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ScienceDirect

Procedia CIRP 120 (2023) 9–14

www.elsevier.com/locate/procedia

56th CIRP Conference on Manufacturing Systems, CIRP CMS ‘23, South Africa

Fully automated tool path planning for turbine blade repair

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Abstract

The recontouring process of aircraft engine parts like turbine blades is a manual or in best-case semi-automated process due to high individuality of the workpiece. This leads to in-process scrap because of low process stability and high process times. An automation of process planning reduces both. This paper introduces a method for a fully automated and individual tool path planning using 3D-scan data. Geometric parameters of the degenerated blade were considered to find best-suitable target geometry in a robust way. For turbine blade repair, the process stability is increased while meeting the dimensional tolerances required for the international aviation certifications.

Keywords: Computer automated process planning (CAPP); Geometric modelling; Tool path; Reverse engineering; Simulation; Automation; Turbine blade

1. Introduction

The regeneration of complex capital goods plays a significant role in the highly competitive and rapidly growing aviation industry. Maintenance, repair and overhaul (MRO) activities are responsible for the regeneration process. In addition to ensuring flight capability and meeting high quality standards, costs and lead times have to be minimized [1]. MRO on engine components is currently carried out by experienced employees based on guidelines, either with a high level of manual effort or in a partially automated manner. Fully automated planning and execution of repair work are not yet possible on an industrial scale, especially for highly stressed components such as turbine blades, due to the individuality involved in their operation [2]. An important process step in turbine blade repair is recontouring. This machining step determines the resulting blade geometry and is particularly responsible for the aerodynamic properties and, thus, the efficiency of the aircraft engine. Currently, existing approaches from the literature still lack robustness, which would be necessary for a fully automated application.

This paper contributes to an adaptable, fully-automated and individual process planning of the recontouring process considering 3D scan data in order to improve the repeatability and efficiency of turbine blade repairs. Knowledge is generated for the automated calculation of a best-suitable target geometry as well as for 5-axis tool path planning of blade profiles. The virtual modeling of the recontouring process by a geometric process simulation is used for predictive investigation of the recontouring result during process planning. This enables an optimized process design. It is followed by experimental validation using realistic reference parts of turbine blades.

2. State of the art

Challenges in process planning of recontouring processes are directly associated with the individual geometry of worn turbine blades. For these components, flight operations cause a deviation in shape from the original CAD model, which is why methods of advanced reverse engineering must be used to adapt the repair area of the blade to the remaining geometry. For this reason, the manufacturing processes are currently carried out manually based on experience or CNC-based using mostly 3-

10.1016/j.procir.2023.08.003

axis milling processes. The resulting restrictions in terms of feasible part shape, result in deteriorated fluid mechanical properties of repaired turbine blades. In addition to high labor costs, manual machining results in lower process reliability, which can lead to in-process scrap [3].

Therefore, current research projects aim to increase automation whereby the limits of automation are largely determined by the complicated shape and the generation of a suitable target geometry [4]. Bremer et al. have developed an automated repair system for turbine components. Here, the CAD surface reconstruction of the unknown nominal shape (reverse engineering) is considered and integrated into an overall process for recontouring the components [5]. A geometric simulation-based approach is only demonstrated by Biermann et al. for the possibility of low-vibration machining of turbine blades [6].

