

# Driving the Technological Edge in Airbreathing Propulsion

Klaus Steffens

Rainer Walther

MTU Aero Engines

D - 80976 München

Germany

## 1. ABSTRACT

The targets for future engine technology developments are presented. Recent technologies which are aimed at meeting the demanding challenges are described. These cover innovative engine concepts, efficient engine components as well as economic and high quality manufacturing and repair processes.

## 2. INTRODUCTION

Modern air transport has developed into an indispensable means of transportation for everybody. Apart from short-term fluctuations, the average worldwide growth is expected to continue at about 5 per cent per annum. To a large extent, the previous strong growth was enabled by the longterm development and application of advanced engine technologies which focussed on minimum fuel consumption as well as on economic manufacturing and maintenance of engine components.

Caused by the strong growth of air traffic, considerable efforts were initiated to improve the environmental friendliness; this is in fact mandated by a number of international official regulations.

Long-term targets necessary to improve engine efficiency, economy and ecology, necessitate ongoing development in engine technology, Tab. 1. This requires well-founded experience in combination with extensive competence.

Today, MTU Aero Engine looks back on 30 years of design, manufacturing and maintenance experience in compressor and turbine components. The begin-

nings date back to the early 70' ties. At this time the military engine RB199 (the powerplant for the multirole Tornado aircraft) was developed.

Specific Fuel Consumption:	-15-20 %
Noise Emissions, rel. stage 3, cum.:	- 30 dB
NOx-Emissions:	- 80 %
Weight:	- 30 %
Development & Manufacturing Costs:	- 30 %
Maintenance Costs:	- 40 %

Tab. 1: Technological Targets 2020

Based on this early experience, all new and improved technologies have found application in several engine and technology programs. As a recent example, MTU's outstanding component technologies are applied in the engine programs PW6000 and GP7000, Figs. 1 and 2.

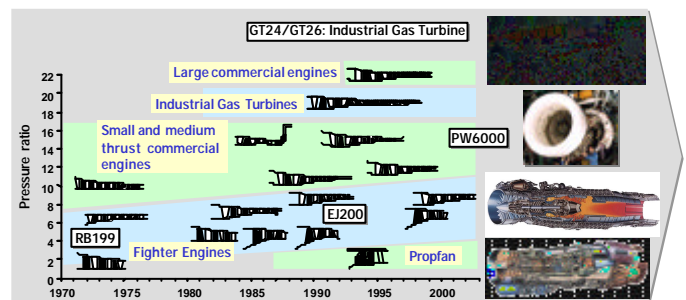


Fig. 1: Experience in Compressor Design

## 3. CREATING INNOVATIVE ENGINE

## CONCEPTS

One major target for innovative engine concepts is the further reduction in specific fuel consumption by increasing the engine's thermal and propulsion efficiency.

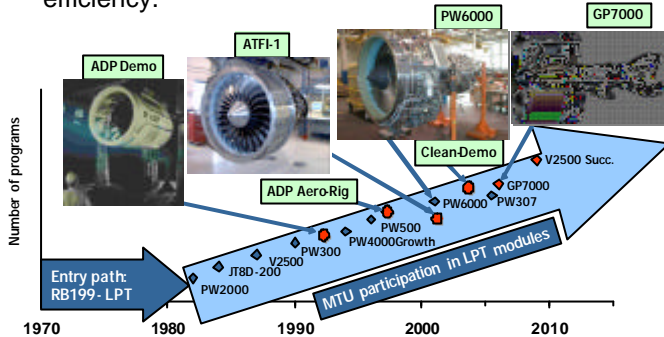


Fig. 2: Experience in Turbine Design

The thermal efficiency of present aero engines is the result of a long-term development process over several decades. Among other measures, it was mainly obtained by an increase in engine's overall compression ratio, a continuous increase of turbine entrance temperature and by optimum components efficiencies. Thermal efficiency of the order of 50% is common for today's turbofans.

Theoretically, the propulsion efficiency grows continuously with increasing bypass ratio. For present commercial engines the bypass ratio is about 7-8 resulting in an ideal propulsion efficiency of about 80%.

