Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 22 (2014) 256 – 262

www.elsevier.com/locate/procedia

3rd International Conference on Through-life Engineering Services
Session: Recent Progress in Jet-Engine Regeneration

Recent Progress in Turbine Blade and Compressor Blisk Regeneration

Jens Aschenbruck[a,*], Rafael Adamczuk[a], Joerg R. Seume[a]

[a]*Institute of Turbomachinery and Fluid Dynamics, Leibniz Universitaet Hannover, Appelstr. 9, 30167 Hanover, Germany*

[*] Corresponding author. Tel.: +49-511-762-17855; fax: +49-511-762-3997. *E-mail address:* aschenbruck@tfd.uni-hannover.de

Abstract

The regeneration process of jet engines is a highly complex, expensive and time-consuming. Especially the regeneration of high pressure turbine blades and compressor blisks are at the border of what is technically feasible. These components are highly loaded and thus substantial wear occurs. The blades and blisks must be overhauled or replaced regularly. The existing repair methods for these parts are inflexible and cannot be applied in many cases, resulting in a large number of scrapped parts.

Therefore a new turbine blade regeneration process is presented. The goal of the improved process is to reduce the scrap rate and cost. This process includes an early evaluation of the condition of the hot-gas path components before disassembly, new detection methods for defects on the turbine blades surfaces, and more flexible manufacturing processes. The process is supported by production process simulations and functional simulations to predict the optimal regeneration path depending on the blade condition and the business model of the customer.

The paper also presents a new approach for compressor blisk regeneration. This process will be developed and validated in the next years. New challenges in structural mechanics, aerodynamics, and manufacturing must be addressed due to the complexity of blisks. As part of the ongoing research, three new blisks will be designed and subjected to the complete regeneration path, which is also supported by simulations. In order to validate the simulations, their results will be compared to experimental results of the regenerated components on a compressor test rig.

Peer-review under responsibility of the Programme Chair of the 3rd InternationalThrough-life Engineering Conference

Keywords: Jet-Engine Overhaul; Compressor Blisks; Turbine Blade Repair; Regeneration

1. Introduction

The regeneration of jet engines, also called overhaul, is of high interest for airline operators because 8 % of the operating cost of an airplane are due to engine maintenance and overhaul. Approximately 50 % of the overhaul cost are caused by the airfoils. These cost are mainly produced by the replacement of worn blades from the high-pressure turbine. These blades are among the most highly loaded parts in jet engines. Thus, turbine blades have to be repaired or replaced often. A complete new set of rotor blades of the first stage (GE CF6-80C2) cost almost $ 500,000 [1].

In order to address these facts, the Collaborative Research Centre (CRC) 871 “Regeneration of Complex Capital Goods” aims to develop the scientific basis for the maintenance of jet engines, which are among the most complex capital goods. The main goal of the CRC 871 is to save as many of the worn components as possible. At the same time, the functional properties of jet engines have to be restored and/or even improved. The improvement of the turbine blade regeneration process should reduce the number of necessary new parts. For this purpose, new repair methods are developed and the existing methods are improved to increase flexibility. The turbine blade regeneration process is analyzed and individual steps are being investigated by a subproject within the CRC. New manufacturing processes are developed and the functional benefit of regenerated components and of the entire regenerated jet engine are assessed by model-based simulations.

The regeneration of turbine blades has been the main research object in the CRC 871 since the beginning of 2010. In the literature, Bremer [2,3] developed a procedure to automate work steps in the repair process of turbine components. Another focus was placed on the adaptive machining technology using measuring devices to compensate the part-to-part variations and inaccurate clamping positions. A holistic approach of the turbine blade regeneration process considering the inspection, production process simulation, functional simulation, and evaluation of different regeneration paths has not been published before.

With the beginning of 2014 the repair of blade integrated

Peer-review under responsibility of the Programme Chair of the 3rd InternationalThrough-life Engineering Conference
doi:10.1016/j.procir.2014.07.016

disks (blisks) has been added as a main research object. In modern civil jet engines, blisks are becoming more common in the compressor to reduce weight. In a few years, these engines are going to require a first complete overhaul. Consequently, this topic will be of high interest in the next few years. The regeneration of blisks offers new challenges to engineers as there exist less repair methods, the handling of the components is difficult, and aspects of structural mechanics as well as aerodynamics have to be considered [4–6]. The repair of these parts is more important than that of single compressor blades, which are mounted on a disk. If one compressor airfoil of a blisk is damaged, nowadays in many cases the blisk cannot be repaired or the repair cost are too high so the blisk must be replaced by a new one. For the regeneration of compressor blisks, new repair methods, measuring systems, and evaluation methods are being developed within the CRC. The aim is to repair more of the damage typically occurring in compressor blisks.

