Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 102 (2021) 174–179

www.elsevier.com/locate/procedia

18th CIRP Conference on Modeling of Machining Operations

Integrated force interaction simulation model for milling strategy optimization of thin-walled Blisk blade machining

Matej Sulitka*, Jiri Falta, Michal Stejskal, Barbora Kociánová

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Production Machines and Equipment, Horská 3, Prague 128 00, Czech Republic

* Corresponding author. Tel.: +420 605 205 927; *E-mail address:* m.sulitka@rcmt.cvut.cz

Abstract

Complex shaped thin-walled blades that are extensively used in jet engines or stream turbines are very difficult to machine due to low rigidity of the blades, typically limited space between the blades and strict requirements on the surface quality and accuracy. The paper focuses on multi-axis machining of thin-walled and complex shaped Blisk blades made of aluminium alloys. The resulting surface quality and accuracy is mainly affected by the risk of elevated vibration occurrence, both forced and self-excited, and static deflections between the compliant tool and workpiece. An innovative integration of the transformed FE model of the blade into virtual machining simulation has been proposed, allowing to effectively solve the complex optimization task considering both the criterion of stable machining condition and static deflections as well. When choosing a machining strategy and cutting conditions, there are many variables that fundamentally affect the process. These variables are not easy to choose correctly the first time, so it is advisable to choose to use a simulation model in production preparation. The proposed simulation model allowed to effectively optimize the process parameters to keep the machining process stable and the static deformation of tool and workpiece under a defined level. The proposed model and optimization strategy was validated on a thin-walled blade machining. At the top part of the blade, the surface roughness decreased from 1.6 Ra to 0.84 Ra, and the maximum deviations from the reference model were reduced from 0.18 mm to 0.08 mm.

Keywords: Digital Twin; Virtual machining; Stability, Milling; Static deformation; Thin-walled blade

1. Introduction

Productive machining of complex shape parts such as thin flexible blades is a technologically demanding task in which it is necessary to achieve the highest possible quality of the workpiece and at the same time minimize the machining time. Flexible thin-walled workpieces are significantly represented in key sectors of the aerospace, automotive or energy industries. The lower static and dynamic stiffness of these products poses challenges during the machining process due to higher risk of workpiece and tool deformation and vibration. In many cases, manual finishing of the workpieces is necessary, which significantly prolongs the production time and brings additional geometric inaccuracies.

There are two main issues related to the dynamics of the flexible workpiece. The first one is a stable machining, which is a necessary condition for achieving both accuracy and surface quality of the workpiece. The second one is a static deflection of the tool and workpiece due to cutting forces. Despite significant progress in the last decades, the problem of machining stability in 5-axis milling remains a rather difficult task in comparison to turning or face milling because of complex geometric relations which make process modelling difficult to formulate. Possibly the biggest obstacle is the determination of tool-workpiece engagement in case of general

2212-8271 © 2021 The Authors. Published by Elsevier B.V.

10.1016/j.procir.2021.09.030

tool-workpiece orientation. Less demanding issue is a time-dependent cutting force reaction to small displacement changes, which complicates the stability formulation in milling in general. To simplify the problem and to allow formulation of the problem in Laplace domain, so called ZOA method was introduced by Altintas and Budak [1]. Altintas and Merdol [2] present a virtual machining application for optimizing the conditions of milling operations. Li et al. [3] present a voxel model based method to visualize the workpiece and a method to mitigate the deformation of the workpiece and to avoid chatter, proposing a new machining strategy based on alternating between roughing and finishing operations. Zhao et al. [4] solved the issues linked to the process of thin-walled blades machining with the requirement of increased accuracy, considering the deformations of the tool based on several variants of the distribution of the estimated total cutting force along the contact of the tool and the workpiece. A power model of the cutting force was used to estimate the force, however the disadvantage consists in a very limited validity regarding the orientation of the tool and the workpiece – its components depend only on the radial and axial depth of cut and feed. Huang et al. [5] address the reduction of vibrations and deformations in the milling of thin-walled blades with a ball mill using an optimized tool and workpiece orientation. They work with a more accurate model of force based on the integration of force through the cutting edge. The prediction of deflection errors in the circumferential milling of thin-walled workpieces is presented by Kang and Wang [6]. Similarly, Khandagale et al. [7] reduce static deflection when milling subject parts. Del Sol et al. study milling operations of light alloys with thin-walled structures in order to reduce deflection errors caused by instability and deformation of machined parts. The use of virtual machining modeling for its optimization and application is discussed in depth in several articles by Soori et al. [8], [9]. Another challenge after eliminating dynamic and static errors is to achieve productive machining. The solution may be to set the right strategy and cutting conditions. For example, by preprocess optimizing variable spindle speed and feed rate along the tool path, both higher stability and higher productivity can be achieved, see the Vavruska articles [10], [11].