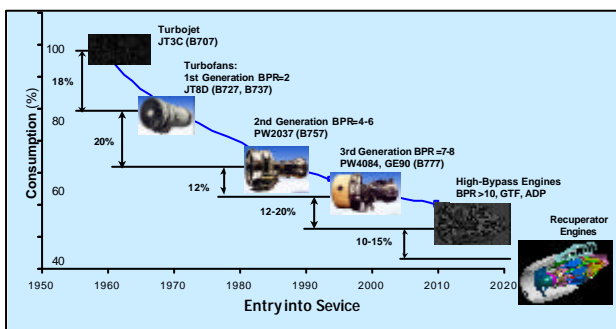


Fig. 3: SFC-Reduction by Innovative Engine Concepts

Forthcoming benefits in specific fuel consumption through a further increase in bypass ratio and thermal efficiency are shown in Fig. 3.

Geared turbofans for example, will enable the bypass ratio to be extended beyond values of 10, whereas thermal efficiency can be further improved by intercooled, recuperative engine concepts, Fig. 4.

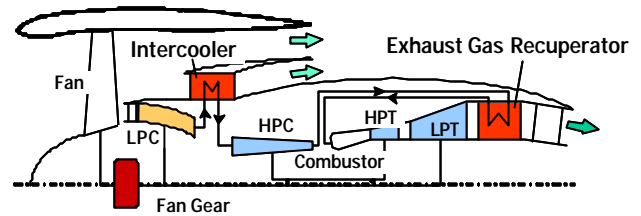
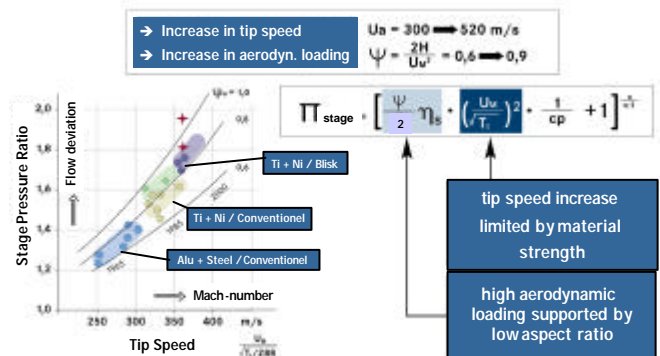


Fig. 4: Intercooled, Recuperative Engine Concept

Within the technology demonstration program "CLEAN", funded by the European Community, european engine companies are jointly preparing advanced technologies for future recuperative aero engines. The demonstrator tests are scheduled to start in 2004 at the Altitude Test Facility in Stuttgart.

## 4. DEVELOPING EFFICIENT ENGINE COMPONENTS

In order to guarantee economic manufacturing and maintenance of engine components, a minimum number of stages in the turbomachinery components is one of the key challenges with advanced aero engines. As a consequence, previous trends in axial compressor development were characterized by a continuous increase in stage pressure ratio combined with a strong increase in blade tip speed, Fig. 5.



**Fig. 5: Increase in Stage Pressure Ratio of Engine Compressors**

The combined increase in mechanical and aerodynamic loading was enabled through the introduction of low aspect ratio bladings, which allow stronger flow decelerations within the compressor cascades.

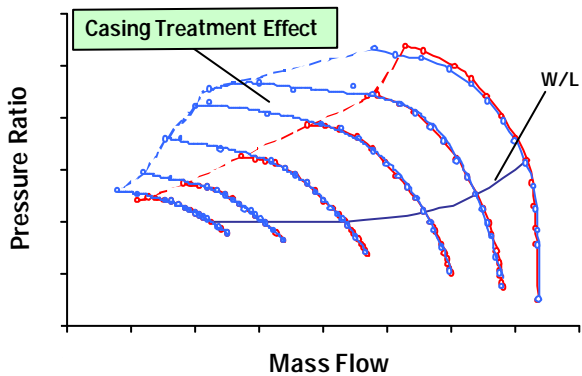
In order to meet the high aerodynamic and mechanical challenges, the design process must ensure that all physical reserves are completely explored using powerful and validated design tools. To give an example, for the detailed and systematic aerodynamic optimization, MTU applies advanced 3-dimensional CFD-tools, Fig. 6.



