PHASES OF HIGH-TECH REPAIR IMPLEMENTATION
DEFINITION, DEVELOPMENT, ADAPTATION, VALIDATION AND QUALIFICATION, IN CASE OF PATCH-REPAIR ON BLISK-BLADES

ARMIN EBERLEIN
MTU AERO ENGINES GMBH
D-80976 MUENCHEN, GERMANY
Armin.Eberlein@muc.mtu.de

ABSTRACT

The repair of engine components is getting more and more important taking a considerable volume of the aero-engine business. Increasing spare parts costs and the trend to high value engine components makes the invest in high-tech repair profitable.
This paper describes the different phases of a high-tech repair implementation from the definition, through the development of the technology key-repair-processes and their adaptation on the component to the validation and qualification of the repair, in case of Patch-Repair on Blisk-Blades.

The main phases are:
Repairability analysis

Engineering investigation and specification of the repair requirements.

Definition of validation requirements.

Development and optimization of the required manufacturing processes.

Application of the repair processes to the engine component.

Analytical modelling and simulation for process optimization and stabilization.

Validation and certification of the repaired specimens and engine parts.

Qualification by an engineering assessment.

Abbreviations

Blisk	Blade integrated disk
LPC	Low Pressure Compressor
EM	Engine Manufacturer
LCC	Life Cycle Cost
L/T	Leading/Trailing edge
NDT	Non Destructive Testing
HAZ	Heat Affected Zone
HV05	Hardness Check to Vickers
HPC	High Pressure Compressor

INTRODUCTION

The repair business of engine components grew dramatically up in the last years and takes a considerable volume of sales in aero-engine business.
In the recent years there was a trend to reduce the number of components per engine but on the other hand the value of the single component increased, as with the Blisk. The Blisk is a innovative and challenging design, blades integrated with the disk.
The initially application of blisk was achieved in small helicopter engine for the compressor and turbine section.

In the nineties due to the requirements from the military customers, the blisk has been established in most of the modern military engines. To achieve a maximum of thrust-to-weight ratio, the blisk has found its main application field in low and high pressure compressors, as single or drum design with 3D aerodynamic airfoils (Fig.1.).

Fig.1: LPC Blisk 1-3 (EJ200)

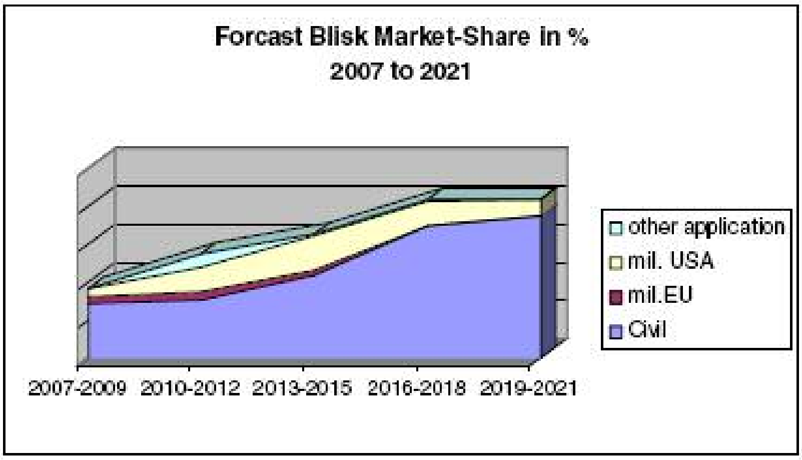


FIG. 2 FORCAST BLISK-MARKET

In the meantime the blisk design has invaded the territory of the commercial turbofan and turboprop engines, due to the essential advantages such as weight reduction, elimination of leakage flow through the blade root and rotor slot, increased accuracy of the gap between blade tip and abradable coating of the casing.
All these aspects improved significantly the efficiency, fuel consumption and emission rate compared to the conventional design with blades and disk assembled.
The blisk has started to supersede the conventional design. According to the aircraft OEMs, nearly each future aircraft will contain a blisk design in any way.
A forecast for the future blisk market is shown in fig. 2
In addition to the benefits of the blisk, some drawbacks are to be mentioned such as the high complexity of manufacturing, the special effort for handling and the necessity for comprehensive repair capability. The availability of economical repair processes is essential for reducing the Life Cycle Costs (LCC) and getting the acceptance from the customers in particular from airlines for a increased use of blisks.