In the work of Zhang, an automatic reconstruction of a blade is performed and a tool path for recontouring is generated. Wavelet decomposition of individual cutting curves is used to determine a new nominal shape, based on which the subsequent milling process is adjusted [7]. A semi-automated geometric algorithm for the virtual repair of defective blades was developed by Piya et al. [8]. The algorithm uses the sectional Gauss map to generate a series of prominent cross-sections along the longitudinal axis of the defective airfoil. Nevertheless, a consideration of torsion and twist is not feasible. Wu et al. provide an overview of investigated methods for 2D and 3D reconstruction of geometries. The methods are based on the offset of a defect-free cross-section (airfoil) over the blade length. According to the authors, automatic reconstruction can already be implemented in practice with little effort only for blades with separate geometric criteria and without twisting [9]. Zheng et al. describe a method for adapting the tool path for recontouring to the contour without prior reverse engineering. For this purpose, tactilely measured cross-section profiles are shifted to the nominal CAD model of the blade. However, this ensures a constant-curvature transition only if the blade is not severely deformed in the undamaged region [10]. The method described by Su et al. works with polygon models or surfaces. However, since polygon models are unsuitable for tool path planning in CAM systems, the resulting model must be manually post-processed (PP) to generate ruled surfaces from the polygon surfaces [11]. Chui et al. demonstrate an automated method for deriving a triangular grid from measured point clouds based on a 3D biarc fitting technique. This grid is used to directly generate tool paths. The selection of the point density, which strongly influences the result, is considered problematic [12].

It was shown that several approaches in the literature focus on a software-supported process planning for the repair process of worn turbine blades. However, most approaches either lack robustness regarding damage caused by changes in the blade geometry, have high process times or have less adaptability. The current research on tool path planning for turbine blade repair is stated in Tab. 1. The overview emphasizes the demand for a more robust planning method that works for strong defects in complex curved turbine blades and that generates the tool path in a full-automated way without manual after-processing.

Table 1. Overview of the current research on automated tool path planning for the application of turbine blade repair (01/2010 – 05/2023)

Ref.	Year	Author	Innovation	Deficit
[13]	2010	Yilmaz[1]	Adaptive reconstruction via NURBS	Verified only for compressor blades Manual reconstruction
[7]	2010	Zhang[1]	Wavelet decomposition	Verified only for compressor blades
[8]	2011	Piya[1]	Sectional gauss map Suitable for middle region of blade	No consideration of torsion and twist
[9]	2013	Wu[1]	Offset of defect-free cross-sections	Only for blades without twisting
[4]	2014	Rong[1]	Free-form deformation (FFD) of template curves	Unsuitable for CAM system without processing to NURBS
[14]	2017	Hou[1]	Direct compensation of clamping errors	Only suitable for the middle region of compressor blades
[10]	2020	Zheng-Qing[1]	No prior reverse engineering	Smooth transition only for not severely deformed regions
[11]	2020	Su[1]	Polygon models of surfaces	Unsuitable for CAM system without manual PP
[15]	2021	Wu[1]	Linear combination of base curves blending algorithm	Verified only for compressor blades
[16]	2021	Xiao[1]	Direct and quick tool path generation without surface fitting	Point cloud mainly affects the accuracy of the tool path

[1] *et al.*

3. Approach

In this paper, an adaptable, fully-automated process planning of the recontouring process of turbine blades is presented. The method can be divided into two sub-methods. In the geometry processing method, a suitable target model is calculated. Therefore, the blade geometry is reconstructed based on 3D scan data and blade aero parameters are determined. Then, a target model is calculated. On this basis, in the process planning method, a 5-axis tool path is generated (Fig. 1).

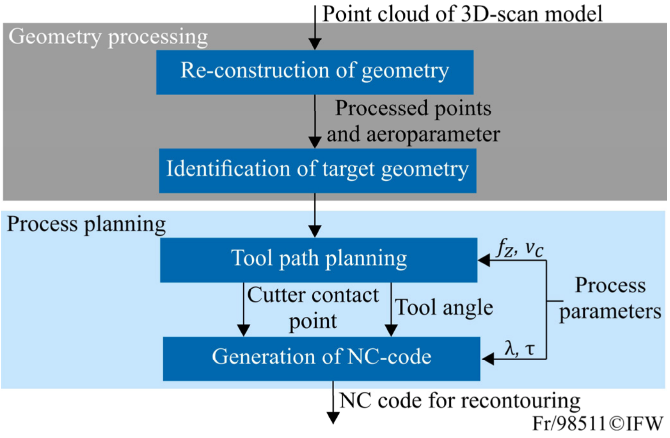


Fig. 1. Overview of the fully-automated tool path planning method

4. Geometry processing

Macroscopically visible damage to the turbine blades, such as chipping or cracking, is removed at the tip of the blade by weld preparation and is therefore of secondary relevance to the subsequent repair process. The resulting deviations from the nominal component geometry (CAD file) necessitate a component-specific generation of a new nominal geometry (target geometry). Based on the given information about the current component geometry as well as requirements of the aviation certification, the following requirements are defined:

- The actual geometry must not be violated during processing.
- The current component geometry (actual geometry) must be considered when creating the target geometry.