Nomenclature

[K]	stiffness matrix
[M]	mass matrix
[C]	damping matrix
$\boldsymbol{u}$	deflection vector (subscripts s–static, d–dynamic)
$\mathbf{K}_c$	cutting coefficient
[T]	transformation matrix from local to global c.s.
h	chip thickness
τ	small time difference
$\bar{\boldsymbol{F}}$	averaged cutting force
$\overline{[A]}$	averaged directional matrix
$[\Phi]$	eigenmodes matrix
$[\Omega]$	diagonal matrix of eigenfrequencies
ρ	distance to the tool axis
S	tool-workpiece engagement surface

2. System for virtual machining of thin-walled blades

In this study, the 5-axis milling simulation is realized in the internally developed software for virtual machining, MillVis, which combines the mathematical methods used for material removal, machine tool dynamics and cutting force interaction of cutting tool and workpiece and tool-workpiece dynamics. While the machine tool dynamics can be described using reduced FE models and cutting tool dynamics can be represented by a simplified beam model, the representation of a flexible workpiece is more challenging.

For fast simulation of the material removal, distance field representation of the cutting tool and workpiece is used because it allows faster calculation than other visualization methods. At the same time, it provides higher accuracy and resolution of the machined surface prediction. It is based on a voxel grid and the signed distance function which for each point in space returns its distance to the workpiece surface, with a negative sign for the points outside of the workpiece and positive for those inside. In practice, the sign is determined by the outer normal.

The value of this distance function is saved at each vertex of the voxel grid. The approximate distance of any point from the workpiece surface can be reconstructed by trilinear interpolation from the nearby vertices. This is useful for visualization but also for material removal simulation. In each step, it is determined whether there is any tool point inside of the workpiece. If the tool intersects the workpiece, the distance values stored in the corresponding vertices are updated.

In order to analyze the stability of the machining process, the cutting forces must be computed first. The implemented model is based on [1], where the essential parameter is the chip thickness. Edge and cutting force coefficients, specific for each material, cutting edge geometry and cutting conditions, are considered as parameters of the model used. The cutting forces are evaluated in discretized points on the cutting edges of the tool, in tangential, radial and axial directions. Then they can be projected into the Cartesian coordinates system and the total cutting force is computed as their curve integral along each cutting edge in cut.

This model was further modified in order to increase the computation speed and to effectively use the data computed during the material removal simulation. If the cutting conditions remain the same, it is possible to represent the cutting force by Fourier series. The Fourier coefficients are computed numerically as surface integrals over the engagement area. This is based on a reformulation of the classical definition which requires calculation of a double integral – one integral over one revolution and another over the the engaged cutting edge. The surface integral is discretized using the voxel mesh. Within each voxel, the tool-workpiece contact is represented by an implicit formulation based on a trilinear function defined by the distance field which represents the machined surface. However, due to high computation cost, the implicit formulation is not suitable for the surface integral calculation. For the purpose, the surface within a voxel is approximated by a planar surface, which can be fitted into the distance field efficiently.

Such formulation allows to compute only a desired number of Fourier series members, adjusted to the problem.

2.1. Implementation of the workpiece and cutting tool dynamics

To be able to effectively simulate and optimize the machining of flexible workpieces, an original implementation of the workpiece dynamics into the distance field model has been developed. The strategy consists in creating a FE model, see Fig. 1 left, which is subsequently transformed and reduced by modal transformation into the distance field model using selected eigenfrequencies and eigenmodes in a grid of points along the workpiece surface, see Fig. 1 right.

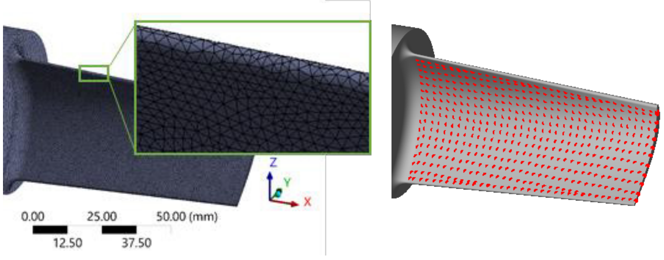

Fig. 1. FE mesh of the blade (left) and grid of points on the blade surface in which the modal transformation of the blade FE model is performed (right).

