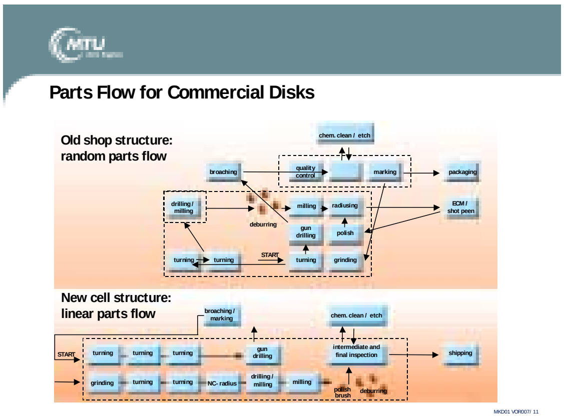
Figure 10



Parts Flow for Commercial Disks

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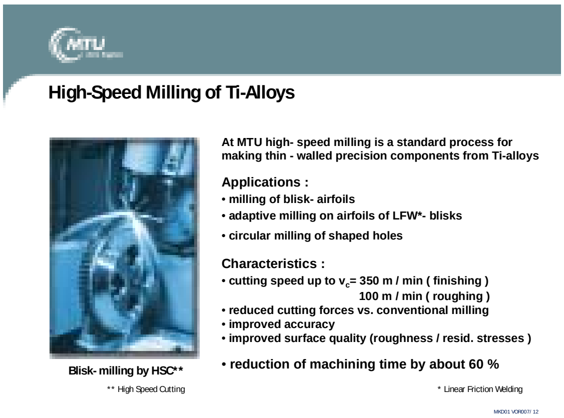
Figure 11



High-Speed Milling of Ti-Alloys

Blisk- milling by HSC**

** High Speed Cutting

At MTU high- speed milling is a standard process for making thin - walled precision components from Ti-alloys

Applications :
- milling of blisk- airfoils
- adaptive milling on airfoils of LFW*- blisks
- circular milling of shaped holes

Characteristics :
- cutting speed up to v_c= 350 m / min (finishing)
  100 m / min (roughing)
- reduced cutting forces vs. conventional milling
- improved accuracy
- improved surface quality (roughness / resid. stresses)
- **reduction of machining time by about 60 %**

* Linear Friction Welding

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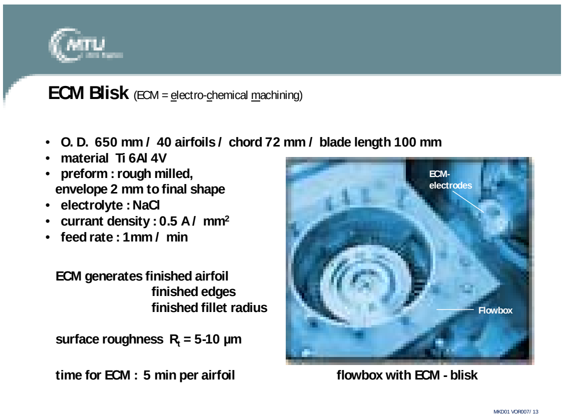
Figure 12



ECM Blisk (ECM = electro-chemical machining)

- O. D. 650 mm / 40 airfoils / chord 72 mm / blade length 100 mm
- material Ti 6Al 4V
- preform : rough milled, envelope 2 mm to final shape
- electrolyte : NaCl
- currant density : 0.5 A / mm^2
- feed rate : 1mm / min

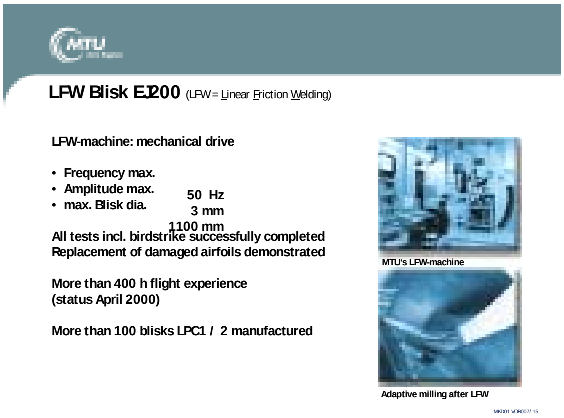
ECM generates finished airfoil
finished edges
finished fillet radius

surface roughness R_t = 5-10 µm

time for ECM : 5 min per airfoil

flowbox with ECM - blisk

Figure 13



LFW Blisk EJ200 (LFW = Linear Friction Welding)