4.1. Reconstruction of geometry

First, the geometry of the turbine blade is measured using a coordinate measuring machine (CMM). The output is a point cloud model in a coordinate system that is uniform throughout the entire process chain. Then, the point cloud of the current blade must be further processed into a uniform data model.

Subsequently, the 3D point cloud is sliced into 2D airfoils. The distance between the airfoils corresponds to the line width b_r of the recontouring process. With a subsequent Chebychev, interpolation a constant high point density with 500 airfoil points could be reached for each of the airfoils, which increases the robustness of the method.

Next, the points of the camber line are calculated. This is done with a Delaunay triangulation. Some of the calculated points are not part of the camber line since they have a high distance to the expected line. These foreign points are caused by curvature changes and negatively affect the accuracy of the camber line calculation. For this reason, three filter algorithms were developed and implemented to reduce the number of foreign points.

To validate the accuracy of the calculated camber line, the distances between the camber line and the suction side s_1 as well as between the camber line and the pressure side s_2 are calculated for each point. According to the mathematical definition of an ideal camber line, which is equivalent to the skeleton line, the difference of the distances for each point is ideally $\Delta s = 0$. The calculated differences showed that the interpolated camber line has deviations Δs in the range of < 22 µm. Thus, it can be stated that the method leads to an accurate approximation.

After trimming the camber line, it must be extended by an extrapolation up to the point of intersection with the profile contour. The best results are obtained with a linear extrapolation for the trailing edge (TE) and with a quadratic extrapolation for the leading edge (LE) which leads to a smooth curvature line. The difference in the distances is < 12 µm. At the TE, an increase in the difference becomes obvious. However, this is expected due to the cooling air holes at the TE. The observed behavior at the TE is tolerated in favor of a smooth curvature line which can be ensured with the described procedure.

Subsequently, the thickness distribution is calculated for each profile by determining the distances between the pressure side and the camber line perpendicular to the camber line. The reconstruction of the actual 3D geometry is done by combining the processed 2D airfoils.

4.2. Calculation of suitable target geometry

First, the camber lines from the area of the reconstructed geometry are extrapolated into the unknown area. This is implemented using a three-dimensional polynomial regression with a polynomial degree of three in the y-direction and a degree of five in the z-direction. The coefficients were calculated with a linear least square's algorithm. Due to the polynomial behavior of the curvature, a coefficient of determination R^2 of the regression function of 0.999 could be achieved, which proves a very high agreement between the data points and the model. By the individual regression equation, the camber lines in the unknown area can be calculated as a function of the z-position. This is done up to a target height z_{max} of 63.0 mm. The regression function is shown in Fig. 2.

To calculate the profile contours in the unknown area, knowledge of the thickness distributions as a function of the z-height is necessary. As before, the profile thickness is modeled via a three-dimensional regression function. The same type of polynomial functions was used and proved to be accurate also for this use case. Using the individual regression equation, the unknown thickness distributions in the damaged region can be modeled as a function of the z-position. For the turbine blade investigated in this work, a coefficient of determination R^2 of 0.998 is obtained. Due to the high prediction quality, it may be assumed that the function leads to a valid prediction of the thickness distribution in the target area.

