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Design of individual re-contouring processes

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Abstract

The re-contouring process of turbine blades is performed subsequently to the material deposit and restores the shape of the blade. Each process within the process chain has to be adapted to an individual repair case depending on size, location and specification of the damage. Each damaged blade represents a batch size of one. Hence, there is no run-in on the machine tool. This leads to the requirement of an error-free process from the very beginning. Therefore, a reliable process design is needed, including an evaluation of technological blade properties. This paper introduces an integrated method for the design of re-contouring processes. The presented conceptual design considers special requirements regarding an individual repair case, e.g. an individual blade shape, blade properties and material deposit. The method encompasses the definition of an individual repair case and the tool path planning using an interface of a commercial software for computer aided manufacturing (CAM). For evaluation of the tool path, the method contains a high-resolution material removal simulation and a downstream analysis of engagement conditions.

Keywords: Process design; Process simulation, Milling, Re-contouring

1. Introduction

The international MRO (Maintenance, Repair and Overhaul) market has an expected growth rate of 4.1% per year until 2025. Especially the annual spending in the sectors “engine repair” and “engine overhaul” will increase about \$13.7 Billion each year.

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Therefore, aerospace companies will extend their financial effort in new MRO technology [1]. This necessitates cost-saving repair methods, which forces automation in MRO processes. Due to the variety in components regarding engine repair, the automation is a tough issue. Engine components, e.g. turbine or compressor blades, exhibit a wide range of individual damages. Carter describes and quantifies possible blade failures [2]. The various types of damages represent big challenges in process design, compare Fig. 1. Currently, MRO processes include many manual working steps. Thus, MRO can be compared to a workshop production. Therefore, automation aims for prevention of errors due to uncontrollable manual processing of the blades [3].

Necessary steps in repair of turbine or compressor blades are the material deposit, which includes laser beam welding, and the restoration of the blade shape, called re-contouring. The latter includes machining, e.g. 5-axis ball end milling, and significantly affects the blade and its surface properties. Moreover, the re-contouring is a process step that directly affects the final shape of the blade and the performance of the regenerated engine. Hence, the requirements for the accuracy are as high as in the manufacturing of new blades [4]. Eberlein gives an overview of the patch repair of a single compressor blade. This industrial approach shows the positioning of the patch using FEM and the quality assurance, including geometry, residual stresses and an FE-based vibration test [5]. In general, research considers automation and optimization of the material-deposit and the re-contouring. This particularly includes upstream and downstream treatment of the blade like optical measurement, geometry reconstruction and machine tool devices. Huang *et al.* introduce a robotic belt grinding and polishing for the repair of turbine blades. This includes an automated handling of the blade between the blade measurement, grinding and polishing. The application is supposed to save up to 42% of the process time [6; 7]. Uhlmann *et al.* present a robotic belt grinding, including an automated path planning. The path planning provides an autonomous definition of machining offsets and divides the process into a roughing and a finishing step [8]. Denkena and Floeter show how to cope with changing engagement conditions in re-contouring by the use of an adaptive force control [9]. Bremer points out the need of connected machine tools. Hence, he introduces a web-based data management system, being able to connect processing cells even across different locations. The presented commercial system has the objective to reduce repair cost and process time by 40% each [3]. Gao *et al.* show an automated repair process chain based on reverse engineering (RE) of the blade shape and the derived tool path for re-contouring. Furthermore, they use a clamping system, which keeps the blade in a stationary position all over the repair process. Still, a critical aspect is the time dependent RE process, which also predominantly affects the accuracy of the whole repair process [10]. The RE process represents a bottleneck in blade repair. Taking into account the several different damages and the twisted blade shape, RE will hardly be automated in the near future