In this paper the structure and the projects of the CRC are briefly described and the improved turbine blade regeneration process which is developed and proposed by the CRC is presented. The paper also provides an outlook on the ongoing research and describes the new focus on compressor blisk regeneration.

2. Structure and Projects of the Collaborative Research Center 871

The CRC 871 exists since 2010 and is financed by the German Research Foundation (DFG). In the first four years (2010 till 2013), some of the scientific fundamentals for the overhaul of turbine blades of jet engines were developed in 17 subprojects. The turbine blade regeneration process was thereby improved. More details are given in subsequent session 3. In [7], the titles and contents of the subprojects are briefly described.

The subprojects of the CRC 871 are grouped into four project areas. These project areas and subprojects are depicted in Fig. 1 and were derived from the need to conduct research on the regeneration of jet engines. Project area A “Inspection and Diagnostics” aims to improve the volume and quality of information from the inspection, which is necessary for planning the regeneration process. The subprojects of this project area develop methods for an earlier, cheaper, and faster detection of the condition of the engine or of single components.

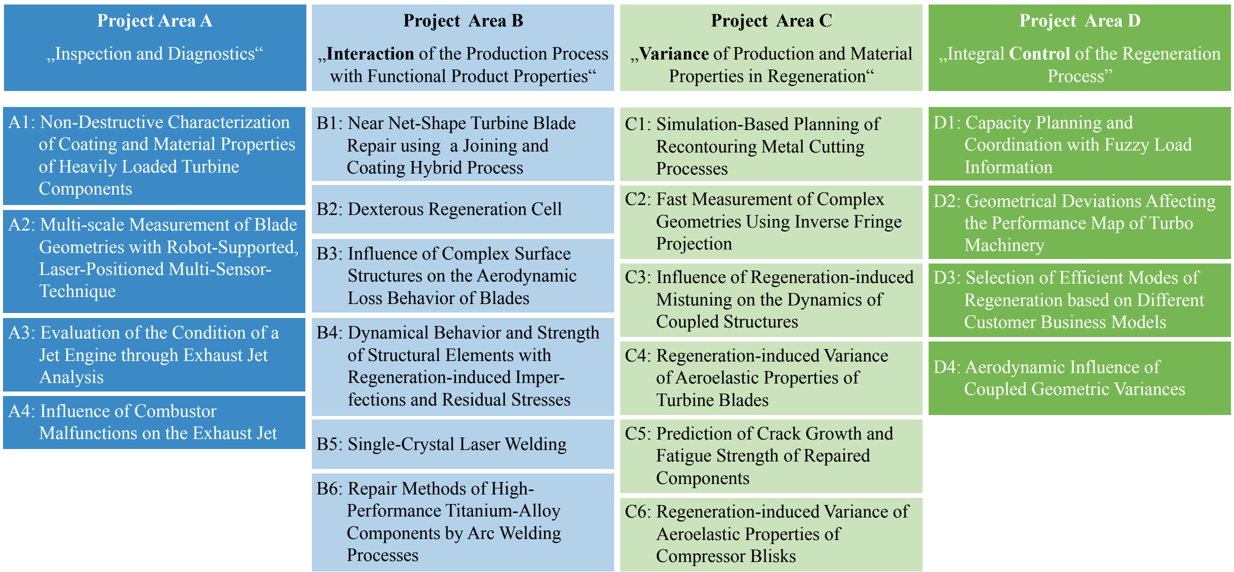
In project area B “Interaction of the Production Process with Functional Product Properties”, the goal is to determine and to consider the complex interaction between production processes and functional properties of the components. To this end, the subprojects also simulate the production process. The results of these simulations are used to determine the influence on the functional properties like the life cycle, fuel consumption or vibration behavior.

The focus of project area C “Variance of Production and Material Properties in Regeneration” is on the variances which occur due to operation and overhaul. The goal is to handle these variances and to estimate the influence of these variances on the functional properties.

In project area D “Integral Control of the Regeneration Process”, the results from the other project areas are used for the integral control of each regeneration step in order to build an integrated process. Another aim is to integrate the simulations of the functional properties of the components. By integrating these simulations, it should be possible to evaluate the functional properties of the whole system, so that the complete process can be controlled.