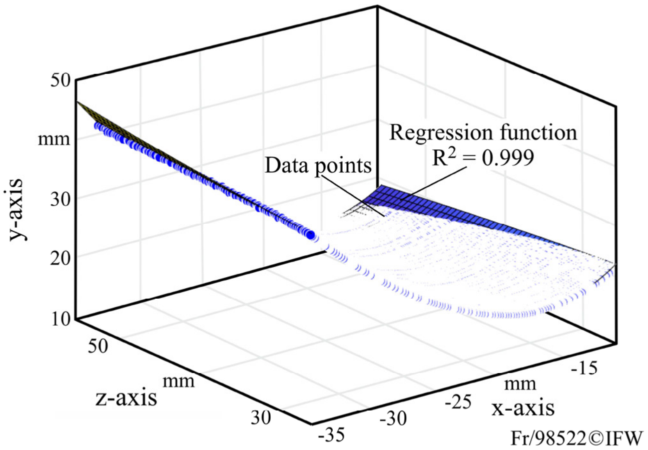


Fig. 2. Functions for the extrapolation of camber lines

The surface function extends beyond the boundaries of the turbine blade in the x and y directions. For this, the function needs to be trimmed based on the LE and TE points. Therefore, the course of the LE and TE is modeled via a quadratic and linear polynomial respectively. The quadratic function results in a good approximation for the LE ($R^2 = 0.979$) and the linear function for the TE is also valid ($R^2 = 0.981$). Possible remaining degenerative damage (e.g. small dents) is compensated in this way. Based on the equations, the positions of the LE and TE are also extrapolated up to the target height z_{max}. Subsequently, the camber lines and the thickness distributions are trimmed outward at the intersections with the LE and TE. Thus, the surface curves of the curvature lines and thickness distributions lie consistently within the profile.

In the next step, the contour points are calculated. This is done by combining the information about the profile thickness and the extrapolated camber line for each z-height in the unknown area. For this purpose, circles are generated at each position of the camber line for each z-height. Thereby, the individual diameter of each circle corresponds to the predicted profile thickness at the respective position. The contour is obtained by calculating the envelope of all circles of a profile. Due to the curvature of the circles, a slight deviation between every two circles becomes apparent. By choosing a high resolution the resulting deviation can be neglected. For validation, an extrapolated target profile was generated at the level of the highest profile. This allows a comparison of the profiles to evaluate the accuracy of the method (Fig. 3).

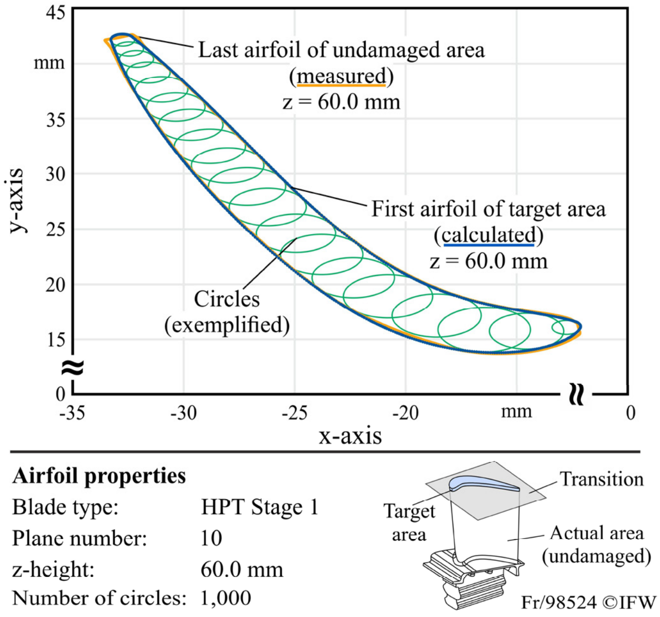


Fig. 3. Comparison of measured and calculated airfoil of the same z-level

A very accurate approximation to the actual range is achieved at the pressure and suction side since both profiles are almost congruent there. The TE has an almost angular shape. Therefore, the approximation is geometrically limited at this point. Besides, a latent deviation at the LE became obvious. This is due to the cooling air holes, which are in particular at the LE and in this case lead to a flattening of the LE shape. Moreover, it can be attributed to deviations in the regression model of the thickness distribution. As shown in Fig. 4, higher deviations of the model in relation to the real data can be observed especially at the LE. The course of the real data shows a kink in this area, which cannot be represented by the polynomial function equation. However, it was proved that the overall accuracy is sufficiently accurate. By combining the reconstructed blade and the extrapolated geometry, the overall target model of the individual blade is obtained (Fig. 4).

