Process Characterization and Evaluation of NC Machining Processes based on Macroscopic Engagement Simulation

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Keywords: Numerical Control Machining Simulation, NC Machining Process Evaluation, Material Removal Simulation.

Abstract: With a view to achieve stable production, nowadays the process design and planning goes through a time and resource intensive correction loop. The process output after machining trials is used to determine the critical process sections, and hence the experience of the process designer is decisive in the productivity of the optimization loop and the process. The implementation of a machining simulation can enhance the productivity of the process design and planning phase. The macroscopic engagement simulation provides an efficient tool for process evaluation. Moreover, it provides a basis for derivation of microscopic geometric process parameters, which have a direct correlation to mechanical and thermal loads. Thus, detailed information relating to the cutting loads on the tool is derivable at every point on the toolpath, enabling analysis of NC machining process based purely on the macroscopic geometric engagement between the cutting tool and workpiece. This information regarding the engagement conditions can be used to proactively identify potential critical process sections in a virtual environment thereby increasing the process reliability. Thus a process design for an optimal tool load is possible resulting in improved tool life, process efficiency and reduction in utilised resources.

1 INTRODUCTION

Milling technology is the most commonly used material removal method in the manufacturing of high value components, such as the turbine blades, bladed discs (blisks), press tools (moulds and dies) etc. These components are characterized by a complex geometry of sculpted or free formed surfaces (Choi et al., 1998). Moreover, aerospace components are manufactured from Titanium and Nickel based alloys which have high strength and temperature resistance but poor machinability which is a challenge in manufacturing. (Klocke, 2011). Due to the complex geometry of the parts needed in the mentioned industry sectors, there is a complex kinematic of the machining processes. This leads to variable contact conditions and variable load between workpiece and cutting tool, followed by acceleration of tool wear.

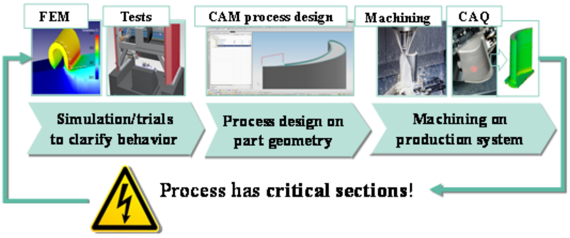

Figure 1: CAx process chain.(Minoufekr et al., 2013).

The state of the art CAx process chain is depicted in Figure 1, where CAx stands for computer based technology. The process design is performed on the basis of information derived from the simulation tests, and study of fundamental process kinematics i.e. orthogonal cutting conditions (Minoufekr et al., 2013, Zabel, 2010). A process design based on the fundamental studies leads to selection of conservative process parameters, resulting in reduction of productivity. Moreover, the critical sections in the process are first captured during the stage of the NC machining the actual part geometry. Thus, for a stable production with an optimal process, an optimization loop of the NC machining is necessary (Schug, 2012). If this process is carried out in a simulation environment and verified virtually, improvement in productivity and reduction in costs can be achieved (Zabel, 2010).

Minoufekr M., Schug P. and Joshi M..
Process Characterization and Evaluation of NC Machining Processes based on Macroscopic Engagement Simulation.
DOI: 10.5220/0005054606610670
In *Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2014), pages 661-670
ISBN: 978-989-758-040-6

The process analysis in a simulation environment enables the process designer to understand the critical section in the process. With this information pertaining to the process technology, an optimal process design is possible. Thus this paper presents an approach to create the technological basis necessary for the analysis of multi-axis NC milling processes. Section 2 provides a brief overview of the existing machining simulation systems, and the macro-simulation results are described. In Section 3, directly derivable process characteristics are assessed based on macro simulation. Furthermore, the macroscopic simulation results are extended to derive extra process knowledge regarding the machining conditions. This is necessary for process characterization and the subsequent evaluation of NC machining processes. The paper is concluded in Section 4.

2 TECHNOLOGICAL BACKGROUND AND PROBLEM DEFINITION

With the increase in the importance of the multi-axis milling processes in the industry, the deployment of computer based technologies (CAx technologies) is imperative. The computer based technologies are involved in the planning and verification of the entire milling process in advance (refer Figure 1). For this purpose, a virtual simulation of the NC machining processes can provide an insight about the real process conditions. Nonetheless, in the existing simulation systems neither the process behavior nor the phenomena occurring during the process are considered.

2.1 State of the Art in Machining Simulation

The last decades have seen a number of simulation approaches being developed specifically for determination of machining process parameters. The most common approaches are the finite element (FEM) based, analytical model based, and geometrical model based (refer Figure 2). Constructive Solid Geometry (CSG) based models and the spatial partitioning models are the most frequently deployed geometrical models for the evaluation of the entire NC processes (Zabel, 2010).