In addition to the regeneration of turbine blades, the overhaul of compressor blisks is the focus of research in the CRC 871 since 2014. For this new research subject, three new subprojects were started:

- B6 “Repair Methods of High-performance Titanium-alloy Components by Arc Welding Processes”
- C6: “Regeneration-induced Variance of Aeroelastic Properties of Compressor Blisks”
- D4: “Aerodynamic Influence of Coupled Geometric Variances”



Project Area A	**Project Area B**	**Project Area C**	**Project Area D**
„Inspection and Diagnostics“	„**Interaction** of the Production Process with Functional Product Properties“	„**Variance** of Production and Material Properties in Regeneration“	„Integral **Control** of the Regeneration Process”
A1: Non-Destructive Characterization of Coating and Material Properties of Heavily Loaded Turbine Components	B1: Near Net-Shape Turbine Blade Repair using a Joining and Coating Hybrid Process	C1: Simulation-Based Planning of Recontouring Metal Cutting Processes	D1: Capacity Planning and Coordination with Fuzzy Load Information
A2: Multi-scale Measurement of Blade Geometries with Robot-Supported, Laser-Positioned Multi-Sensor-Technique	B2: Dexterous Regeneration Cell	C2: Fast Measurement of Complex Geometries Using Inverse Fringe Projection	D2: Geometrical Deviations Affecting the Performance Map of Turbo Machinery
A3: Evaluation of the Condition of a Jet Engine through Exhaust Jet Analysis	B3: Influence of Complex Surface Structures on the Aerodynamic Loss Behavior of Blades	C3: Influence of Regeneration-induced Mistuning on the Dynamics of Coupled Structures	D3: Selection of Efficient Modes of Regeneration based on Different Customer Business Models
A4: Influence of Combustor Malfunctions on the Exhaust Jet	B4: Dynamical Behavior and Strength of Structural Elements with Regeneration-induced Imperfections and Residual Stresses	C4: Regeneration-induced Variance of Aeroelastic Properties of Turbine Blades	D4: Aerodynamic Influence of Coupled Geometric Variances
	B5: Single-Crystal Laser Welding	C5: Prediction of Crack Growth and Fatigue Strength of Repaired Components	
	B6: Repair Methods of High-Performance Titanium-Alloy Components by Arc Welding Processes	C6: Regeneration-induced Variance of Aeroelastic Properties of Compressor Blisks	

Fig. 1. Project Areas and Subprojects of the CRC 871

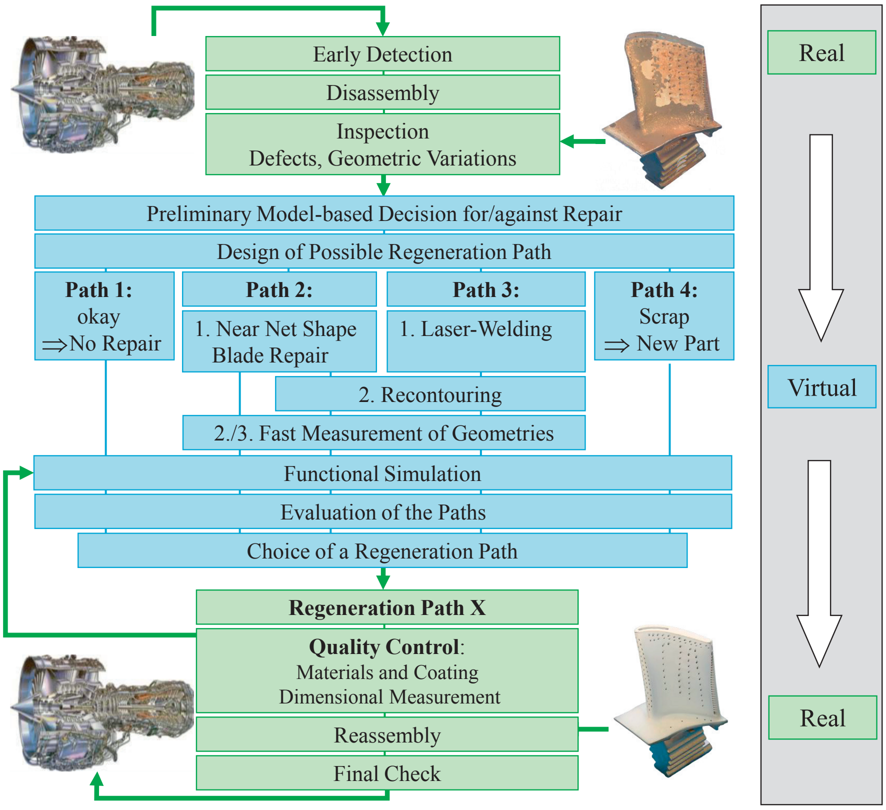


Fig. 2. Turbine Blade Regeneration Process

3. Improvement of Turbine Blade Regeneration Process

Blades of high pressure turbines are aerodynamically, thermally, and mechanically highly loaded leading to substantial wear. For this reason, a high portion of the blades have to be replaced and cannot be repaired because no suitable regeneration process exists for repairing these worn blades.