**Fig. 6: Optimum Aerodynamic Stage Loading by Advanced CFD-Techniques**

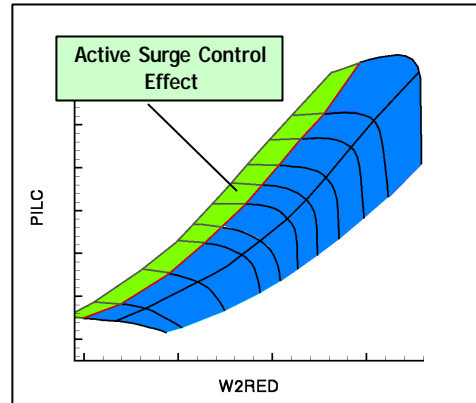
Examples of key technologies to improve efficiency and stability of aerodynamically highly loaded compressor stages are 3-dimensionally designed bladings, powerful casing treatments and design features using intelligent compressor control techniques. Extensive testing of advanced casing treatments demonstrate considerably improved stability in spite of high aerodynamic loading without compromising efficiency and mass flow, Fig. 7.

**Demonstration of Casing Treatment Technology**



**Fig. 7: Increased Stability by Powerful Casing Treatments**

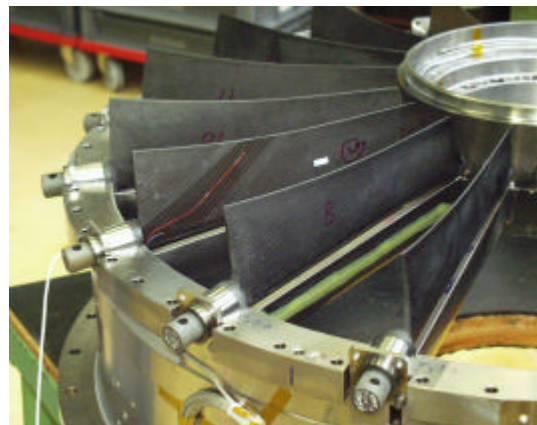
Intelligent control techniques for example, include active surge detection and control for increased stability, active damping of blade vibrations aimed to facilitate optimum, non-compromised aerodynamic designs and active clearance control, Fig. 8.



**Fig. 8: Increase in Stable Operation Range by Active Surge Control**

In order to meet the high mechanical challenges the development and application of light-weight materials at superior strengths is an essential task. Integral structure designs like Blisks and Blings in combination with fiber-reinforced materials offer substantial potentials for weight reduction without compromising the component life.

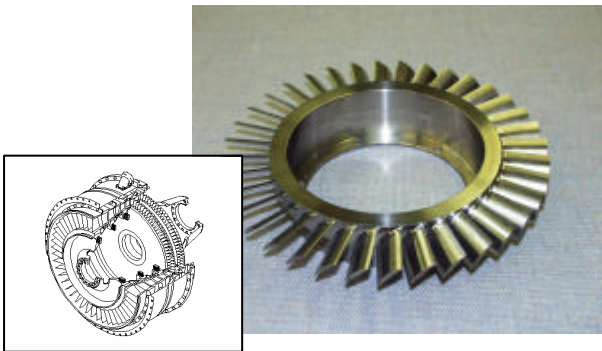
To give an example, for a military low pressure compressor demonstrator, the inlet guide vanes have variable flaps made from carbon fiber reinforced plastics, Fig. 9.



**Fig. 9: Variable Carbon Fiber Reinforced Plastic Flaps of the Inlet Guide Vane**

The weight saving potential compared to a full titanium design is about 60 %. The integral titanium / composite structure ensure full bird strike and surge capability whereas protective coating systems and metal leading edge shields provide high erosion resistance.