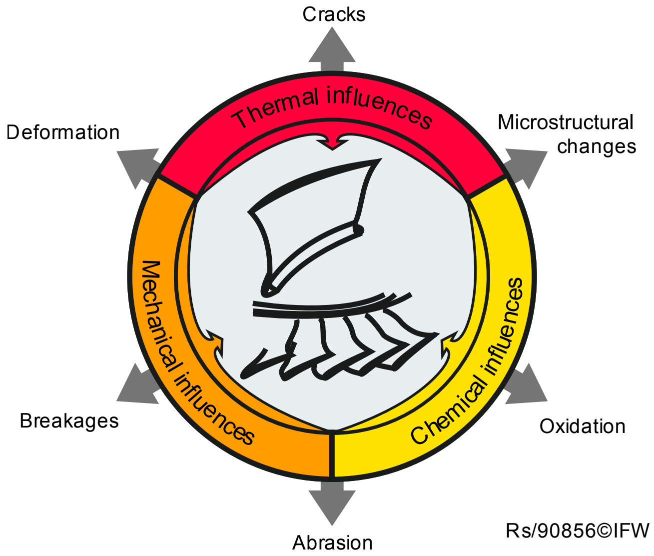

Fig. 1: Causes for damages on blades

[11]. An automated curvature analysis, described by Yilmaz *et al.*, enables creating surface patches reaching G1 continuity. The downstream tool path generation chooses the number of tool path intervals automatically based on a maximum scallop height. The authors declare a 30% reduction of repair time [12]. Surface and blade properties, which are defined throughout the machining process, recently receive more consideration in literature. Process induced residual stresses after re-contouring have been investigated in [13]. The cutting edge rounding has major influence on residual stresses. Moreover, it was shown that the feed per tooth and the lead angle affect the residual stresses. Nevertheless, the work presents a detailed process simulation, which allows a technological evaluation of the re-contouring process. Denkena *et al.* use this simulation approach for evaluation of a 5-axis re-contouring process [14].

In the field of geometric simulation of a machining process different models have been evolved in the past. This includes constructive solid geometry (CSG) [15; 16] and dexel and voxel representation [17]. All three methods allow a geometric evaluation of the tool path and resulting engagement of tool and workpiece. In combination with empirical models prognosis of technological based part aspects is possible with each model [18]. CSG uses combination of simple bodies to represent complex shapes. Therefore, high computation effort is necessary when the level of detail reaches surface topography. The dexel model is scalable without excessive increase of computation time. Regarding the number of elements n, the memory requirement of the dexel model is equal to $O(n^2)$, whereas the voxel model is equal to $O(n^3)$ [15].

Past studies mention crucial tasks in the design of a re-contouring process. However, not all issues have been addressed for an integrated process design, yet (see Fig. 2 marked in bold). Each blade repair is individual and consequently represents a batch size of one. Hence, an evaluation of the individual created tool path is necessary. Therefore, an integrated solution for the design of the re-contouring process, which includes an evaluation of an individually adapted tool path, is not achieved so far.

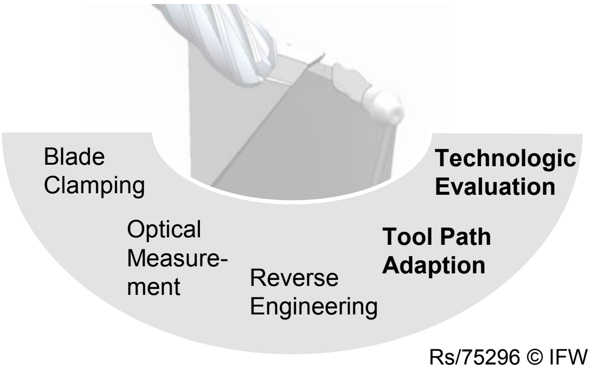

Fig. 2: Aspects of process design for re-contouring

This paper aims for the link between tool path planning and technological evaluation. The proposed method for process design allows a technological evaluation of the process in terms of surface properties of the blade. The following sections include the conceptual design of the simulation system, a description of the process design interface, including definition of the repair case and tool path planning as well as the dexel simulation approach itself. The method considers the finishing process only. This is due to the fact that todays and future re-contouring processes will deal with small allowances resulting from direct 3D metal deposition [19–21]. Anyway, this approach uses the patch repair as a repair example.

2. Conceptual design

Table 1 summarizes challenges regarding the re-contouring of blades, sorted by their resolvability through current engineering methods in descending order.