To reduce the scrap rate and to repair more blades, the turbine blade regeneration process, shown in Fig. 2, is improved in the CRC 871. In this process, rule-based decisions for or against the repair of components are made. These rules are developed based upon functional simulations of the components and simulations of the production process. For this purpose, it is first necessary to determine the condition of an engine's components.

3.1. Early Detection and Inspection

In subproject A3 "Evaluation of the Condition of a Jet Engine through Exhaust Jet Analysis", the condition of hot gas path components can be analyzed by using the optical background-oriented schlieren method (BOS) [8–10]. In the BOS method, the density field of the exhaust is reconstructed tomographically. The advantage of this method over current procedures is the fast detection of the engine's condition before the disassembly (see Fig. 2, "Early Detection").

In the next step, the disassembled turbine blades are inspected for defects or geometric deviations. The coating and the material conditions of the turbine blades are investigated with High Frequency Eddy Current Technology and High Frequency Induction Thermography. Both methods were developed by the subproject A1 "Non-Destructive Characterization of Coating and Material Properties of Heavily Loaded Turbine Components" [11]. The geometries of the blades are measured with a multi-scale measurement system. Using this system, it is possible to measure the macro- and the micro-geometry of the blades. A multi-sensor head is used for these measurements. This system was developed in the subproject A2 "Multi-scale Measurement of Blade Geometries with Robot-Supported, Laser-Positioned Multi-Sensor-Techniques" [12]. The information obtained by the inspections are processed quantitatively and used as input parameters for simulations of the regeneration path.

3.2. Design of Regeneration Paths

In the subsequent steps, possible regeneration paths for the turbine blade repair are created virtually. The paths are being designed by the subprojects D1 and D3 which deal with the planning of the capacity and the selection of efficient modes for different customer business models. For each of these regeneration paths, the production processes are simulated to determine the cost for this repair. In Figure 2, four exemplary paths are depicted for the regeneration of worn turbine blades. No repair is necessary in two cases because in path 1 the blade is in the tolerances and can be used further without repair and in path 4

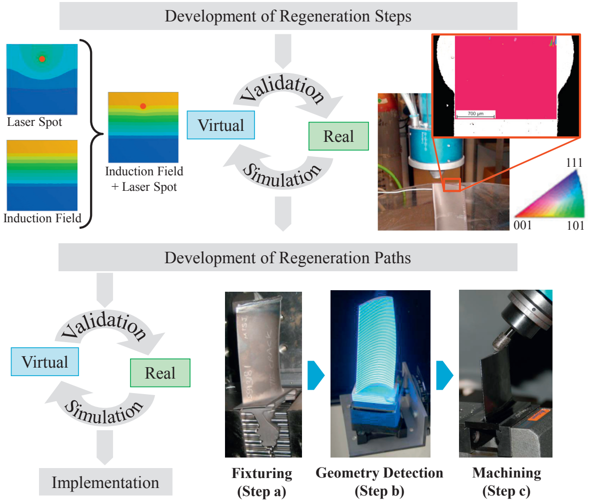


Fig. 3. Development of Regeneration Steps for the Turbine Blade Repair

the worn blade cannot be repaired and has to be replaced. Two new repair methods are shown for the repair of defect turbine blades in path 2 and 3.

3.3. Production-Process Simulation

The first method is the near net-shape repair depicted in path 2. This method was developed by subproject B1 and is a coating and joining hybrid process [13,14]. It can be used for small defects like nicks, scratches, and small cracks.

For larger cracks in blade tip region, single crystal welding is being developed by subproject B5 [15]. The challenge of this new method is to obtain the single crystal structure of the base material during and after the welding process. The development of this regeneration step is depicted exemplarily in Fig. 3. For the integration of a new step in the process, this step must also be simulated. The virtual results are then validated experimentally. Afterwards, the new step is integrated in a regeneration path which consists of several regeneration steps (see Fig. 3).

After the first step of the regeneration path (see Fig. 2), the turbine blades are recontoured. In some cases of the near net-shape repair, the recontouring is not necessary. The simulation of the recontouring process is very complex because different material properties occur in the heat-affected zone of the welded turbine blades. The simulations of such repairs are investigated in subproject C1 [16].

During the real regeneration process, the geometry of the turbine blades must be checked as to whether the repair methods were successful and the blades are within the limits. This assessment of the geometry must be quick. For this purpose, the inverse fringe projection was developed by subproject C2 [17,18].