The FEM based models are computationally intensive and possess limited predictive capabilities, thus their implementation in the milling process planning is not practical due to the amount of time to be invested for the calculation efforts. The analytical model for cutter workpiece engagement cannot be implemented for freeform surfaces since analytical model equations are only valid for simplified workpiece geometry. The geometry based models focus mainly on the visual aspects of the resulting geometry deriving very limited access to technological process quantities.

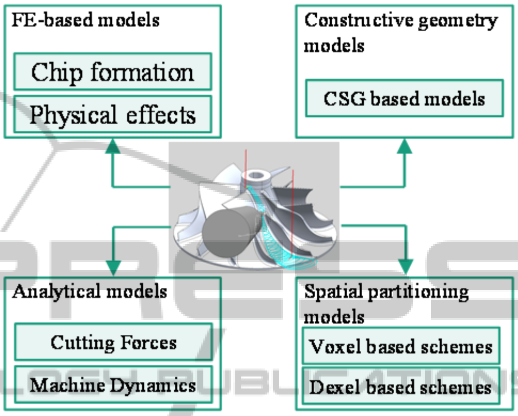

Figure 2: Overview of existing simulation models for machining processes. (Minoufekr et al., 2013).

The available milling simulation approaches based on the dexel and voxel models focus less on the physical properties. For e.g. Vericut provides options for collision detection for three and five axis milling processes (CGTech 2013). The obtained results in the geometry based models are insufficient since the modelling approaches are highly simplified. Minoufekr et al. present a novel alternative in (ICINCO, 2013), wherein the macroscopic contact conditions are calculated for every point on the cutting tool axis for every toolpath point in the multi-axis milling. The approach is referred to as macro simulation. However, the model needs to be extended so that the engagement on individual cutting edges can be analysed.

2.2 Modelling of Macroscopic Engagement Conditions

In the macro simulation, a slice model for a cutting tool is used along with a multi-dexel model for the workpiece in order to calculate the engagement conditions along the tool axis at discrete points on the toolpath. This modelling approach enables an efficient calculation method for large toolpaths for multi-axis machining of free-form surfaces. The contact angle ϕ_c is determined using the following equation:

$$\phi_c = \phi_{ex} - \phi_{st} \quad (1)$$

where, ϕ_{st} and ϕ_{ex} are the entry angle and the exit angle respectively, as illustrated in Figure 3. The axial depth of cut is denoted by a_p, the cutting tool radius by r_t and the direction of the cutting velocity and tool rotation by v_c. Since the calculation of ϕ_{st} and ϕ_{ex} is independent of the cutting edges of the cutting tool, these quantities are considered to be macroscopic (Meinecke, 2009).

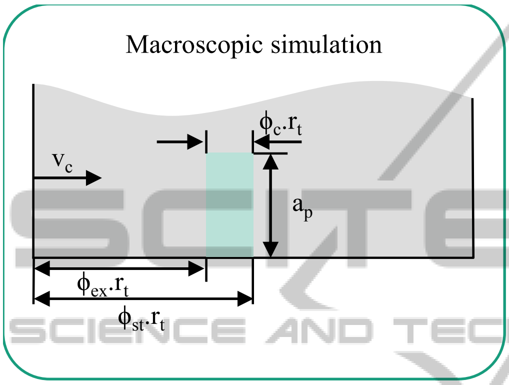

Figure 3: Macroscopic engagement conditions calculated in macro-simulation (Meinecke, 2009).

In multi-axis machining, the tool orientation with respect to the workpiece and the feed direction is constantly changing along the NC toolpath. Due to changing engagement conditions, the contact angle is also varying along the tool axis and along the NC tool path. This information can prove pivotal in process evaluation. In order to calculate and use this information, the cutting tool is discretized in slices along its axis. Every tool slice is represented by k ϵ [0, n], n being the total number of tool slices. For axial slices, height for each tool slice is Δa_p. The contact angle for every tool slice is calculated considering the surface envelope of the cutting tool geometry using equation (2):

$$\phi_c(k) = \phi_{ex}(k) - \phi_{st}(k) \quad (2)$$

Additionally the contact arc length (l_{arc}) can also be calculated according to equation (3):

$$l_{arc}(k) = \phi_c(k) \times r_T(k) \quad (3)$$

where, $r_T(k)$ is the radius of the tool slice. On the one hand, the macro simulation delivers an efficient approach for fast calculation of the tool workpiece engagement in multi-axis milling on a high level of abstraction. On the other hand, the macro simulation cannot provide information relating to the individual cutting edges in contact.