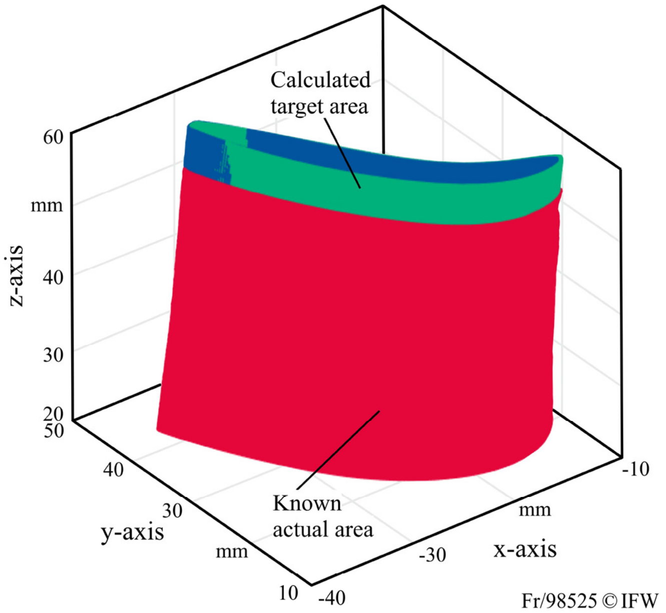


Fig. 4. Automated calculated target model for the individual blade

5. Automated process planning

The procedure for an automated tool path planning of the recontouring is shown in Fig. 5.

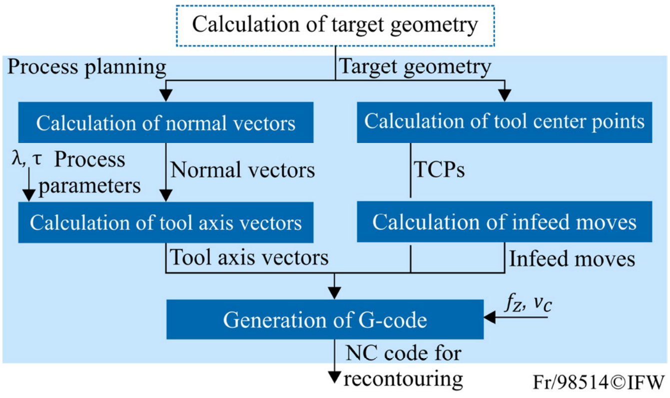


Fig. 5. Algorithm for automated tool path generation

5.1. Automated tool path planning

The surface normal vectors are calculated for each profile. The profile points correspond technologically to the cutter contact point (CCP) with the variable CCP_i, where the index i denotes the current airfoil point. The feed direction vector f_i is determined for each cutter contact point CCP_i by calculating the difference between the preceding profile point CCP_{i+1} and the previous profile point CCP_{i-1}. The calculation of the surface normal vectors $\tilde{n}_i$ is based on the feed direction vector f_i and the direction vector z for all profile points (Eq. 4).

$$\tilde{n}_i = f_i \times z = (CCP_{i+1} - CCP_{i-1}) \times \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad (4)$$

The calculation results in a secant error, which depends on the position and distance of the two profile points considered. Next, the normal vectors are smoothed to ensure a jerk-free process on the machine tool. Afterward, the normal vectors are normalized to a uniform length. The tool axis vector is defined by rotating the normal vector by the lead angle λ and the tilt angle τ. If the vector $t_{\lambda,\tau} = [t_x \quad t_y \quad t_z]^T$ satisfies the following condition ${t_x}^2 + {t_y}^2 + {t_z}^2 = 1$, then the components of the tool axis vector $t_{\lambda,\tau}$ are obtained by the definition given in Eq. 5.