3.4. Functional Simulation

The information of the geometry and properties of the repaired turbine blades are necessary for the functional simulations of the overhauled blade. In these simulations, the influence of the regeneration process on the crack growth [19–21], dynamic behavior, mistuning effect [22,23], aeroelastic effects [24,25], and the aerodynamic loss behavior caused by surface roughness [26,27] are evaluated.

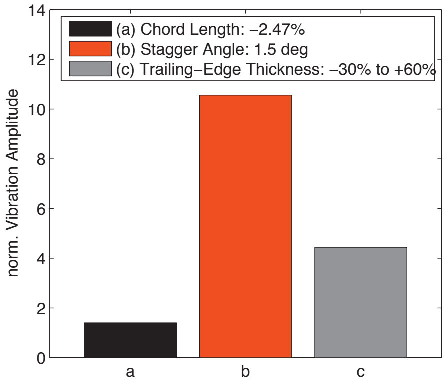


Fig. 4. Normalized Vibration Amplitude of Turbine Blades for Alternating Variations on Stator Vanes

In Figure 4 and in Table 1, exemplary results of the functional simulations are presented. The aerodynamic investigations of regeneration-induced variances are conducted with a turbine blade profile which was designed for experimental investigations in a cascade wind tunnel [26]. The geometric variances in the macro-level have a maximal influence of 0.8% on the turbine efficiency (see Tab. 1). The reduction of the blade thickness and of the trailing edge thickness increases the turbine efficiency. In contrast to this, the efficiency is decreased by a reduction of the chord length and of the stagger angle. The microscopical variances also reduce the efficiency but they have less influence. This influence strongly depends on the roughness position and roughness height. Further details of these results are presented in [27].

The regeneration-induced variances also influence the aerodynamic excitation. These investigations are conducted in the 5-stage air turbine of the Institute of Turbomachinery and Fluid Dynamics. Depending on the geometric variations and on the patterns of the variations, the vibration amplitudes of the downstream blade row can significantly increase (see Fig. 4). The study shows the highest influence due to stagger angle variations. The amplitude is over ten times higher compared to the configuration without variations [24].

Using these evaluations, it is possible to estimate the gain in functional properties (e.g. higher efficiency, extended life limit,

Table 1. Changing of Total Pressure Loss and Turbine-Efficiency depending on Geometric Variations (Macro- and Micro-Level) [27]

Geometric Variations	Change in Total Pressure Loss in (%)	Change in Turbine-Efficiency in (%)
Equivalent Sand Grain Height		
• at Leading Edge 500 μm	+0.5	-0.025
• on Suction Side 500 μm	+5.5	-0.123
Blade Thickness −5%	-10.5	+0.525
Trailing Edge Thickness −50%	-16.3	+0.815
Stagger Angle −1.5 *deg*	+1.2	-0.060
Chord Length −2%	+2.2	-0.110

lower exhaust gas temperature, higher thrust, lower vibrations) of the jet-engines depending on the repair path. These evaluations were developed and integrated in the regeneration process.

3.5. Evaluation of the Paths

The results of the production process simulation and functional simulations are needed to select the optimal regeneration path as a function of the customer requirements. For this purpose, the benefit of the regeneration path is compared with the cost of the production process. A cost-model was developed for this evaluation by subproject D3, in which the business model of the customer is considered [28]. Depending on the costumer requirements, the optimal regeneration path is selected by using the results of the preceding steps of the virtual regeneration process.

3.6. Execution of the Selected Regeneration Path

Subsequently, the optimal regeneration path is executed in reality. The turbine blade is repaired according to one of the four paths. After finishing the repair, a quality control of the turbine blade is conducted as depicted in Fig. 2. The quality control consists of the same methods as the inspection before the simulations of the regeneration paths. The results are fed into the production process and functional simulations for validation and improvement of the prediction of the regeneration process.

Finally, in the future regeneration process, the components and the whole engine are reassembled and a final check is conducted in the test cell. In this test, the BOS-method could then used to check the hot gas components. However, the reassembly and final check are not done in the CRC 871.

4. Future Trends in Compressor-Blisk Regeneration

In recent years, compressor blisks became more common in civil aircraft engines. Blisks combine the blades and the disk in just one element so that it is not necessary to attach the blades to the disk. Thus, assembly cost is reduced. The biggest advantage, however, is the reduction of specific fuel consumption due to the reduction of weight as well as drag. Furthermore, without blade roots, crack initiation and propagation is reduced.

However, engineers are faced with several challenges and disadvantages when designing blisks. Aerodynamics, vibrations, and aeroelastic coupling are of higher importance because the natural damping of a dovetail root of typical blades is eliminated. Thus, the regeneration of blisks is more complex and costly. In general, a blisk needs to be removed from the engine if there is damage beyond small dents. The inspection and repair of a blisk is more complex also because of component handling and because it is harder to inspect the surface with optical measurement methods. Greater damage might make it necessary to replace the whole blisk. In the case of repairing the component, it is necessary to take into account the increased interaction between tooling and work piece because the profiles are thin and tend to deform under cutting forces.