Table 1: Differences in blade repair and new blade production

New blade production	Blade repair
Recurring raw part shape	Unknown raw part shape
Mostly homogeneous material	Inhomogeneous material
Cutting conditions evaluable	Cutting conditions change between blades
Uniform processing	Locally restricted, asymmetric process possible
Replicable process, workpiece behavior similar	Unique process / unknown workpiece behavior
Reference based on the raw part	Missing Reference
Vibration-optimized process	Process vibration because of thin profile

The presented approach addresses the re-contouring via ball end milling using common tool path planning via a CAM-system. One obstacle is the unknown shape of the excess material resulting from the material deposition. This necessitates shape measuring of the blade before tool path planning. Likewise, an evaluation of process parameters used for the re-contouring is necessary, as the final workpiece quality is sensitive to the area of damage or the shape of the material deposit. In new blade production, NC-simulation (for prognosis of geometrical properties), FE-simulation (e.g. for prediction of mechanical distortion) and experimental procedures are used to achieve an optimal process design. In contrast to this, each re-contouring process concerns a different workpiece geometry. Hence, each new workpiece requires a new FE model, calculation and evaluation each time. To avoid this, the presented process design method includes a geometric simulation and analysis only, in order to receive instant feedback on local workpiece quality and to reduce planning effort. The geometric simulation provides cutting conditions for a various amount of process parameters. The process design method, see Fig. 3, is embedded into an existing software solution for geometric process simulation, namely IFW CutS [22]. It includes the three consecutive modules “Process Design Interface”, “Geometrical Process Simulation” and “Process Analysis” to meet the aforementioned challenges.

For the re-contouring process, it is crucial to identify the area of material deposit via scanned CAD data representing the workpiece before and after the material deposition. These workpiece models, including different material areas, form the basis for the tool path planning. A commercial CAD-CAM system is used for definition of the tool trajectory. This allows an application of well-developed tool path algorithms associated with specific requirements in re-contouring. Currently, the planning includes two steps:

1. Limiting the area of re-contouring, based on the repair case
2. Application of a set of rules for re-contouring, defining process parameters

The calculated tool path is available as cutter location data (CLData). The downstream geometrical process simulation provides local cutting conditions. In the process analysis, the cutting conditions are the basis of a technological process evaluation. In the following, this paper focuses on the “Process Design Interface” and the “Geometrical Process Simulation”.