The eigenvectors are transferred to the distance field structure of the workpiece in such a way that in each step of the material removal simulation, the closest point of the blade surface grid to the current tool position is found and its data is used for the stability and static deformation computation. In the case of blade finishing machining, the change of the workpiece dynamic properties during the milling process is negligible, as the axial depth of cut is typically very small. Therefore, the dynamic model corresponding just to the final volume of the blade is used. For representing the dynamics of a compliant cutting tool, modal data at the tool tip is considered.

2.2. Formulation of the static deflection and machining stability prediction

In predicting the stability limits, the effect of dynamic chip thickness is considered. The static deflection is based on an averaged cutting force over one tool revolution $\overline{\boldsymbol{F}}$ and the stability is based on ZOA method which requires averaged directional matrix $\overline{[A]}$**.** The equations of motion for the averaged system are

$$(s^2[\mathrm{M}] + s[\mathrm{C}] + [\mathrm{K}])\,\boldsymbol{u} = [P]\overline{\boldsymbol{F}} \;+ [P]\overline{[A]}[P]^T(1 - e^{-s\tau})\boldsymbol{u}$$

where $\boldsymbol{u}$ is an averaged Laplace image of the deflection in all degrees of freedom on the grid, $[P]$ represents distribution of the force and its reaction to regenerative vibration along the grid. Both static component of the deflection and machining stability formulation are based on the equation. The static deflection calculation is based on formula

$$\boldsymbol{u_s} = [\Phi][\Omega]^{-2}[\Phi]^{\mathrm{T}}[P]\overline{\boldsymbol{F}}$$

where the stiffness matrix at given point is approximated using modal truncation, which gives accurate results if used carefully.

The stability formulation is based on the homogeneous equation

$$\left(s^2[\mathrm{M}] + s[\mathrm{C}] + [\mathrm{K}] - [P]\overline{[A]}[P]^T(1 - e^{-s\tau})\right)\,\boldsymbol{u_d} = \boldsymbol{0}$$

The average force reaction to a displacement (force gradient) is formulated using a novel approach as

$$\overline{[\mathrm{A}]} = \int_S \frac{[\mathrm{T}(x)]}{\rho(x)}\boldsymbol{K_c}\boldsymbol{n}^{\boldsymbol{T}}dS$$

where $\boldsymbol{n}$ is a surface normal at given point of the engaged surface S, $[\mathrm{T}(x)]$ is a transformation matrix from local cutting force basis at the point to the world coordinate system, $\rho(x)$ is a distance of the point from the axis of rotation and $\boldsymbol{K_c}$ is a cutting force coefficient vector. The equivalence of the presented formula to a standard approach to the directional matrix averaging will be treated in a separate article.

The process stability problem leads to a generalized eigenvalue problem for Laplace parameter s. The maximum real part of all dynamical system's eigenvalues is an indicator of its stability. If it is not positive, the process is stable and the chatter does not occur. However, if the real part of any eigenvalue is positive, the vibrations start to grow exponentially, which causes chatter marks on the surface and increases tool wear. As the generalized eigenvalue problem is nonlinear with respect to the eigenvalues, they are found iteratively by a modified Newton method developed by Harrar [12].

The physical meaning of the characteristic exponent λ used for machining stability evaluation is demonstrated in Fig. 2. The sign of the exponent shows if the vibration exponentially grows or declines as a response to the external force excitation, depending on the dynamics of the tool and workpiece and process stiffness and damping.

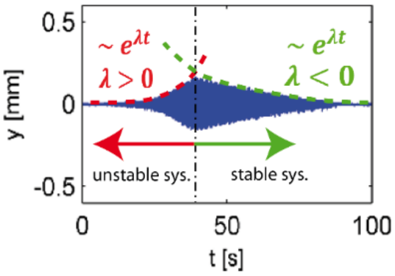

Fig. 2. Demonstration of the physical meaning of the characteristic exponent for describing the process stability. Positive value of the exponent λ (red) indicates exponential growth of the vibration and hence the system is unstable. Negative value of the exponent λ (green) represents exponential decline of the system vibration excited by external force and indicates a stable system.