On blisks, as on conventional bladed disk constructions, a differentiation has to be made between damage to the disk and to the blading. If it is to the disk, the types of damage encountered are very much the same for blisks as for conventional rotors. The most frequently performed repairs here involve the blending of surface damage to the disk body and seal fins, and the coating or plating of mating diameters. Additionally, renewal of wear-inhibiting coatings on seal fins or even restoration by build-up welding may become necessary.

The majority of damage occurs mostly on the blade airfoils, but since on blisks, replacement of the damaged blade as practiced on conventional rotors is prevented, a repair strategy needs to be developed for blisks that keeps life cycle costs (LCC) acceptable and makes the use of blisks economically acceptable.

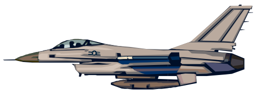
Analyses of a large number of engines in-service revealed the following causes and accompanying types of damage.

Cause of damage:
- foreign object (FOD)
- bird strike
- rub-in
- erosion
- surge

Type of damage:
- impact (light to heavy)
- tip wear
- L/T edge wear
- distortion of blade section

Damage patterns and frequency of occurrence are largely affected also by the type of aircraft, operator and application. See Fig. 3.

DAMAGE RATE DUE TO ARICRAFT TYP AND MISSION



Military Combat Aircrafts

Damage	Mission Low Altitude	Mission High Altitude
FOD	+++	++
Bird Strike	+++	++
Rub-In	+	+
Deterioration*	++	+

Civil Aircrafts

Damage	Mission Short Distance	Mission Long Distance
FOD	++	+
Bird Strike	++	+
Rub-In	+	+
Deterioration*	+	+

* Deterioration due to long term use

+ Normal ++ Significant +++ Heavy

Fig. 3 DAMAGE RATE DUE TO AIRCRAFT TYPE AND MISSION

Based on these types of damage and frequencies of occurrence, see Fig. 4, the following blisk repair concept has been developed, see Fig. 5.

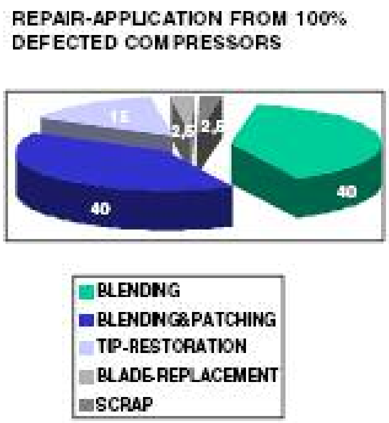


Fig. 4 DAMAGE RATE OF 100% DEFECETED COMPRESSORS

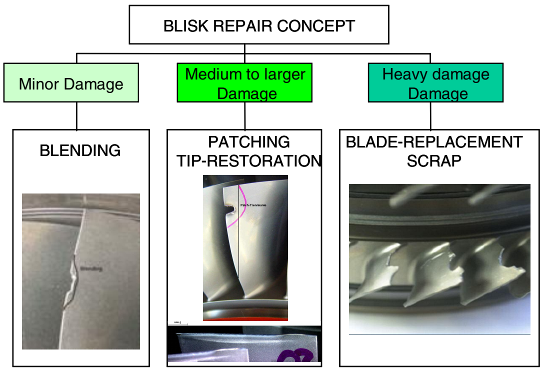


FIG. 5 BLISK-REPAIR CONCEPT

A typical repair solution called patching is used to describe the various phases.