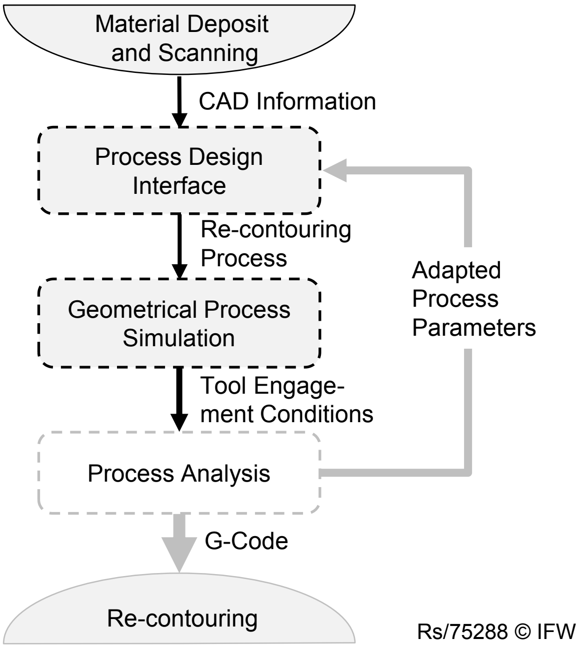

Fig. 3: Conceptual design

3. Process design interface

The interface closes the gap between the actual tool path planning and the geometrical process simulation for evaluation. Therefore, it uses a commercial CAD-CAM-system “Siemens NX 10”. This allows the interface to apply established algorithms, which define trajectories in the area of excess material. Fig. 4 shows the structure of the interface. The used CAD-CAM system includes an application programming interface (API). After definition of the repair case, the process design interface provides the master part to the CAM system, containing tool path information for a new blade of the same type. For generation of individual tool paths for the damaged blade, the CAD-CAM system receives information about the repair case, e.g. material specific process parameters. Therefore, the interface uses a set of rules for re-contouring to pick a parameter combination, which fits the current material combination. A set of rules for the re-contouring of welded titanium (Ti-6Al-4V) using different filler materials has been scientifically investigated and established in earlier studies [23–25]. Through multi dimensional analysis of experimental data process limits have been defined in terms of surface roughness. For instance this leads to an upper feed rate limit of 0.1 mm and a cutting speed of 60 m/min, preventing tool vibration.

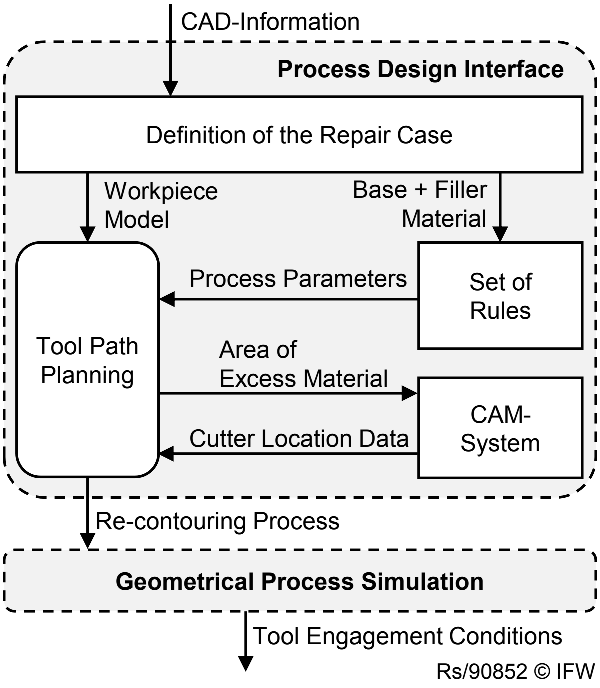

Fig. 4: Process design interface

3.1. Definition of the repair case

The conceptual design of the presented method (see Fig. 3) allows consideration of various repair processes. According to [5] the patch repair method is used for most types of damages on compressor blades. To carry out the welding of the patch, the damaged blade needs a prepared joint zone (see Fig. 5). The patch consists of the same material as the base material of the blade. The welding process itself uses additional filler material. Hence, to define the repair case, different material properties need to be considered in the process analysis. Therefore, the cutting conditions during re-contouring are associated to local material conditions. This way, different material properties are taken into account from the very beginning of the process design. The information about technological properties for different material is achieved through experimental data, e.g. parametrization of force models. In combination, a local evaluation of material dependent surface properties is possible. Furthermore, the process design interface receives information about the workpiece before (prepared workpiece) and after (repaired workpiece) the material deposition. These two workpiece models are produced by optical measurement before and after the material deposition. For the 3D scan of each workpiece state, the measuring system GOM ATOS Core 200 is used. A subtraction of both workpieces allows the quantitative determination of the different material areas. This step requires:

I. The presence of each 3D model before and after material deposition
II. Identical spatial orientation of each workpiece

Orientation of 3D models by a best-fit algorithm is a common functionality in today’s measurement software. Hence, the second step is carried out using the software “GOM ATOS”. After subtraction, the repaired workpiece is represented by a dexel model, which segments the 3D model into line elements (called dexel), defined by its start and end point [17].