$$t_x = t_y \tan\lambda, \quad t_y = \frac{1}{1+\tan\ ^2+\mathrm{ta}\quad ^2}, \quad t_z = t_y \tan\tau \quad (5)$$

In the general form, the basis is defined as the three directional vectors x_f, y_f, z_f. It is assumed that the global coordinate system is of the form $i = [1 \quad 0 \quad 0]^T, j = [0 \quad 1 \quad 0]^T,\ k = [0 \quad 0 \quad 1]^T$. The rotation matrix $\boldsymbol{R}$ then has the general form shown in Eq. 6.

$$\boldsymbol{R} = \begin{bmatrix} x_f \cdot i & x_f \cdot j & x_f \cdot k \\ y_f \cdot i & y_f \cdot j & y_f \cdot k \\ z_f \cdot i & z_f \cdot j & z_f \cdot k \end{bmatrix} \qquad (6)$$

The relationship can be transferred to the present case, where the normal vectors all lie in the xy-plane due to the two-dimensional view of the airfoils. The following definition can be derived for the three direction vectors (Eq. 7-9).

$$x_f = [x_{f,1} \quad x_{f,2} \quad 0]^T \qquad (7)$$

$$y_f = [y_{f,1} \quad y_{f,2} \quad 0]^T \qquad (8)$$

$$z_f = [0 \quad 0 \quad 1]^T \qquad (9)$$

The tool approach vector w_i is then calculated by multiplying the rotation matrix $\boldsymbol{R}_{n,f,z}$ by the vector $t_{\lambda,\tau}$:

$$w_i = \boldsymbol{R}_{n,f,z} \cdot t_{\lambda,\tau} \qquad (10)$$

For the ball end milling tool, the TCP is located in the center of the ball. The specific tool center point of each tool path point TCP_i is therefore obtained by vector addition of the surface contact point CCP_i and the product of tool axis vector w_i and tool radius r (Eq. 11).

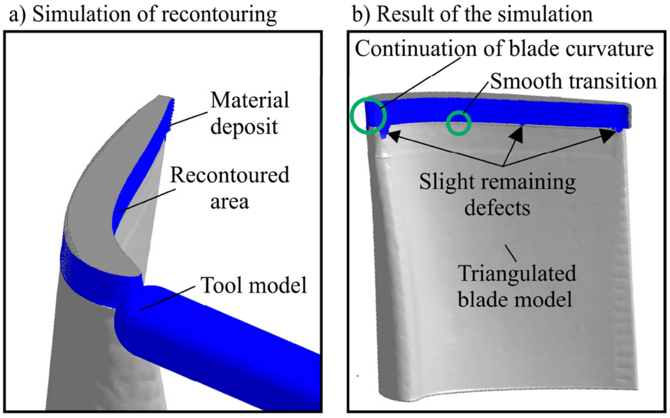
$$TCP_i = CCP_i + w_i \cdot r \qquad (11)$$

5.2. NC-code generation

A post-processor was developed which automatically generates a machine-universal G-code for recontouring on a 5-axis milling machine. To be able to use the G-code individually regarding the machine tool, the ORIWKS function is used, which enables an interpretation of the axis movements based on the planned TCP and the tool axis vectors. Finally, the G-code is transferred to the machine control.

6. Validation

The validation has been carried out with four damaged turbine blades. The material removal simulation software IFW CutS was used to validate the geometrical correctness [17]. The simulation of the recontouring is conducted using the rotational body of a ball-end cutter (Fig. 6a). The simulation shows that the generated target geometry in combination with the 5-axis tool path and leads to a smooth surface. However, tiny defects become apparent (Fig. 6b). These defects can be due to deviations in the calculation of the normals which lead to slight tool contact with the actual geometry. Moreover, a small rest of the material remains at the TE since the tool path does not include the entire allowance of the material deposition.