REPAIRABILITY ANALYSIS

Patch repair is intended to cover most types of blade damage that are beyond repair by blending.
An important advantage of patch-repair is the unchanged FOD-capability due to the same material of patch and blade, unlike to a build-up weld repair.

The necessary patch geometries to be used on the blisk airfoils needs definition depending on the engine type and low- or high-pressure compressor involved, see fig.6.

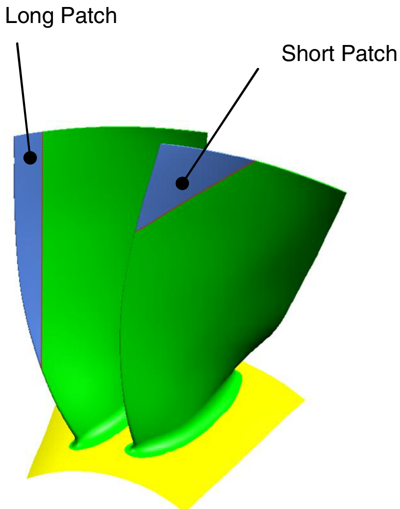


Fig. 6 DIFFERENT KIND OF PATCHES

Access for repair tools has to be considered in the design of the patch in addition to the type of damage because adjacent blisk areas are net-shape and should not be affected unduly.

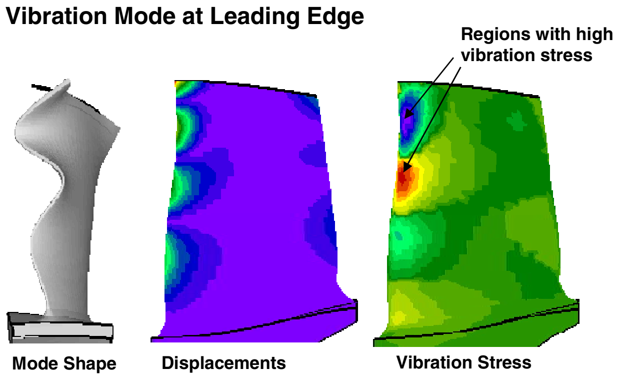


Fig. 7 TYPICAL LEADING EDGE VIBRATION STRESS

Another significant factor to consider when designing the patch geometry is that the airfoil should first be analytically investigated for regions of relatively low vibratory stresses at the various operating points.
A typical result is shown in fig. 7
The plane separating the patch from the rest of the blade should be located in areas of low vibratory stress, considering that the material properties of the weld will not in all areas match those of the basic material.

Engineering investigation/specification of the repair requirements

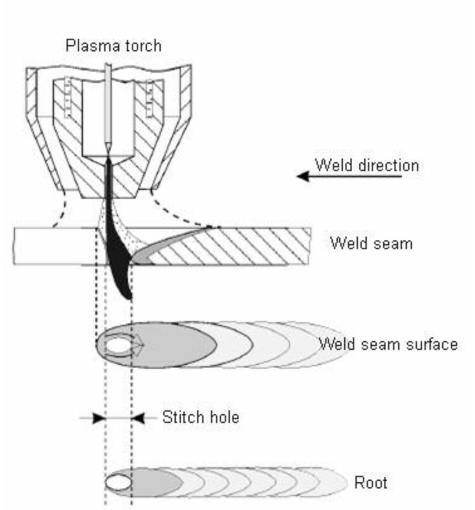
As previously described, for selecting the patch, the airfoil needs to be analytically investigated and, moreover, attention has to be paid to the geometric constraints of the blisk as well.
Under a repair development program, the various program stages are defined.
These include:

- Basic technological development, including selection of manufacturing and test methods, fixture concepts, spare parts variants.
- Definition of the necessary repair steps, including design and material specific properties and requirements of the repaired blisk blade.
- Specification of acceptance criteria for critical processes, such as welding and milling.
- Definition of the necessary investigations to be made, such as metallography, determination of material characteristics and residual stress measurements.
- Specification of the necessary tests and their scopes.