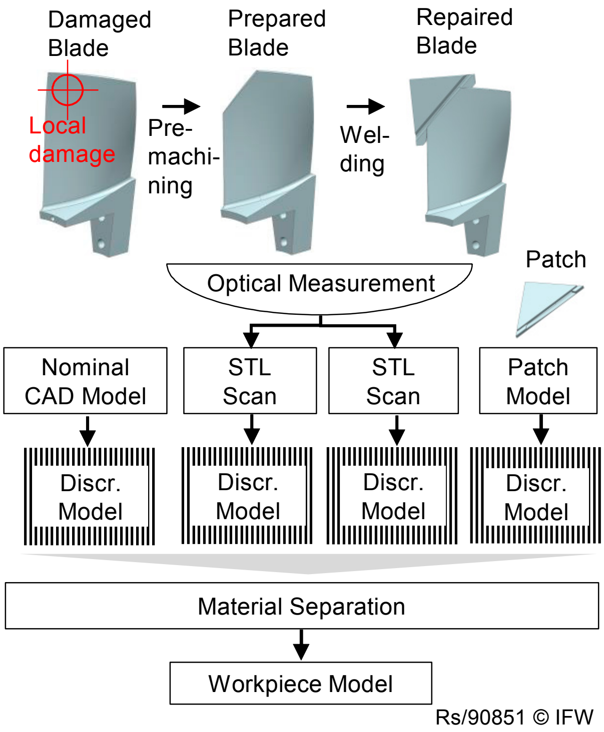

Fig. 5: Definition of the repair case

The subtraction method performs a calculation of intersection points of each dexel of the repaired workpiece with the prepared workpiece, resulting in spatial definition of the material deposit. The dexel model of the repaired workpiece originates from a triangle based representation of the workpiece (STL). As both models, damaged and repaired, originate from measurements, the models differ in most of the areas. This includes areas, where no material has been deposited. The reason for this is the different distributions of surface points within the scanning procedure and the tolerances in measurement and approximation. The difference in non-processed areas causes incorrect interpretation of material areas. To solve this problem, the subtraction algorithm eliminates elements of small length, which are filtered by a defined maximum value. This value depends on the tolerance of the scanning device and the point density. The used measuring system for scanning of the blades needs a tolerance factor of 0.01 mm to produce sufficient results. The nominal workpiece model helps to define areas to be removed trough the re-contouring. Adding the patch model, filler material originating from the welding process may be identified.

3.2. Tool path planning

The process design interface refers to a master workpiece that contains an initial tool path information for a nominal blade model. Hence, the blade type of the master workpiece has to be the same as the repaired workpiece. In this case, the initial tool path is a spiral strategy that describes the finish process for a new blade production. Fig. 6 (bottom left) shows the initial strategy. The first step of tool path adaption to the individual repair case is a reduction based on the information about identified excess material.

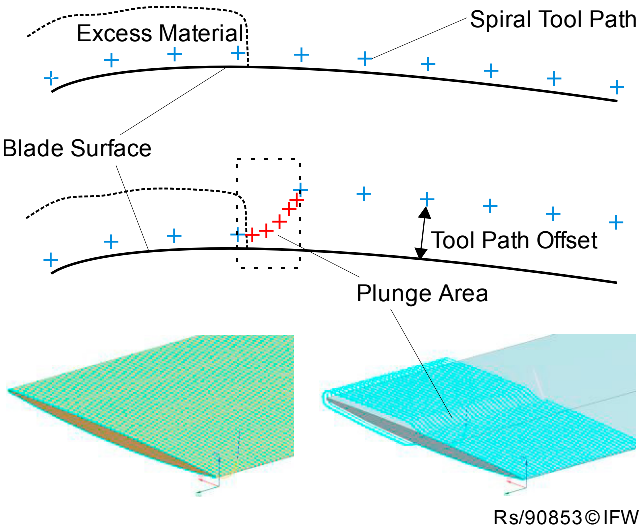

Fig. 6: Tool path adaption of a spiral tool path

A crucial issue in local machining of the blade is the step formation through continuous plunge motions of the tool when entering the excess material.