Process parameters:		**Tool parameters:**	
Cutting speed v_c	= 30 m/s	Tool diameter D	= 6 mm
Feed per tooth f_z	= 0.08 mm	Lead angle λ	= 15°
Line width b_r	= 0.1 mm	Tilt angle τ	= 15°

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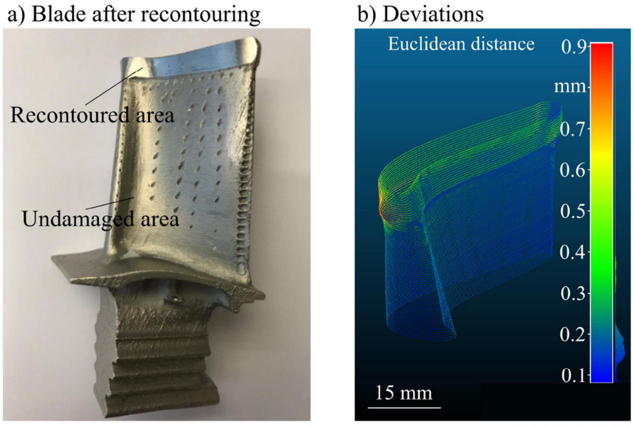
Fig. 6. Simulation-based 5-axis recontouring of a turbine blade

In addition to the simulations, the influence of errors that result from the machine control, machine tool, workpiece or tool should be taken into account. Therefore, two experimentally recontouring processes were conducted on a 5-axis milling machine (Milltap 500). Two reference blades were used which are based on real turbine blades in combination with a CAD-constructed weld seam. These blades were additively manufactured via selective laser sintering (SLS) with Inconel 718. The results are presented in Fig. 7.

The recontouring tests show that a good surface quality could be reached compared to the simulation also. However, some tiny irregularities in the surface became obvious. These can be due to variances in the determination of the TCPs which result from deviations in the calculation of the normal vectors (Fig. 7a). Fig. 7b shows the Euclidean distance between the recontoured turbine blade and the nominal target model and represent the shape error caused by process planning and the process itself. At the LE, high deviations of 0.88 mm can be observed. However, in the recontoured area of the blade, the deviations are significantly lower and amount to 300 - 400 µm. These deviations result from force-induced deflection of the blade and the tool as well as the compliance of the fixture.


a) Blade after recontouring

b) Deviations

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Fig. 7. Results of the experimental 5-axis recontouring of turbine blades

7. Conclusion and Outlook

This paper presents a novel method for fully-automated planning of recontouring processes for turbine blades. The recontouring of the blades shows that the method allows a processing time of 8:56 min. (and 17:52 min. if roughing is needed) which is significantly faster compared to conventional repair processes. The time for the calculation of the target geometry and G-code took only 7:27 min. using a conventional laptop with an Intel i7 processor. In addition, the method was implemented in a demonstrator of a full-process chain for the repair of turbine blades including a virtual twin that enables a continuous exchange of information [18].

In future work, the process time for geometry measurement should be reduced by using a continuous touch probe in-machine. In future work, the 2D calculation of normal vectors will be replaced by a 3D calculation and increased density of profile points. Moreover, the results of the machining tests show non-negligible shape deviations due to the process load. The generated tool path is capable of adaption at any number of support points. Therefore, the method will be complemented in terms of compensation strategies of shape deviations. In addition, the preceding additive manufacturing process also plays a decisive role and will be investigated in combination.

After enabling these topics, the implementation in the industry could prospectively lead to higher process repeatability of the repair process of turbine blades due to the mathematical calculations instead of human-based experiences. At the same time, manual effort is reduced due to a high degree of automation which directly leads to a decrease in costs during MRO.

Acknowledgements

The authors are grateful for the support within the Collaborative Research Centre 871 ‘Regeneration of complex durable goods’, funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB 871/3 – 119193472. The results of this work were mainly created in the sub-project C1 [19] and the transfer project T6. Moreover, the authors thank the DFG for the financial support within the Priority Program 1480 and the Institute of Turbomachinery and Fluid Dynamics (TFD).

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