A full analysis of the virtual machining operation including the workpiece and tool dynamics is described by the flowchart in Fig. 3.

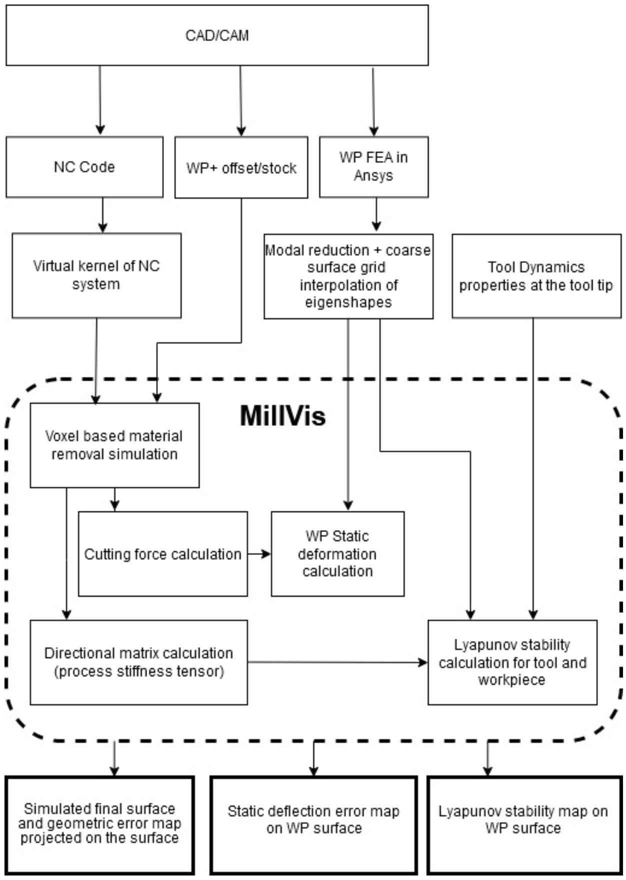

Fig. 3. Flowchart of digital machining simulation including flexible workpiece and cutting tool in MillVis system.

3. Case study

The application of the system developed for a case study of a thin-walled Blisk blade machining and optimization is demonstrated. The steps of the Blisk blade machining simulation workflow are:

- FEA of the blade in FE software (Ansys);
- Modal reduction and interpolation of blade eigenshapes on a grid on the machined surface;
- Virtual machining simulation using the blade dynamic model and virtual interpolation of the NC code.

3.1. Optimization of a Blisk blade machining

The aim is to prepare a production of a Blisk blade. Common approaches applied in the industry rely on a number of testing machinings, which iteratively test different cutting conditions, tool path strategies or machine tool control parameters until an acceptable result is achieved. This is mainly due to the fact that in common CAM systems it is not possible to evaluate the complex dynamic behaviour of the cutting tool and workpiece flexible system and to check relevant results of machining operations.

The main challenge in using the advanced virtual machining simulation, presented in Section 2, is to predict and minimize the static deflection of the blade, which is caused by the tool-workpiece force interaction, and to predict the risk of forced and self-excited vibrations at the same time. The aim is to achieve the required geometric accuracy and surface quality of the blade without the need of performing multiple testing machinings on the machine. NC code and machining strategy optimized using virtual simulation are validated in a real machining process.

A total of two blade segments were made to demonstrate the effectiveness of the simulation method described. The first blade was machined using an original setting of toolpaths in CAM and cutting conditions according to the toolmaker. The second blade was machined using NC code optimized by virtual simulation.

3.2. Machining setup

The considered Blisk blade segment is made of EN AW 7075 material and it is machined using a five-axis mill-turn machine MCU700 (KOVOSVIT MAS Machine Tools, a.s.). Milling strategy is point machining with a constant angle of tilt and lead along the helical toolpath for each test, see Fig. 4.

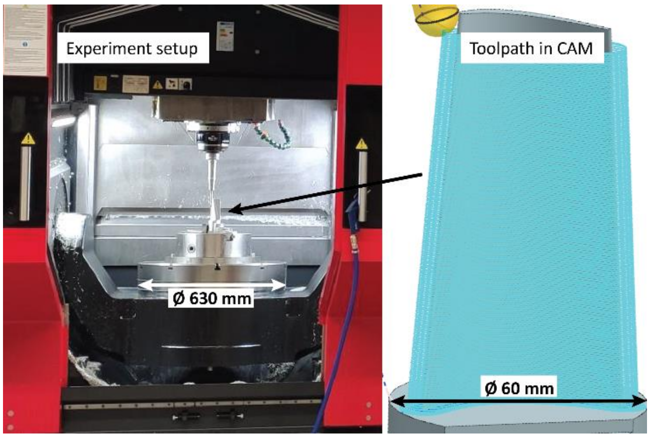

Fig. 4. Experimental setup (left); CAM toolpath (right).