LFW-machine: mechanical drive

- Frequency max. 50 Hz
- Amplitude max. 3 mm
- max. Blisk dia. 1100 mm

All tests incl. birdstrike successfully completed
Replacement of damaged airfoils demonstrated

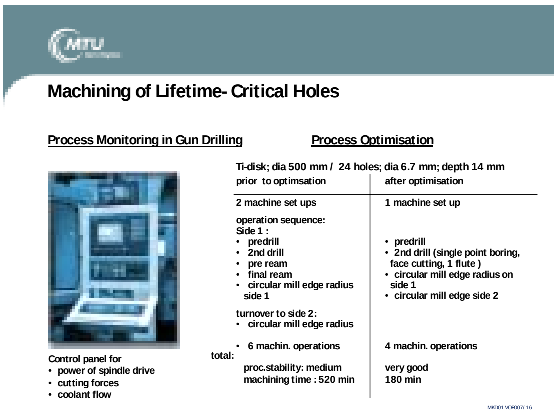
More than 400 h flight experience
(status April 2000)

More than 100 blisks LPC1 / 2 manufactured

MTU's LFW-machine

Adaptive milling after LFW

Figure 14



Machining of Lifetime- Critical Holes

Process Monitoring in Gun Drilling

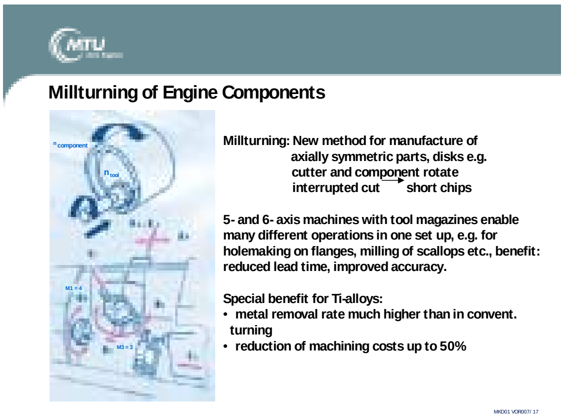
Control panel for
- power of spindle drive
- cutting forces
- coolant flow

Process Optimisation

Ti-disk; dia 500 mm / 24 holes; dia 6.7 mm; depth 14 mm

	prior to optimsation	after optimisation
	2 machine set ups	1 machine set up
	operation sequence: Side 1 : • predrill • 2nd drill • pre ream • final ream • circular mill edge radius side 1	• predrill • 2nd drill (single point boring, face cutting, 1 flute) • circular mill edge radius on side 1 • circular mill edge side 2
	turnover to side 2: • circular mill edge radius	
total:	• 6 machin. operations proc.stability: medium machining time : 520 min	4 machin. operations very good 180 min

Figure 15



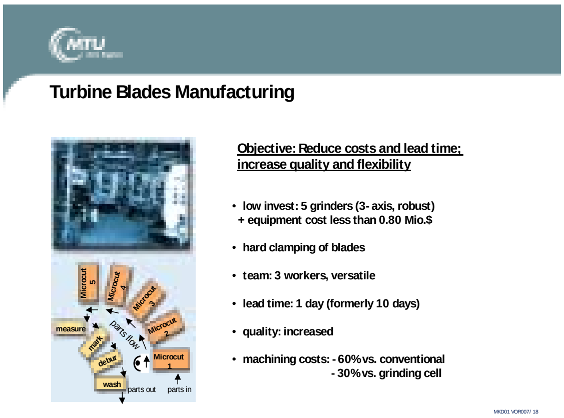
Millturning of Engine Components

Millturning: New method for manufacture of
axially symmetric parts, disks e.g.
cutter and component rotate
interrupted cut → short chips

5- and 6- axis machines with tool magazines enable many different operations in one set up, e.g. for holemaking on flanges, milling of scallops etc., benefit: reduced lead time, improved accuracy.