To take care of this issue, the process design allows for an offset in the non-damaged area of the blade, following the blade shape in a safe distance. Likewise, this avoids unintended transfer motions, which may lead to potential collision of the tool. Furthermore, the specification of a plunge area (see figure) allows to insert additional waypoints for the tool. Additionally, through definition of straight or parabolic plunge motions, a smooth transition area can be realized, preventing surface edges. Following steps lead to a second step of tool path adaption:

I. apply spatial information about the excess material
II. create an extrusion based on spatial information in longitudinal direction of the blade
III. define the intersection of extrusion and master workpiece as re-contouring area
IV. regenerate tool path trajectory based on the re-contouring area
V. define a tool path offset in non-damaged areas along the transverse direction
VI. define plunge motion in plunge area

The steps are performed automatically, using functions provided by the API. After tool path generation, the trajectory is applied in the geometrical simulation using a cutter location source file description (CLSF). The CLSF format is used due to the machine properties and machine axes that are not taken into account in the conceptual design. The simulation system IFW CutS compiles the CLSF data into signature control commands. This way, additional information like spindle speed are added to the code in order to complete the initial planning procedure.

4. Geometrical process simulation

The simulation of geometrical cutting conditions allows a characterization of the process and an identification of critical values. For a technological evaluation, an analysis of the engagement conditions of the tool is performed afterwards. The simulation model uses information about the repaired and the reference workpiece, the tool path, the milling tool model and parameters for the simulation. The rotating milling tool includes cutting edges. To resolve cutting conditions, a high temporal resolution is necessary. The time step defines the process time between two consecutive kinematic states. The suitable temporal resolution depends on the feed rate, cutting speed and the required resolution of tool rotation. Fig. 7 shows the re-contouring simulation of a patch-repaired blade, regarding local direction of cut. For the simulation, a resolution according to a tool rotation of 0.5 degree was chosen, leading to a time step of

$$\Delta t_{0.5} = \frac{\pi \times D \times 60}{v_c \times 1000 \times z \times 360} = 6.5 \times 10^{-5}\,s \qquad (1)$$

choosing a cutting speed of $v_c = 40\ m/min$ and tool with a diameter of 10 mm and two cutting edges. The blade clamp is used for process damping on the machine and needs consideration in terms of collision detection in the simulation.

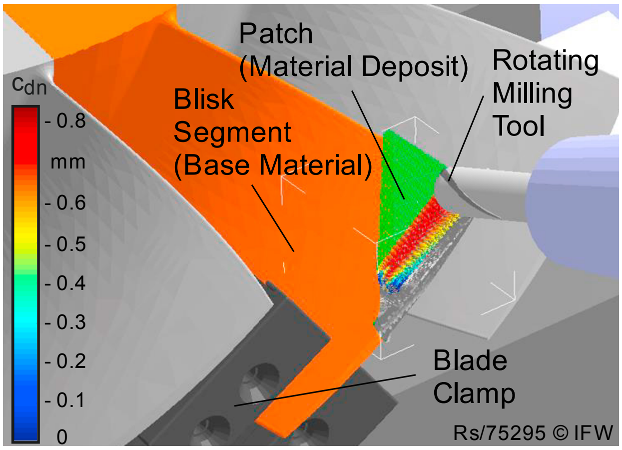

Fig. 7: Exemplary representation of the process simulation including determination of the component of direction of cut c_{dn}

The characterization is carried out based on local cutting parameters. This example considers the direction of cut, detected locally at the rotating cutting edge. Due to the rotary motion of the tool, the direction of cut changes relatively along the tool path and within a complete rotation of the tool. The absolute value is depending on the milling tool and the tool angle. Using ball end milling tools with a high helix angle, the direction of cut can hardly be calculated analytically, as it depends on the depth of cut, the tool angle as well as the orientation of the cutting edge. For simulation-based modeling, the direction of cut is calculated locally at the point of intersection of the tool geometry and the dexel-discretized workpiece. It is determined by two consecutive kinematic states of the tool (see Fig. 8). Starting point of calculation are the position arrays of the tool for two consecutive kinematic states S_n and S_{n-1}as well as the associated angle positions Ω_n and Ω_{n-1}.