Development/Optimization of the required manufacturing processes

To implement the patch repair, the development, selection and optimization of key repair techniques became necessary, such as welding, local heat treatment, machining and inspection techniques.

Welding process, spare part and weld joint interface are essentially critical factors in achieving acceptable weld integrity while only moderately affecting the component. The weld integrity should approximate the properties of the base material. Deviations are only allowed in certain areas where low vibrational loading permits it.
Weld testing and development was conducted using a number of different weld processes (EB, laser and plasma arc welding) on test specimens of identical material.
Plasma arc welding using the stitch-hole technique qualified itself for this purpose due to high process stability, flexibility in use, adequate weld integrity and economic application, to name just a few reasons for its selection.
Fig.8 Plasma Arc Stitch-Welding

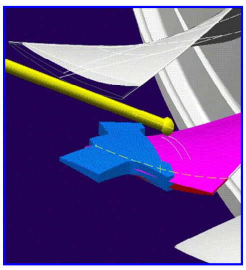


Heat treatment is required to reduce residual stresses and create a material balance; the final contour of the component permits a local heating only. A number of different heat sources were tested on specimens resembling the original component in terms of material and geometry. To satisfy requirements such as inert or vacuum atmosphere, adequate and uniform heat transfer and observance of a defined temperature gradient, heating by induction was selected.

Machining requirements were exacting considering the complex, integral construction and the 3D blade geometry. Additionally, geometric and dimensional manufacturing tolerances with deviations caused by service or damage need to be considered. This requires 5-axis NC machining equipment, intelligent software that processes nominal CAD data in keeping with individual actual data of the airfoil under repair and generates a suitable machining program, all of which is described by the term "adaptive machining process". As an EM, MTU has accumulated ample know-how and considerable depth and width of experience in the manufacture of military and commercial blisks. This background in data management, measuring and milling strategy, as well as fixture and tool selection, provides a basis and means of development of a repair application.

The necessary adaptive machining steps in a patch repair are:

- gauging and recording the geometric data of the damaged airfoil, fig.9.
- sectioning the damaged area along the defined patch geometry
- gauging the blade geometry after the patch has been welded in place
- generating an individual NC program in consideration of the actual and CAD data
- milling the welded patch continuously within a few hundredth of a millimetre relative to the rest of the blade, fig.10 and 11



Measurement of remaining blade

FIG. 9 BLADE GAUGING

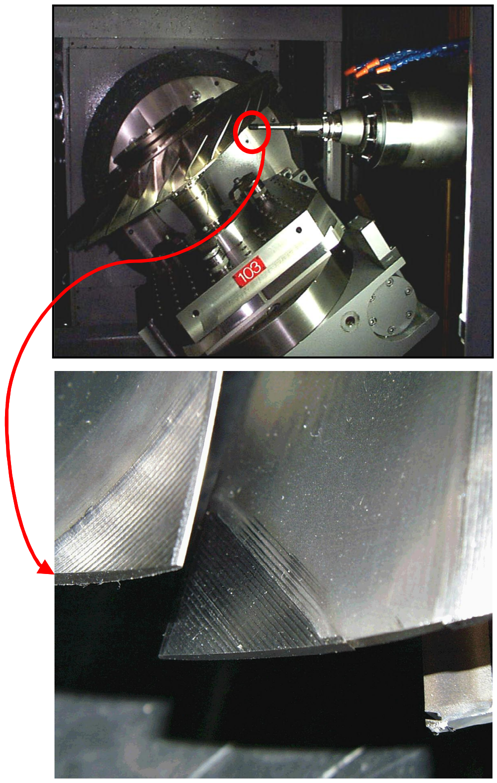


Fig. 10 and 11 ADAPTIVE MILLING OF WELDED PATCH

Application of the repair processes to the engine component

In the next phase, the repair processes as developed and suited to specimens are transferred and adapted to the original component.