Special benefit for Ti-alloys:
- metal removal rate much higher than in convent. turning
- reduction of machining costs up to 50%

Figure 16

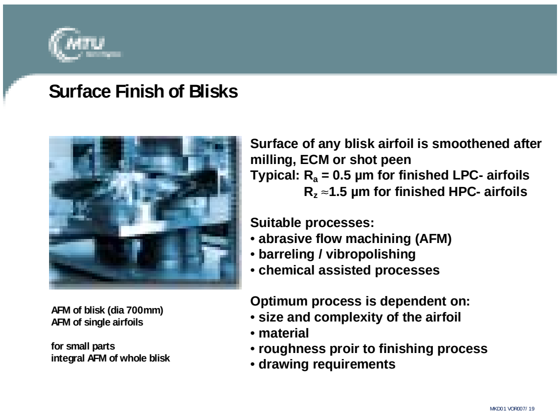


Turbine Blades Manufacturing

Objective: Reduce costs and lead time; increase quality and flexibility

- low invest: 5 grinders (3- axis, robust) + equipment cost less than 0.80 Mio.$
- hard clamping of blades
- team: 3 workers, versatile
- lead time: 1 day (formerly 10 days)
- quality: increased
- machining costs: - 60% vs. conventional
  - 30% vs. grinding cell

Figure 17



Surface Finish of Blisks

AFM of blisk (dia 700mm)
AFM of single airfoils

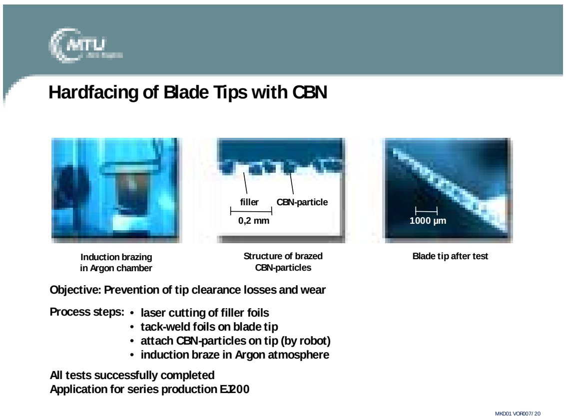
for small parts
integral AFM of whole blisk

Surface of any blisk airfoil is smoothened after milling, ECM or shot peen
Typical: R_a = 0.5 µm for finished LPC- airfoils
R_z ≈1.5 µm for finished HPC- airfoils

Suitable processes:
- abrasive flow machining (AFM)
- barreling / vibropolishing
- chemical assisted processes

Optimum process is dependent on:
- size and complexity of the airfoil
- material
- roughness proir to finishing process
- drawing requirements

Figure 18



Hardfacing of Blade Tips with CBN

Induction brazing in Argon chamber

Structure of brazed CBN-particles

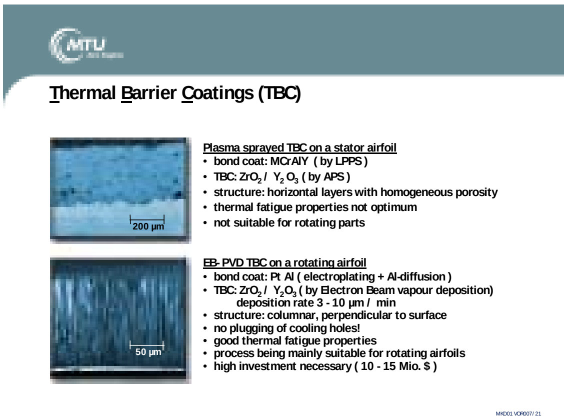
Blade tip after test

Objective: Prevention of tip clearance losses and wear

Process steps:
- laser cutting of filler foils
- tack-weld foils on blade tip
- attach CBN-particles on tip (by robot)
- induction braze in Argon atmosphere

All tests successfully completed
Application for series production EJ200

Figure 19

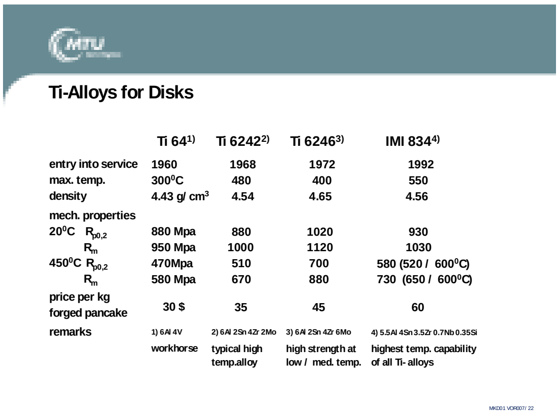


Thermal Barrier Coatings (TBC)

Plasma sprayed TBC on a stator airfoil
- bond coat: MCrAlY (by LPPS)
- TBC: ZrO_2 / Y_2O_3 (by APS)
- structure: horizontal layers with homogeneous porosity
- thermal fatigue properties not optimum
- not suitable for rotating parts