For long-term applications MTU is investigating the weight saving potential of titanium matrix /SiC fiber reinforced rotor Blings, Fig 10. A full scale demonstration test proved the feasibility of baseline manufacturing techniques and the reliable prediction of the anisotropic material behaviour by non-linear FEM simulations. Compared to monolithic titanium Blisk structures a weight saving potential of about 25% was demonstrated.



**Fig. 10: Titanium Matrix and SiC-Fiberreinforced Bling**

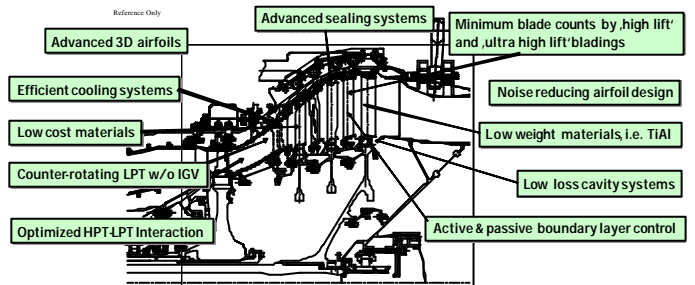
One recent highlight of MTU compressor technology development was the design and testing of a 6-stage transonic High Pressure Compressor (HPC) delivering a pressure ratio of about 12. Compared to other military and commercial compressors in service, this compressor has demonstrated surpassing attributes for most design parameters. In close international collaboration, MTU's HPC12 was successfully validated by engine demonstration tests and selected for the PW6000 engine which will achieve certification by midyear 2004, Fig. 11.

Concerning technology development for Low Pressure Turbines (LPT) MTU successfully pursues a large number of effective measures necessary to achieve the challenging design targets, Fig. 12.

It is well known that the specific fuel consumption of turbofans is highly sensitive to the isentropic efficiency of the LPT component. As a consequence, technologies aimed at increasing the efficiency are under way at high priority and include 3-D airfoil designs, advanced sealing systems, low loss cavity systems as well as active and passive boundary layer control measures. High lift and ultra high lift bladings result in reduction of airfoil count by about 20% without compromising turbine efficiency, Fig.13.



**Fig. 11: Series Introduction of PW6000 HPC**

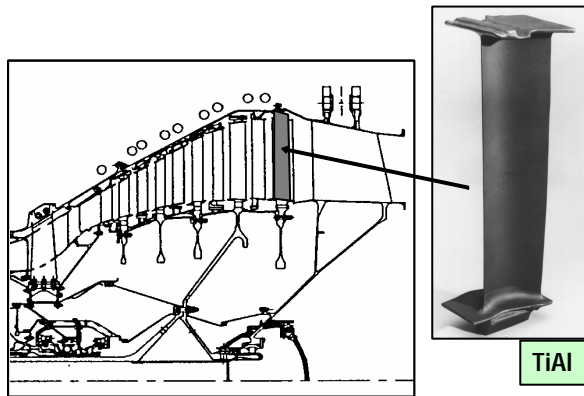


**Fig. 12: Key Elements in Turbine Technology Development**



**Fig. 13: Reduced Airfoil Count by 'High Lift Design'**

With large turbofans the weight of the LPT contributes up to 30% to the total weight of the engine. As a consequence, the application of light-weight materials is most effective with respect to reducing the total engine weight. To give an example, the replacement of a conventional Nickel alloy by Titanium Aluminides in the rear LPT-stages provides a blade weight saving potential up to 40% in combination with improved fatigue strength, Fig. 14.



**Fig. 14: Weight Reduction by Lightweight Materials**

Compared to conventional LPTs, the high circumferential speeds of geared propfan's low pressure spools allow a substantial increase in stage expansion pressure ratio. Recently, this technology has been successfully demonstrated within the Advanced Turbofan Integrator (ATFI) realising an expansion pressure ratio of 4.5 in 2 stages without compromising a low cost design, Fig. 15.