Facing these challenges, the CRC 871 intends to develop the necessary technologies in order to propose a holistic approach for improved regeneration of compressor blisks. The process is illustrated in Fig. 5. The CRC will design three new blisks which will be used for the study of the regeneration-specific effects, as stated before. One blisk represents the reference (as new) state while the other two blisks represent deviations which result from wear due to operation. The design takes into account the determination of geometric variances of overhauled blisks, the design of the disk-gripping and the transfer of typical wear on the blisk. The newly designed blisks can be inspected by using non-destructive methods like eddy current testing, thermography, and optical multi-scale inspection. The CRC has already demonstrated that the methods are capable for the inspection of different small and large scale defects and cracks on turbine blade surfaces and in the material below the coating (e.g. [11,12,29,30]). Next, these methods will be developed further for application to the blisk.

After the inspection, the CRC focuses on two different paths, the virtual one and the real one. Within the virtual path, different repair procedures will be simulated and evaluated. They are complemented by functional simulations of the regenerated blisks. The simulations will include the application of patches to the defect areas. In this context, the development of new scientific principles will be required because the blisks are made of titanium alloys. In order to be able to replace a complete blade, welding processes of titanium alloys will be further developed. Afterwards, the blades will be recontoured to restore the initial form. Based on the findings [16,31,32], the feasibility of this approach was demonstrated for the regeneration of turbine blades; these procedures will now be adapted to compressor blisks.

After the simulation of the repair processes, functional simulations will be conducted along the virtual path. They include the structural mechanics, the aerodynamics, and the aeroelastic evaluation of the overhauled disk as well as the influence of surface roughness. Hereby the findings for turbine blades provide the basis for the evaluation of blisks, i.e. [19–22] for the structural/mechanical, [24,25] for the aerodynamics, and [26,27] for the influence of surface roughness. The knowledge already gained will be expanded to the more complex blisk structure and the flow within a compressor.

The virtual path is validated afterwards with the real process. Within the second phase two damaged blisks will be sent through the whole process. The regenerated components will be inspected by using the inverse fringe projection method [18]. At the moment, the method is capable of inspecting free form surfaces like turbine blades. The method will be augmented by using an extension arm. The functional characteristics will be investigated closely in a compressor test rig. The comparison of the results of the virtual with the real path will provide validation cases for the approach. The goal is to generate a process which will allow engineers to predict the necessary regeneration steps and the resulting component characteristics.

5. Conclusions and Outlook

Within the CRC 871, the challenges of regenerating cost-intensive, highly-loaded high-pressure turbine blades were addressed and a holistic approach was developed within four different project areas. This paper describes a process which includes an early detection of worn blades before disassembly, a fast optical inspection of the blades, and new manufactur-