The cutting tool was a ball-end mill with a diameter of 10 mm (Iscar MM EBA100B07-2T06). Blank for finishing was 0.35 mm. The spindle speed was 12 000 RPM. The feed rate, lead and tilt angle were variable parameters for optimization. This case study compares an original strategy with a lead angle of 0°, tilt angle of 75° and a programmed feed rate of 2500 mm/min versus an optimized strategy with a lead angle of 50°, tilt angle of 5° and a programmed feed rate of 2650 mm/min.

3.3. Model of blade dynamics

The dynamic behavior of the workpiece is approximated using modal reduction to 50 dominant modes. Comparison of full harmonic analysis (1 % structural damping) and modal truncation to 50 modes at two points near the blade tip calculated in Ansys WB is presented in Fig. 5. The reduced model is also used to calculate static stiffness or compliance along the blade. The maximum error of the static compliance at the control points is below 0.05 $\mu\text{m N}^{-1}$ or 0.7 % relatively. Very good accuracy of the reduced model with even relatively low number of eigenmodes used results in this case from high compliance of the workpiece.

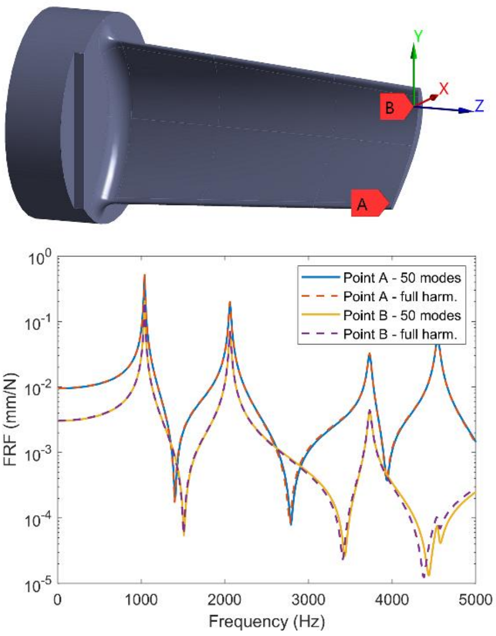

Fig. 5. Comparison of modal truncation to 50 modes and full harmonic analysis for two points at the blade tip.

3.4. Virtual machining simulation

Distribution of the real feed rate resulting from the NC code interpolation by the CNC system for the original and optimized strategy is illustrated in Fig. 6. It may be seen that for both cases the real feed rate significantly differs from the programmed one. This is a typical situation in 5-axis milling of complex shaped surfaces, which relates mainly to the limitation of rotary axes dynamics. Next to it, there is also a risk of deteriorated surface quality generation due to large fluctuations of the feed rate. This issue can be effectively identified even prior to the physical machining thanks to the virtual machining simulation using the real CNC system kernel. In our case study, both the original and optimized strategy reveal almost identical real feed rate distribution and hence also the same machining time.

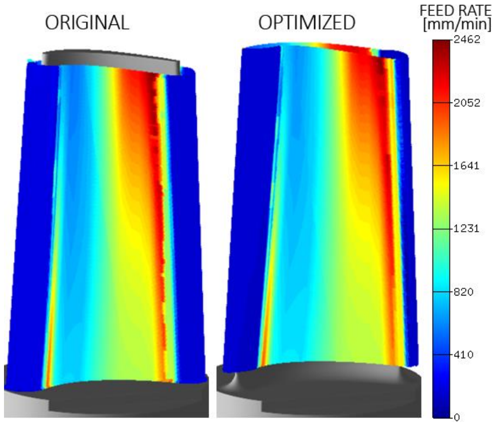

Fig. 6. Visualisation of the feed rate and toolpaths for the original and optimized setting.

Another evaluation factor in the technology preparation of the blade machining is the maximum of static deformation field along the blade. Results for the original and optimized strategy are shown in Fig. 7 with the biggest difference visible at the blade tip.