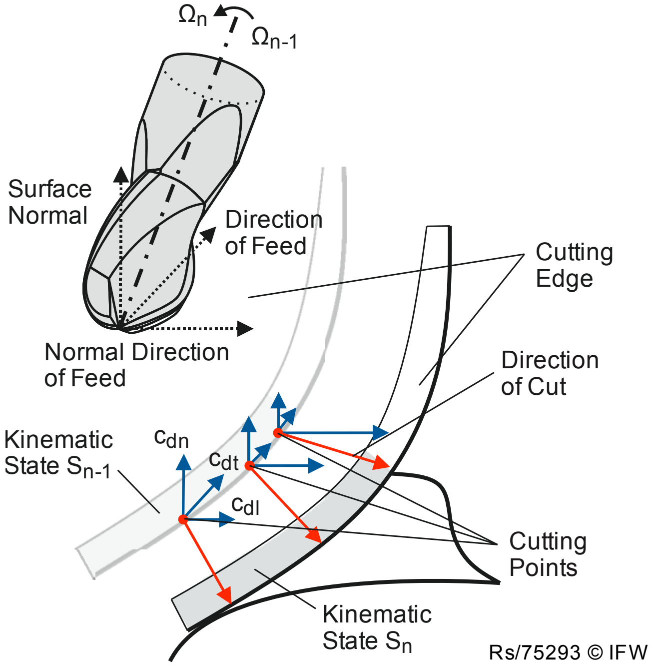

Fig. 8: Direction of cut at the ball end milling tool

The rotation matrix of the tool for the current simulation state n is calculated by multiplication of the kinematic state with the inverted previous kinematic state $n-1$:

$$\boldsymbol{S}_{Rot} = \boldsymbol{S}_{n-1}{}^{-1} \times \boldsymbol{S}_n. \quad (2)$$

The position vector of the cutting point on the workpiece surface $\vec{P}_{cut}$ is then multiplied by the rotation matrix:

$$\vec{P}_{end} = \boldsymbol{S}_{Rot} \times \vec{P}_{cut}. \quad (3)$$

The direction of cut $\vec{c}_d$ is then represented through the difference between vectors $\vec{P}_{end}$ and $\vec{P}_{cut}$:

$$\vec{c}_d = \vec{P}_{end} - \vec{P}_{cut}. \quad (4)$$

For process analysis, the resulting vector is linked to the corresponding dexel. It is decomposed into three components:

$$\vec{c}_d = \begin{pmatrix} c_{dt} \\ c_{dl} \\ c_{dn} \end{pmatrix}, \quad (5)$$

where

- c_{dn} is the component in direction of the surface normal,
- c_{dt} is the component in direction of feed (in transverse axis of the part) and
- c_{dl} is the component in normal direction of feed (in longitudinal axis of the part).

Fig. 9 shows the component c_{dn} for a limited area on the milled final surface. The pattern only considers negative cuts. A negative cut is a cut where the main direction in relation to the surface (c_{dn}) is negative. Hence, areas receiving a positive cut are white. It is evident that a regular pattern forms throughout the process, comparable to the pattern of a surface topography.

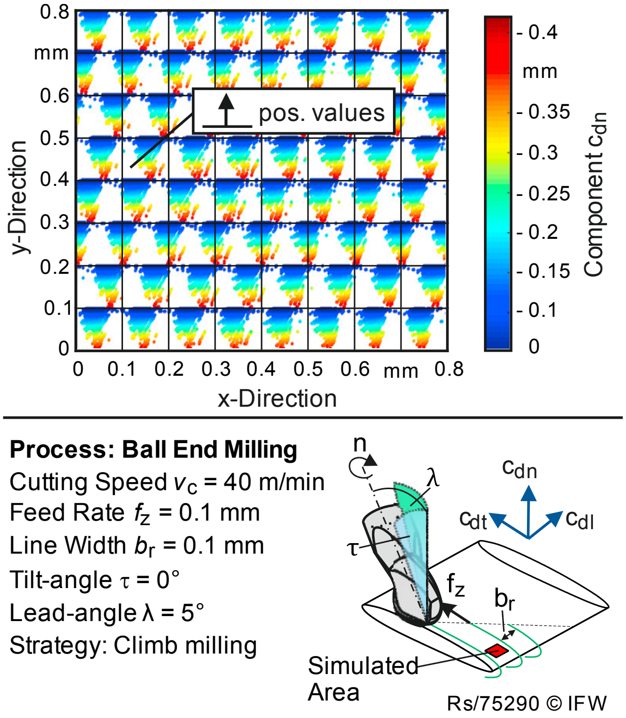

Fig. 9: Pattern describing the cut direction orthogonal with respect to the part surface (only considering negative cuts)