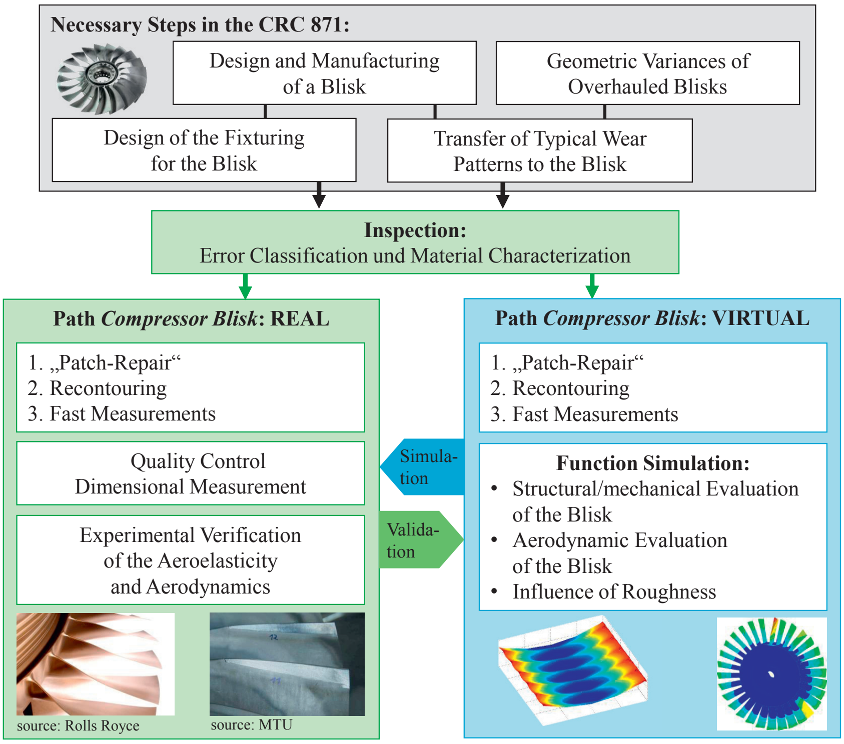


Fig. 5. Development of the Regeneration Path for Compressor Blisk repair

ing processes which help to reduce the scrap rate of worn turbine blades. The process is supported by functional simulations which help the engineer to choose the right regeneration path to predict and achieve the optimal functional characteristic of the overhauled blade within limited cost.

The next steps are the definition and development of a process for compressor blisk regeneration where, due to the complexity of the component, new challenges need to be addressed. Especially, mechanical, aerodynamic, and fixturing issues are of great importance. The proposed process is also supported by functional simulations. Three blisks will be designed and subjected to the complete regeneration process in order to demonstrate the feasibility of the approach and validate the predictions of the virtual path.

Acknowledgements

The authors kindly thank the German Research Foundation (DFG) for the financial support of the Collaborative Research Center (SFB) 871 “Regeneration of Complex Capital Goods”.

References

[1] Rupp O.: Instandhaltungskosten bei zivilen Strahltriebwerken, Deutscher Luft- und Raumfahrtkongress 2001, Hamburg DGLR-2001-008; 2001.

[2] Bremer K.: Automated Repair and Overhaul of Aero-Engine and Industrial Gas Turbine Components. ASME Turbo Expo 2005, Reno, Nevada, USA, June 69, 2005, Paper No. GT2005-68193, pp. 841-846, 6 pages, doi:10.1115/GT2005-68193

[3] Bremer K.: Data Management and Adaptive Machining Technology for Efficient Repair and Manufacture of Turbine Components. ASME Turbo Expo 2008, Berlin, Germany, June 913, 2008; ISBN: 978-0-7918-4311-6

[4] Qi H., Azer M., Singh P.: Adaptive toolpath deposition method for laser net shape manufacturing and repair of turbine compressor airfoils. The International Journal of Advanced Manufacturing Technology, April 2010, Volume 48, Issue 1-4, pp 121-131

[5] Kelbassa I., Albus P., Dietrich J., Wilkes J.: Manufacture and Repair of Aero Engine Components using Laser Technology. Proceedings of the 3rd Pacific International Conference on Application of Lasers and Optics 2008

[6] Richter K.-H., Orban S., Nowotny S.: Laser cladding of the titanium alloy Ti6242 to restore damaged blades. Proceedings of the 23rd International Congress on Applications of Lasers and Electro-Optics 2004, October 4 - 7, 2004, San Francisco, California, USA

[7] Kleppa O., Henke M., Seume J.R.: Verbesserte Nutzung betriebsbeanspruchter Bauteile durch gezielte Regeneration, Deutscher Luft- und Raumfahrtkongress 2010, 31 August - 2 September 2010, Hamburg

[8] Adamczuk R., Seume J.R.: Time Resolved Full-Annulus Computations of a Turbine with Inhomogeneous Inlet Conditions, International Journal of Gas Turbine, Propulsion and Power Systems, Volume 4, Nummer 2; 2012

[9] Adamczuk R., Hartmann U., Seume J.R.: Experimental demonstration of Analyzing an Engines Exhaust Jet wit the Background-Oriented Schlieren Method, AIAA Ground Testing Conference, San Diego, USA, 2013

[10] Adamczuk R., Buske C., Roehle I., Hennecke C., Dinkelacker F., Seume J.R.: Impact of defects and damage in aircraft engines on the exhaust jet, Proceedings of ASME Turbo Expo 2013, San Antonio, Texas, USA, GT2013-95079, June 3-7, 2013

[11] Reimche W., Bruchwald O., Frackowiak W., Maier H.J., Bach Fr.-W.: Non-Destructive Determination of Local Damage and Material Condition in High-Performance Components, HTM - Journal of Heat Treatment and Materials 2/2013

[12] Krauss M., Kaestner M., Reithmeier E. Multi-Scale Inspection of Worn Surfaces for Product Regeneration in Journal of the CMSC 1/2013

[13] Nicolaus M., Mhwald K., Bach Fr.-W.: A New Hybrid Process for Repair Brazing and Coating of Turbine Blades, ITSC 2012, Houston

[14] Nicolaus M., Mhwald K., Bach Fr.-W., Maier H.J.: Heat treatment of

thermal sprayed Ni-base-fillermetal/NiCrAlY-coating systems for repairing turbine blades, Thermal Spray Bulletin, September 2013