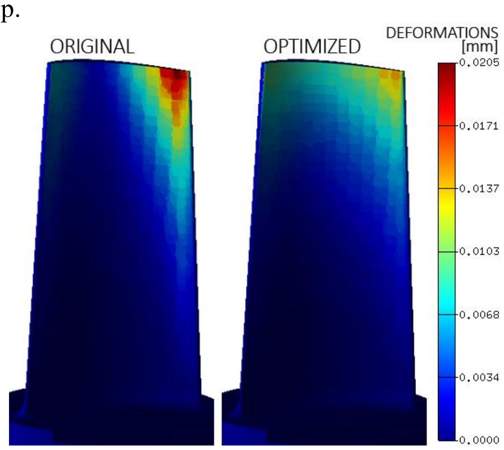

Fig. 7. Static deformation. Optimized machining strategy reveals a significant reduction of the maximum static deflection at the blade tip.

Machining stability calculation for both machining strategies is performed following the approach introduced in Section 2.2. The results show that both the original and optimized strategy lead to stable machining, see Fig. 8.

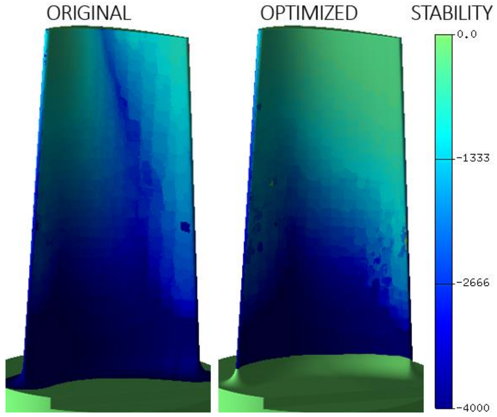

Fig. 8. Map of characteristic exponents which confirm that the process is stable for both strategies.

3.5. Experimental results

Geometric errors of the machined blade surface are checked by 3D GOM scanner for which a measurement accuracy of up to 0.01 mm is declared. For evaluating the surface errors against the reference CAD model, the base geometry of the blade has been used as a reference for aligning the scans.

The measurements confirm that the optimized strategy provides higher machining accuracy compared to the blade machined using the original settings. The maximum deviations of the original blade reached 0.18 mm at the top, while the deviations along the whole optimized blade stayed below 0.08 mm, see Fig. 9. The difference in absolute values of deviations between simulation and measurement is most likely caused by a harmonic excitation of the blade by the varying cutting force component. There is a trade-off between the static deflection of the tool or workpiece and their dynamic excitation, which strongly depends on tool-workpiece orientation. This hypothesis will be studied in the next research.

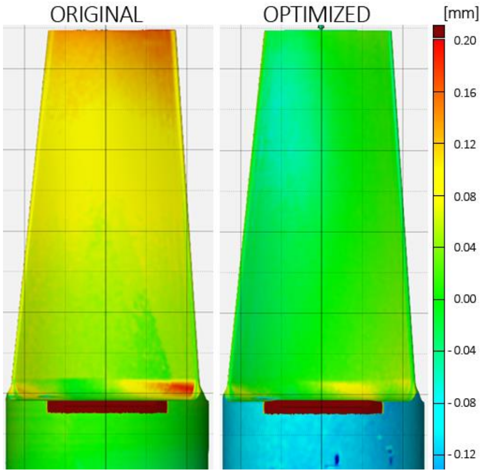

Fig. 9. Deviations measured by GOM 3D scanner.

Surface roughness was reduced from 1.6 Ra for the original case to 0.84 Ra for the optimized case at the critical area of the blade, see Fig. 10. Reduction of the static deformation for the optimized strategy, as predicted by the virtual simulation, thus also positively contributes to improving the surface quality.

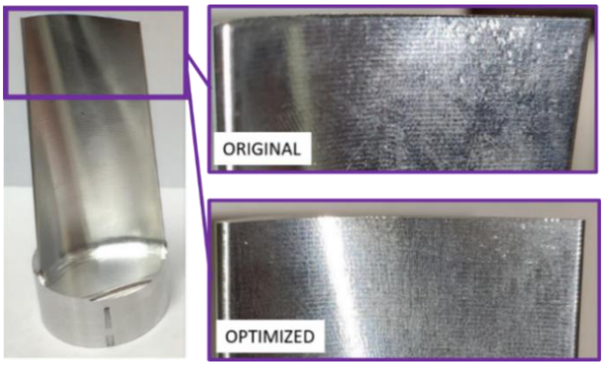

Fig. 10. Final surface after machining blades (original and optimized).