To support and optimize the adaptation process, analytical model investigations and process simulations are made.

During weld adaptation, first weld trials on specimens provide a basis for FEM temperature modelling. Basis for FEM modelling is a 3D CAD model reflecting the geometry of the blisk and the patch. The FEM grid is structured more closely at the patch-to-blisk interfaces to more accurately capture the process effects. Fig. 12 shows the analytically determined temperature profile during the welding process at four different positions. Using the model, the effects of temperature and patch variations are simulated and calibrated using subsequent weld trials.

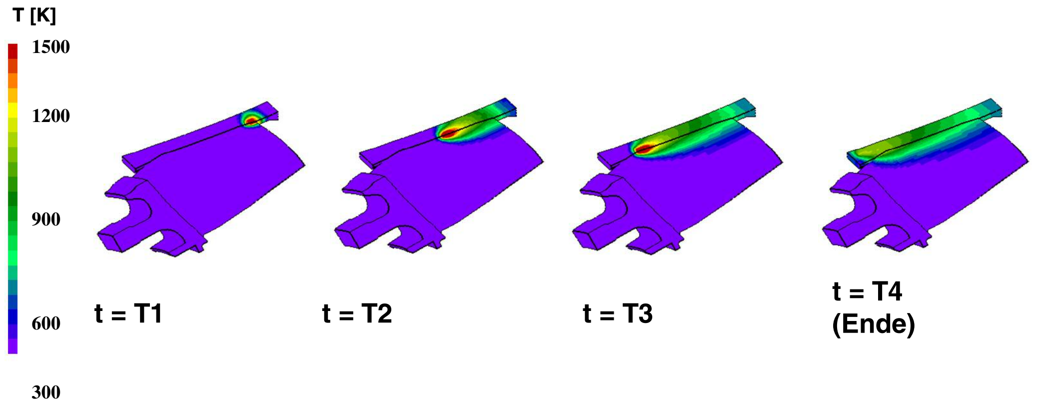


Fig. 12 FEM SIMULATION TEMPERATURE DISTRIBUTION DURING WELDING

When the weld parameters and patch geometry have been finalized, the affected areas, such as fusion and heat affected zone, are determined also analytically and the remaining residual stresses are calculated for the respective material in accordance with the thermal distribution and gradients introduced. Random sampling using the drilled hole method will very much confirm the analytically gained residual stress levels.

Analytical modelling and process simulation are effective also with local heat treatment. The heat treatment temperatures and conditions such as dwell time, cool-down phase and annealing atmosphere, commonly associated with the various materials, should be reproducibly established for the patch repair locally across the affected area.
The graph shows the dimensionless temperature distribution over time. Fig. 13.
An iterative optimization process is conducted between analytical process simulation and technically experimental implementation until the specified standards are achieved.