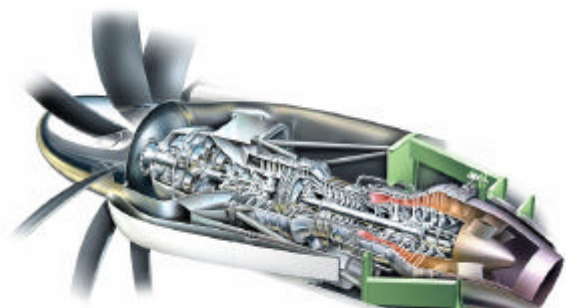
**Fig. 15: Advanced Turbofan Integrator (ATFI)**

A further recent highlight in turbine technology was obtained with testing the 5-stage aero-rig of the GP7000 LPT. The aero-rig featured 'clocking' of all vanes. An outstanding isentropic efficiency of 92.4% was measured. The prepared technology will be applied in the GP7000 engine with the 1<sup>st</sup> engine run scheduled for early 2004, Fig. 16.



**Fig. 16: LPT-Technology Demonstrator for GP7000**

Ongoing challenges in component designs will arise with the development of the turboprop-engine TP400, powerplant for the new European military transport plane A400M. With a maximum power of 11000 H.P. the engine represents the most powerful turboprop of the western world, Fig. 17. MTU's share includes the intermediate shaft with the intermediate pressure compressor and turbine as well as the complete final assembly of all production engines.



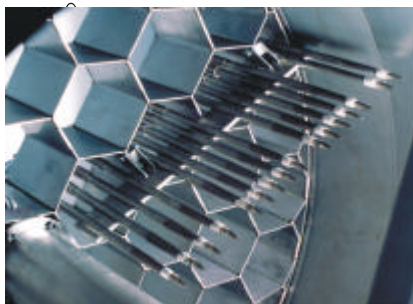
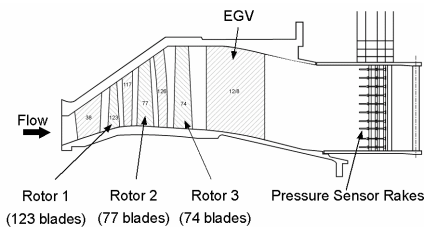
**Fig. 17: European Turboprop-Engine TP400**

**5. IMPROVING ENVIRONMENTAL COMPATIBILITY**

As a result of the strong growth of civil air transportation, noise emissions of aero engines have become a major problem. Driven by international regulations, considerable advances were achieved in the past and future improvements are becoming more sophisticated.

To give an example, ongoing experimental and analytical investigations focus on the understanding of noise generation mechanisms and on the validation of most efficient reduction measures at the point of origin, Fig. 18. It is anticipated that 50% of the total noise reduction target (see Tab. 1) can be obtained by optimizing annulus and blade designs. Among others are appropriate methodologies which include cut-off designs, acoustic clocking, prevention of flow separation, low loss tip clearances and minimum loss cavity flows.

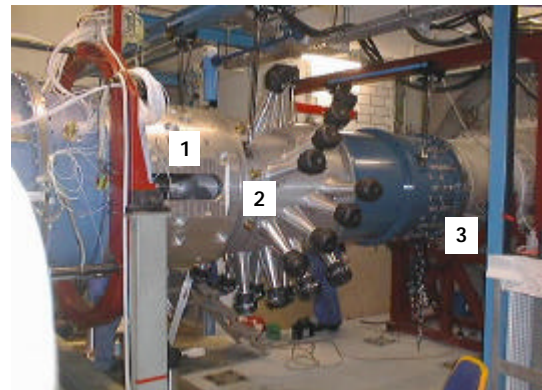
The remaining 50% reduction is expected through active noise control measures. First test series performed with a fan rig indicated a promising sound power reduction potential, Fig. 19. Actual activities are focussed on the development of intelligent, engine feasible small scale actuation systems.