4. Conclusion

Productive and high-quality machining of complex thin-walled parts requires considerable knowledge and experience at all key points in the implementation chain. Conventional approaches of the NC machining technology preparation of thin-walled workpieces rely on a number of machining tests, which is a time and cost demanding process.

To overcome this difficulty, an innovative solution of integrating the thin-walled workpiece dynamic model directly into the virtual machining simulation has been developed. Workpiece computational model is first prepared in a FE software and consequently implemented via modal transformation into the distance field representation, which is used for material removal simulation. Thanks to this, static deflection of the workpiece along the tool path and stability limits are instantly calculated and visualized on the workpiece surface as a result of tool-workpiece force interaction. This approach can be effectively used for demanding tasks of thin-walled workpiece machining simulation and optimization.

The proposed strategy and its benefits have been demonstrated on a thin-walled Blisk blade. The optimized machining strategy and technology parameters have been prepared without the need of machining tests. While the production time remained nearly the same, the process led to the reduction of maximal static error from 0.18 mm to 0.08 mm and to the improvement of the surface quality from roughness of 1.6 Ra to 0.84 Ra.

Next research will focus on a detailed study of the phenomena of a thin-walled blade vibration contribution to the static deflection of the blade.

Acknowledgements

This work was supported by the Grant Agency of CTU in Prague, grant no. SGS19/165/OHK2/3T/12.

References

[1] E. Budak and Y. Altintas, “Analytical Prediction of Chatter Stability in Milling — Part I : General Formulation,” *J. Dyn. Syst. Meas. Control*, vol. 120, no. March 1998, pp. 22–30, 1998.

[2] Y. Altintas and S. D. Merdol, “Virtual high performance milling,” *CIRP Ann. - Manuf. Technol.*, vol. 56, no. 1, pp. 81–84, 2007.

[3] Y. Li, K. Tang, and L. Zeng, “A Voxel Model-Based Process-Planning Method for Five-Axis Machining of Complicated Parts,” *J. Comput. Inf. Sci. Eng.*, vol. 20, no. 4, 2020.

[4] Z. Zhao, Y. Wang, N. Qian, H. Su, and Y. Fu, “A framework for accuracy enhancement in milling thin-walled narrow-vane turbine impeller of NiAl-based superalloy,” *Int. J. Adv. Manuf. Technol.*, vol. 108, no. 11–12, pp. 3925–3938, 2020.

[5] T. Huang, X. Zhang, and H. Ding, “Tool Orientation Optimization for Reduction of Vibration and Deformation in Ball-end Milling of Thin-walled ...,” *Procedia CIRP*, vol. 58, no. July, pp. 210–215, 2017.

[6] Y. G. Kang and Z. Q. Wang, “Two efficient iterative algorithms for error prediction in peripheral milling of thin-walled workpieces considering the in-cutting chip,” *Int. J. Mach. Tools Manuf.*, vol. 73, pp. 55–61, 2013.

[7] P. Khandagale, G. Bhakar, V. Kartik, and S. S. Joshi, “Modelling time-domain vibratory deflection response of thin-walled cantilever workpieces during flank milling,” *J. Manuf. Process.*, vol. 33, no. May, pp. 278–290, 2018.

[8] M. Soori, B. Arezoo, and M. Habibi, “Tool deflection error of three-axis computer numerical control milling machines, monitoring and minimizing by a virtual machining system,” *J. Manuf. Sci. Eng. Trans. ASME*, vol. 138, no. 8, 2016.

[9] M. Soori and M. Asmael, “Deflection Error Prediction and Minimization in 5-Axis Milling Operations of Thin-Walled Impeller Blades,” *Preprint*, 2020.

[10] P. Vavruška *et al.*, “Machining of thin blade using vibration prediction and continuous spindle speed control,” *MM Sci. J.*, pp. 3330–3337, 2019.

[11] P. Vavruška, P. Zeman, and M. Stejskal, “Reducing Machining Time by Control of Spindle Speed and Feed-Rate in Milling Strategies,” *Procedia CIRP*, vol. 77, no. Hpc, pp. 578–581, 2018.

[12] D. L. Harrar and M. R. Osborne, “Computing eigenvalues of ordinary differential equations,” *ANZIAM J.*, vol. 44, no. July, 2003.