The pattern corresponds to a feed rate f_z of 0.1 mm and a line width a_p of 0.1 mm. The direction of cut is calculated in the final cut only, defining the shape of the final workpiece. This is due to the fact that surface properties, e.g. residual stresses, are depending on the cutting conditions inside the generating cross section [13]. The simulated direction of cut depends on the chosen resolution and time step.

If one considers the surface ratio of negative cuts, a fluctuation of the result is visible. This occurs due to a dependency of the sampling location of the sampling resolution, the latter described by the dexel resolution. The sampling location of a single dexel shifts when the resolution is increased, presuming a constant simulation area. Fig. 10 depicts the resulting ratio for an increasing dexel resolution.

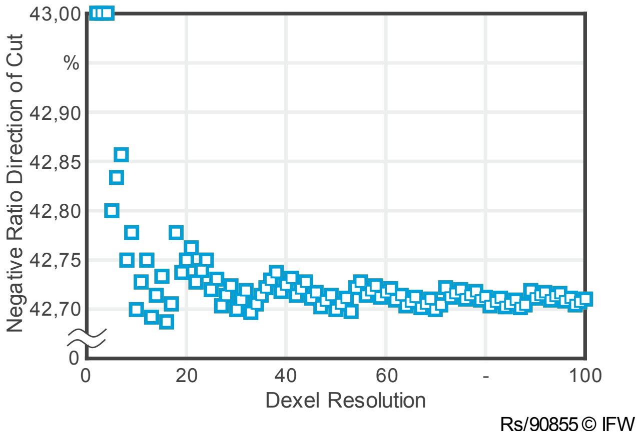

Fig. 10: Ratio of negative cuts

It shows a repeating pattern of fluctuations converging towards a specific value. Therefore, the value for dexel resolution must be high enough in order to reduce the fuzziness of the simulated value. For the simulation of direction of cut, the minimum dexel resolution is a function of process parameters, which kinematically affect the tool engagement, e.g. lead angle λ or tilt angle τ. The simulation reveals that e.g. the process $\lambda = 60°$ and $\tau = 0°$ needs a larger minimum resolution than the process $\lambda = 45°$, $\tau = 45°$.

5. Conclusion and outlook

The paper presents a new method for the automatic design of a re-contouring process. The method allows the re-contouring of a welded blade including consideration of individual shape and location of the material deposit, e.g. a welded patch. Therefore, the process design includes following aspects:

- automatic consideration of different material areas along the repaired workpiece
- a set of rules for the re-contouring of blades of the material Ti-6Al-4V
- automatic tool path restrictions in the area of the excess material based on a spiral strategy
- geometrical process simulation for the technological evaluation of the re-contouring process

The method is based on an existing geometric NC-Kernel as well as an interface to a CAD-CAM software. The simulation of tool engagement conditions is carried out, based on a dexel discretized workpiece model with a high resolution and a rotating milling tool model. In order to reduce simulation time, an exact definition of the dexel resolution is necessary. Moreover, the dexel resolution has a non-linear influence on the simulated tool engagement conditions. This was shown for the direction of cut. Taking this into account, the geometric simulation allows a prediction of workpiece quality parameters.

In the near future, the method will be used for the tool path adaption taking into account residual stress induced part distortion. Considering an analogue repair case, experimental studies are carried out leading to empirical knowledge about part distortion for the material Ti-6Al-4V. This allows a validation of the introduced simulation. In that context, the information about direction of cut is used. Hence, the experiments will focus on a variation of the parameter tool angle . This is carried out within an economical and technological evaluation of the overall approach of process design method. Individual processes will lead to individual distributions of direction of cut. Therefore, measured data including quality parameters from the real re-contouring process will be saved and help to improve future processes right in the process design. A machine learning approach is useful in this context.

Acknowledgements

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