**Fig. 18: Aero-Acoustic Measurements in a 3-Stage LPT**

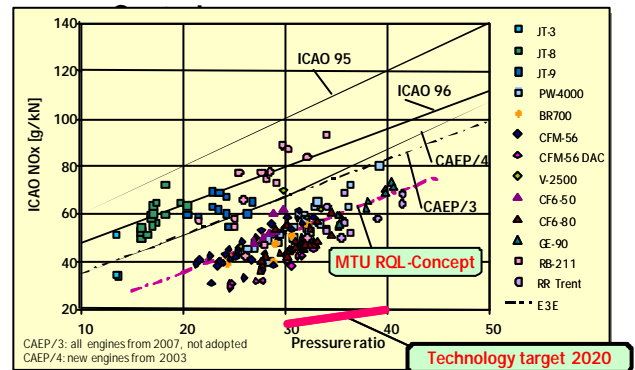
Chemical pollutant emissions are governed by international regulations. The most harmful emis-

sions of aero engines, the emissions of nitric oxides (NOx), are quantified by the ICAO-parameter (International Civil Aviation Organization). The limits given by the parameter have been decreased continuously in the past and will be further tightened from 2007, Fig. 20.



Fan rig with Active Noise Control equipment: 1. Fan Casing 2. Actuators 3. Sensors

**Fig. 19: Noise Reduction by Active Noise**



**Fig. 20: Current ICAO NOx-Limits and Pursued Technology Target**

A 80% reduction of NOx-emissions based on the ICAO 96 limit is expected to be achieved by Ultra-Low-NOx-Combustion, e.g. by premixed, pre-vaporized lean combustion. Due to the high technological risks of this advanced concept, MTU as an interim solution has pursued the Rich-Quench-Lean-Combustion (RQL), Fig. 21. Testing of an annular full scale combustor at realistic inlet temperatures and pressures resulted in emissions which are 40% below the ICAO 96 NOx-limits.



**Fig. 21: Full Scale RQL-Combustor**

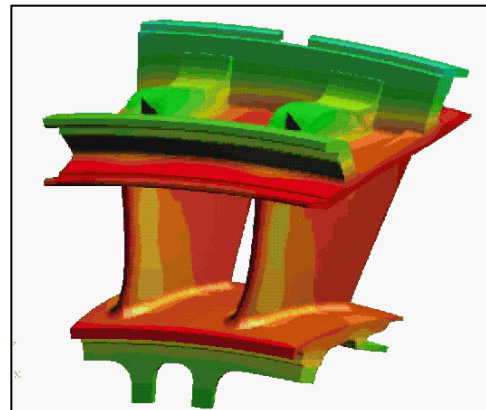
## **6. REDUCING DEVELOPMENT, MANUFACTURING AND MAINTENANCE COSTS**

By improving the design accuracy, advanced and validated design tools offer a high potential to reduce development periods and testing efforts. To give an example, with the thermal design of turbine bladings, 3D analyses of internal and external heat transfer, simultaneously and iteratively coupled to thermal structure computations, result in an accurate and efficient cooling system design and minimizes at the same time the number of test rig build ups required, Fig. 22.

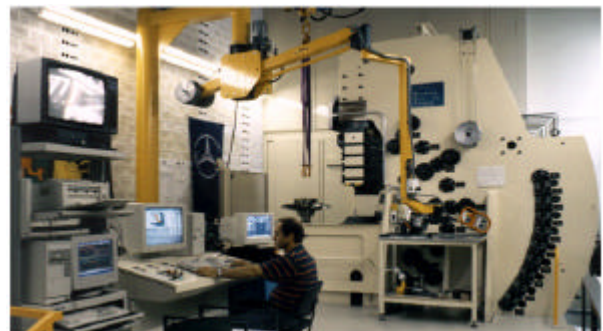
As a result of a strong worldwide competition, engine manufacturers are being driven to reduce costs and product delivery times whilst simultaneously improving performance and reliability of the engines.

This demands economic and excellent quality manufacturing processes. To give an example, for the production of compressor Blisks various technologies have been developed. The Linear Friction Welding Process ensures economic and high quality new parts production and repair of large scale geometries at outstanding High-Cycle-Fatigue- and Low-Cycle-Fatigue-strengths, Fig. 23.