[15] Rottwinkel B., Noelke C., Hustedt M., Kaierle S., Wesling V.: Single Crystal Crack Cladding of CMSX-4, 24th AEROMAT 2013

[16] Boess V., Koehler J., Nespor D., Samp A.: Numerical Simulation of Process Force during Re-contouring of Welded Parts Considering Different Material, Properties in CIRP Journal of Manufacturing Science and Technology 6 (2013) p. 167174

[17] Poesch A., Vynnyk T., Reithmeier E.: Using inverse fringe projection to speed up the detection of local and global geometry defects on free-form surfaces, Proceedings of SPIE, Vol. 8500, ISBN 9780819492173, DOI: 10.1117/12.928700, 2012

[18] Poesch A., Vynnyk T., Reithmeier E.: Fast Detection of Geometry Defects on Free Form Surfaces Using Inverse Fringe Projection, Journal of the CMSC, Vol. 8, No. 1, 2013

[19] Holl M., Loehnert S., Wriggers P.: An adaptive multiscale method for crack propagation and crack coalescence, International Journal for Numerical Methods in Engineering (DOI: 10.1002/nme.4373); Volume 93, Issue 1, pages 23-51; 2013

[20] Holl M., Loehnert S., Wriggers P., Nicolaus M.: Three-Dimensional Crack Propagation in Ductile Media Using The XFEM, CFRAC 2013 Prag, Computational Modeling of Fracture and Failure of Materials and Structures, ISBN: 978-80-01-05279-2; 2013

[21] Holl M., Rogge T., Loehnert S., Wriggers P., Rolfes R.: 3D Multiscale Crack Propagation Using the XFEM Applied to a Gas Turbine Blade. Journal: Computational Mechanics, Volume 53, Issue 1, pp 173-188, 2014, DOI: 10.1007/s00466-013-0900-5.

[22] Hohl A., Kriegesmann B., Wallaschek J., Panning L.: The Influence of Blade Properties on the Forced Response of Mistuned Bladed Disks, Proceedings of the ASME Turbo Expo 2011, Power for Land, Sea and Air GT2011-46826

[23] Pohle L., Panning-von Scheidt L., Wallaschek J.: Reduced order model of mistuned bladed disks using the krylov-subspace combined with the craigbamton reduction technique, 10th World Congress on Computational Mechanics, Sao Paulo 2012

[24] Aschenbruck J., Meinzer C., Pohle L., Panning-von Scheidt L., Seume J.R.: Regeneration-induced forced response in axial turbines. Proceedings of the ASME Turbo Expo 2013,GT2013, San Antonio, Texas, USA, June 3-7, 2013

[25] Aschenbruck J., Seume J.R.: Experimental Verified Study of Regeneration-Induced Forced Response in Axial Turbines. Proceedings of the ASME Turbo Expo 2014, GT2014-25664, Duesseldorf, Deutschland, June 16-20, 2014

[26] Hohenstein S., Aschenbruck J., Seume J.R.: Aerodynamic Effects of Non-Uniform Surface Roughness on a Turbine Blade. Proceedings of the ASME Turbo Expo 2013, GT 2013-95433, San Antonio, USA, 3th-7th June 2013

[27] Hohenstein S., Aschenbruck J., Seume J.R.: Influence of Operation and Regeneration caused Variances of Turbine Blades. VGB PowerTech, International Journal for Electricity and Heat Generation, 11 2013, ISSN 1435-3199 K 43600

[28] Kellenbrink C.: First results on resource-constrained project scheduling with model-endogenous decision on the project structure. Operations Research Proceedings 2012, Springer Verlag

[29] Krauss M., Kaestner M., Reithmeier E.: Evaluation of Worn Surfaces Using Directional Illumination. Optical Measurement Techniques for Systems & Structures^2, ISBN 978-90-423-0419-2, p. 195-203.

[30] Krauss M., Frackowiak W., Poesch A., Kaestner M., Reimche W., Reithmeier E., Maier H.J.: Assessment of used turbine blades on and beneath the surface for product regeneration: Generation of a damage model based on reflection. geometry measurement and thermography, CLEO 2013 16.5.2013 Muenchen

[31] Denkena B., Floeter F.: Adaptive Cutting Force Control on a Milling Machine with Hybrid Axis Configuration. Procedia CIRP, 4 (2012), p. 109-114.; 2012

[32] Denkena B., Floeter F.: Dexterous Regeneration Cell for the Repair of Aircraft Engine Components. New Manufacturing Technologies in the Aerospace Industry, Machining Innovations Conference, 14.-15.11.2012, Hannover; 2012