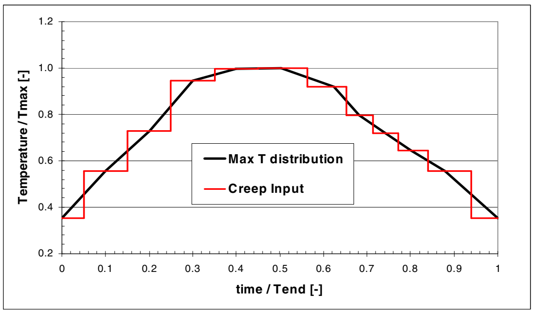


Fig. 13 TEMPERATURE DISTRIBUTION DURING LOCAL HEAT TREATMENT

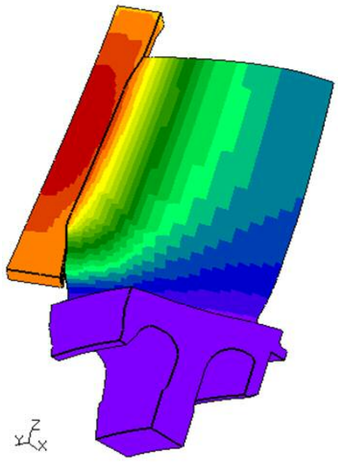


Fig. 14 TEMPERATURE DISTRIBUTION FOR T MAX

Heat treatment serves to reduce manufacturing stresses remaining and produce a thermodynamic material balance in the repaired zone, so that the original mechanical characteristics are restored.

Existing inspection techniques needed development and optimization for this type of repair and the requirements defined.
It was especially for critical process steps, such as welding, heat treatment and machining, that material- and process-specific defect types and severities, such as pores, undercutting, overheating and scoring, needed to be identified.
Sensitivity adjustment and optimum application sequence of the respective NDT technique in the repair cycle were further significant aspects.

The complete repair cycle is described as follows:

- Inspect and assess the damaged airfoil for reparability
- Gauge the damaged airfoil and record the data
- Section the damaged blade area in accordance with the specified patch geometry considering actual data
- Prepare for welding and tack weld the patch in the intended position
- Weld the standardized patch to the prepared blade
- Rough machine the patch allowing a defined offset
- Capture the actual geometry data and generate the NC program in accordance with the specified CAD data
- Finish machine the patch
- Local heat treat
- Surface finish
- Compaction peen
- Final finish
- Balance
- Final inspect

Apart from the plurality of process developments, several IT systems were introduced using the necessary software to achieve automated data management for optimum process control, data communication, logistics and, of course a comprehensive quality control throughout the repair cycle.

VALIDATION AND CERTIFICATION OF REPAIRED SPECIMENS AND ENGINE-COMPONENTS

The last phase describes the validation and certification of the repaired component.
It is already during process development on test specimens and component adaptation that NDT and metallographic investigations are made continuously to determine and finalize quality, reproducibility and process limits.
For final validation and certification, original components are send through the specified repair routine and repaired, depending on the scope of testing and inspection. Comprehensive pre- and post-repair measurements are used to determine the potential dimensional and geometric effects on the blisk.
Airfoil measurements and surface finish measurements of the repaired area complete the geometric data needed for assessment of the repaired blades.

Metallographic investigations are made on the critical blade areas to witness the necessary material structure in the weld and heat affected zone. The attached Fig. 15 illustrates the weld profile of a repaired Ti6-4 blisk airfoil and the associated hardness increase of the material.

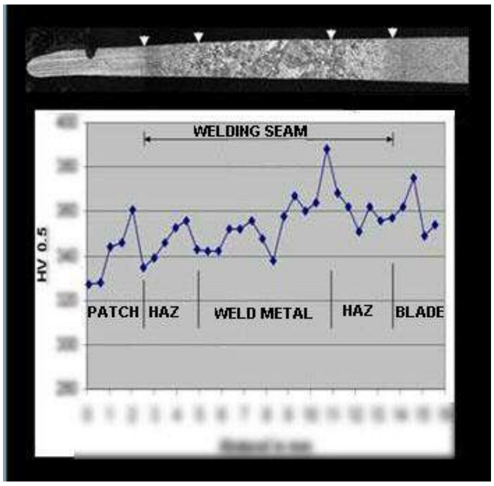
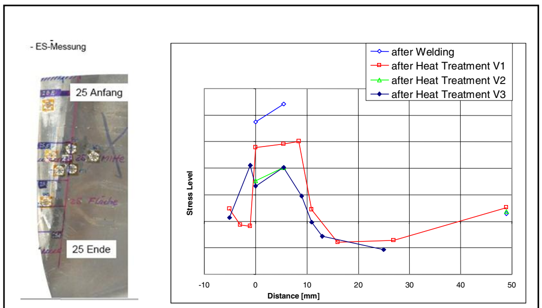


FIG. 15 METALLOGRAPHICAL SECTION OF REPAIRED AREA

As a further validation step, the residual stresses across the repaired area are determined, as shown in Fig. 16. The impact of the various manufacturing operations on the component is investigated to ensure that the required residual stress level upon completion of the repair is achieved.