Supplementary, Electro Chemical Machining is applied for Ti- and Ni-Blisks of medium and small size ensuring high surface quality, whereas milling by High-Speed-Cutting is a very fast and economic process suited for prototype production and for rather small Ti-blades. Adapted processing



**Fig. 22: Computational Grid for 3D Internal Heat Transfer Analysis/ Transient Temperature Field Analysis by FEM**

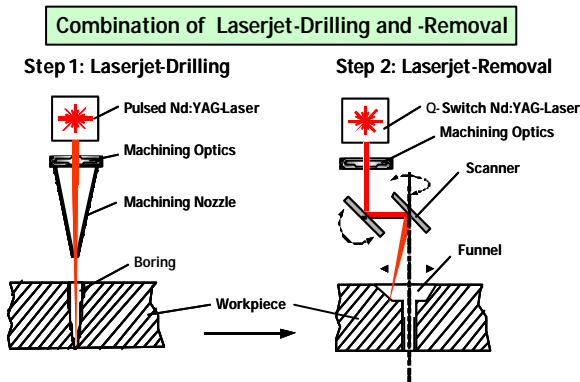


**Fig. 23: Linear Friction Welding Machine at MTU**

parameters assure also the economic and high quality production of Ni-Blisks.

Shaped cooling holes are part of an advanced turbine blade cooling system ensuring a most efficient use of cooling air. Actually, the highly complex exit shapes of 1<sup>st</sup> and 2<sup>nd</sup> generation cooling holes are manufactured by Electro Discharge Machining generally consuming long production times and high tool costs. An alternative economic Laser-Production process is in preparation combining the well established Laserjet-Drilling with a new Laserjet-Removal process, Fig.

24. With this technique high processing flexibility is offered including for example, the potential to process ceramic coated blades. With the development of the process special regard is given to ensure production line capability.

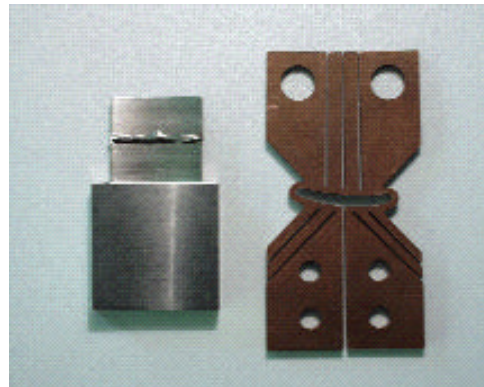


**Fig. 24: Combination of Laserjet-Drilling and -Removal for Shaped Hole Production**

Intelligent engine control & monitoring substantially support the reduction of maintenance costs. Exploiting its longterm experience in the EJ200 DECU / DECMU development, MTU performs substantial technology development which aims at optimum use of life cycle potential and minimum life-cycle-costs by consequent On-Condition Maintenance.

Similar as with new parts production, economic and high quality processes significantly impact maintenance costs. To give an example, Linear Friction Welding and Micro Plasma Welding are well estab-

lished processes for patch repair and blade replacement at Blisk structures. An ad-



**Fig. 25: Sample Tests with Inductive High Frequency Pressing Welding**

vanced repair technology combining minimum pressing forces with minimum processing times is in preparation. With the Inductive High Frequency Pressing Welding the welding energy is generated by induction heating and is suited for economic blade replacement with the blades made from both, Ti- or Ni-alloys, Fig. 25.

## 7. SUMMARY

Today's aero engines have obtained a high technological standard constituting its strong contribution to an economic, safe and environmentally compatible air transport for everybody.

The high technology standard is the result of a long-term development process maintained during several decades of intensive engineering efforts.

Nevertheless, further improvements in efficiency, economy and environmental compatibility, triggered by a highly competitive market and tightening international regulations, necessitate ongoing progress. MTU Aero Engines meets the demanding challenges by focussing its major technology development activities on:

- Efficient engine components and innovative engine concepts
- Economic and high quality processes in production and maintenance
- Sustainable improvements in environmental compatibility

Thus, as an indispensable partner in all major engine programs, MTU is continuously improving its technological competence in order to meet the increasing challenges connected with a sustainable growth of tomorrow's economic and environmentally compatible air transport.

### **Acknowledgement**

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