EB- PVD TBC on a rotating airfoil
- bond coat: Pt Al (electroplating + Al-diffusion)
- TBC: ZrO_2 / Y_2O_3 (by Electron Beam vapour deposition)
  deposition rate 3 - 10 µm / min
- structure: columnar, perpendicular to surface
- no plugging of cooling holes!
- good thermal fatigue properties
- process being mainly suitable for rotating airfoils
- high investment necessary (10 - 15 Mio. $)

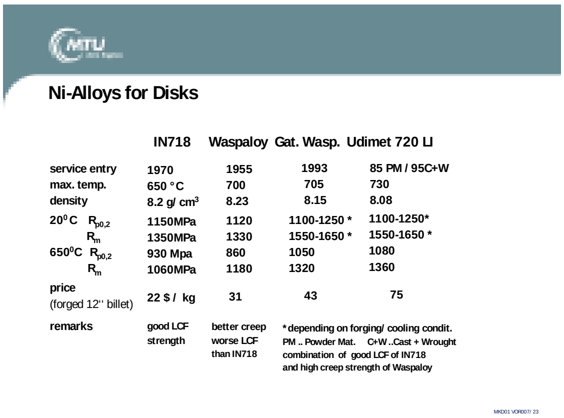
Figure 20



Ti-Alloys for Disks

	Ti 64 1)	Ti 6242 2)	Ti 6246 3)	IMI 834 4)
entry into service	1960	1968	1972	1992
max. temp.	300^{0}C	480	400	550
density	4.43 g/ cm^3	4.54	4.65	4.56
mech. properties				
20^{0}C $R_{p0,2}$	880 Mpa	880	1020	930
R_m	950 Mpa	1000	1120	1030
450^{0}C $R_{p0,2}$	470Mpa	510	700	580 (520 / 600^{0}C)
R_m	580 Mpa	670	880	730 (650 / 600^{0}C)
price per kg forged pancake	30 $	35	45	60
remarks	1) 6Al 4V	2) 6Al 2Sn 4Zr 2Mo	3) 6Al 2Sn 4Zr 6Mo	4) 5.5Al 4Sn 3.5Zr 0.7Nb 0.35Si
	workhorse	typical high temp.alloy	high strength at low / med. temp.	highest temp. capability of all Ti- alloys

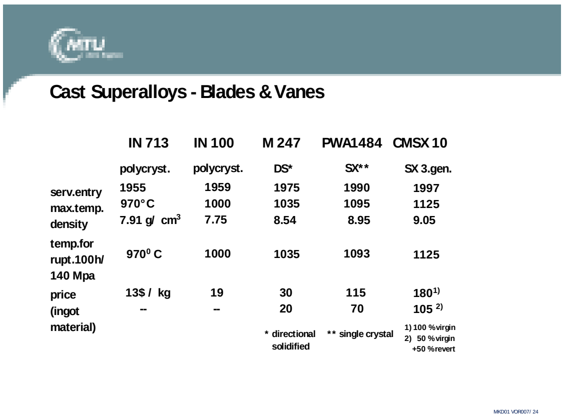
Table 1



Ni-Alloys for Disks

	IN718	Waspaloy	Gat. Wasp.	Udimet 720 LI
service entry	1970	1955	1993	85 PM / 95C+W
max. temp.	650 °C	700	705	730
density	8.2 g/ cm^3	8.23	8.15	8.08
20^0 C $R_{p0,2}$	1150MPa	1120	1100-1250 *	1100-1250*
R_m	1350MPa	1330	1550-1650 *	1550-1650 *
650^{0}C $R_{p0,2}$	930 Mpa	860	1050	1080
R_m	1060MPa	1180	1320	1360
price (forged 12‘‘ billet)	22 $ / kg	31	43	75
remarks	good LCF strength	better creep worse LCF than IN718	* depending on forging/ cooling condit. PM .. Powder Mat. C+W ..Cast + Wrought combination of good LCF of IN718 and high creep strength of Waspaloy	

Table 2



Cast Superalloys - Blades & Vanes

	IN 713	IN 100	M 247	PWA1484	CMSX 10
	polycryst.	polycryst.	DS*	SX**	SX 3.gen.
serv.entry	1955	1959	1975	1990	1997
max.temp.	970°C	1000	1035	1095	1125
density	7.91 g/ cm^3	7.75	8.54	8.95	9.05
temp.for rupt.100h/ 140 Mpa	970^0 C	1000	1035	1093	1125
price (ingot material)	13$ / kg	19	30	115	180 1)
	--	--	20	70	105 2)
			* directional solidified	** single crystal	1) 100 % virgin 2) 50 % virgin +50 % revert

Table 3