Residual stress measurements

Fig. 16 RESIDUAL STRESS MEASUREMENT

To ensure and witness that the repair has not caused intolerable changes in fit, form and function on the blisk, several different component tests are made that reflect service stresses.
These tests provide data on the existing fatigue strength potential and mechanical structural strength of the repaired component. The EM background in blisk design and manufacturing facilitates the repair validation and certification process.

The validation process is supported also during testing by accompanying analytical investigations. The stresses arising in engine service, such as static tensile load triggered by centrifugal force and resultant excitation of vibrations, are simulated in the FEM model at the various operating points to identify the blade stress peaks.
In the subsequent HCF test, these stresses are specifically replicated to obtain evidence of the necessary fatigue strength and mechanical structural strength. Depending on the blade type and patch geometry, various modes of vibration (1F, 1T,1C or 2F) will have to be excited to achieve airfoil vibration peaks in the repaired zone.
Fig.17. shows FEM models of repaired fan-blade under 1F-vibration mode and the test-equipment.
Impact tests to witness FOD sensitivity at the leading edge will not be necessary considering that in patching, the material of the replacement part is similar to that of the blade.
When component tests do not show adequate statistical continuity, an engine test on a repaired blisk, using a focused engine program traversing critical operating points, will become necessary for complete evidence.

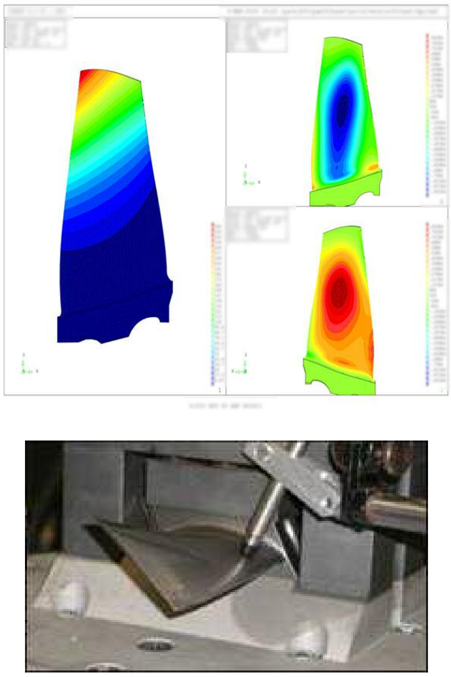


FIG. 17 VIBRATION MODES AND TEST-EQUIPMENT

As a final validation step, all results of the investigation, the validation hardware and the entire test results are analyzed and evaluated under an engineering assessment.
The assessment shall witness that fit, form and function of the repaired part, compared with the original part, were not intolerably altered.

Under a military contract, MTU has developed and certified fan-blisk Patch-Repairs.
The repair processes are released for in-service application.
Adaptation to other blade materials and geometries are in progress including to HPC single- and spool-blisks.
Due to the repair Know-How and experiences this repair technique can also be transferred and used for civil engine blisks.

Summary:

Implementation of high-tech repairs as typified by the patch repair comprises five essential phases:

- Repairability analysis
- Definition of engineering and validation requirements
- Development and optimization of repair manufacturing processes
- Adaptation and transfer of the resulting repair processes to the original component, supported by analytical process modelling and simulation
- Validation and certification of the repaired component through comprehensive investigations and tests concluded by engineering assessment

This manner of implementing a high-tech repair requires the involvement of a wide range of different disciplines like product support, logistics, engineering, analytics, process development, repair and quality, all under the roof of an effective and focused project management.

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