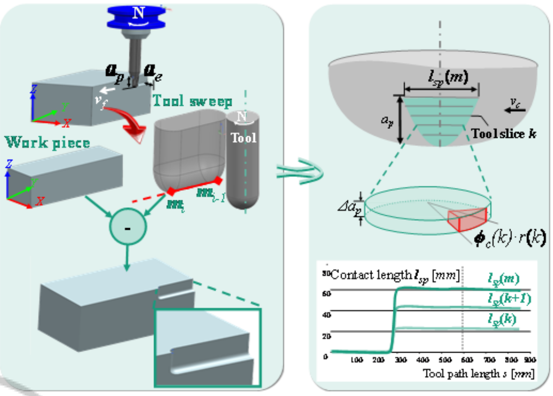

Figure 4: Geometric approach for macroscopic engagement simulation of multi-axis processes. (Minoufekr et al., 2013).

Due to this fact, direct derivation of the process conditions is limited in the macro simulation. To achieve a deeper understanding and to further derive process characteristics, the goal of the current research topic is to extend the macro simulation to obtain detailed information regarding the individual cutting edges.

2.3 Problem Definition and Research Question

Multi-axis milling processes are characterized by the dynamic nature of cutting tool workpiece engagement. Thus mechanical and thermal load on the cutting tool are also changing at different points along the toolpath. Identification of engagement conditions on the toolpath where unpredictable mechanical or thermal load leading to tool wear, in a simulation environment enables to proactively eliminate the critical process phenomenon and thus optimize the machining process. Literature review suggests that mechanical load and thermal load are proportional to geometrical input variables such as axial depth of cut (a_p), radial depth of cut (a_e) (Klocke, 2011) and contact length of cutting edge (Bouzakis, 2008) respectively. Minoufekr et al. established a link between the physical process quantities for e.g. Force (F_c) and the simulated geometrical process quantities for e.g. the contact angle (ϕ_c) by macroscopic contact conditions (Minoufekr et al., 2013). The macro simulation provides a fast model to characterize the NC machining processes on a higher abstraction level. Due to this higher level of abstraction, the capabilities of the macro simulation are limited with regards to direct calculation of process conditions. In the macro simulation, the engagement conditions regarding the individual cutting edges cannot be directly calculated which is essential for a deeper analysis of physical effects on the tool since the engagement conditions on each cutting edge have a direct link to cutting forces. Thus an extension of the existing macro simulation is essential which presents the research question of this work:

How can the macro simulation be extended so that the contact per cutting edge can be determined to characterize and evaluate the multi-axis milling process?

3 SOLUTION AND METHOD

Macroscopic process characteristics such as the cutting method can be determined using the macro simulation result. With the mapping of cutting edge geometry in the macro simulation, engagement analysis of individual cutting edges is possible. From the engagement analysis, the geometrical parameters for process characterization are determined. This enables characterization of the NC machining process based on purely geometric quantities. Then further the process is evaluated based on the instantaneous values of the characterization parameters. This approach is illustrated in Figure 5.

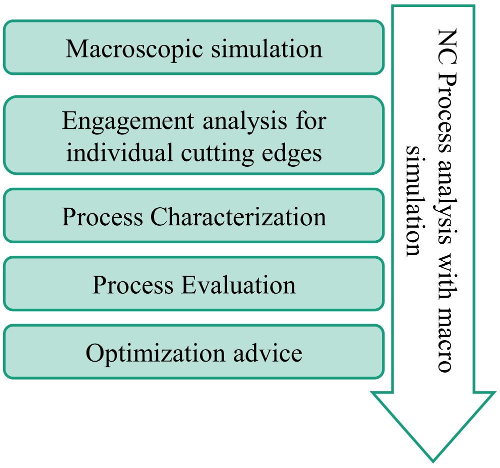

Figure 5: Proposed approach for process analysis with macro simulation.

3.1 Directly Derivable Process Characteristics based on Macroscopic Engagement

An important parameter during process design is the selection of the cutting method, i.e. up-milling and down-milling. C. Gey found that the tool wear in down-milling is lower as compared to up-milling (Gey, 2002), also during machining of aerospace alloys for e.g. titanium alloys and nickel based alloys, there is formation of chip root in up milling and hence should be avoided (Klocke, 2011). Thus identification of the cutting method provides important insight about the engagement situation. The cutting method can be directly interpreted from the result of the macro simulation as illustrated in Figure 6.

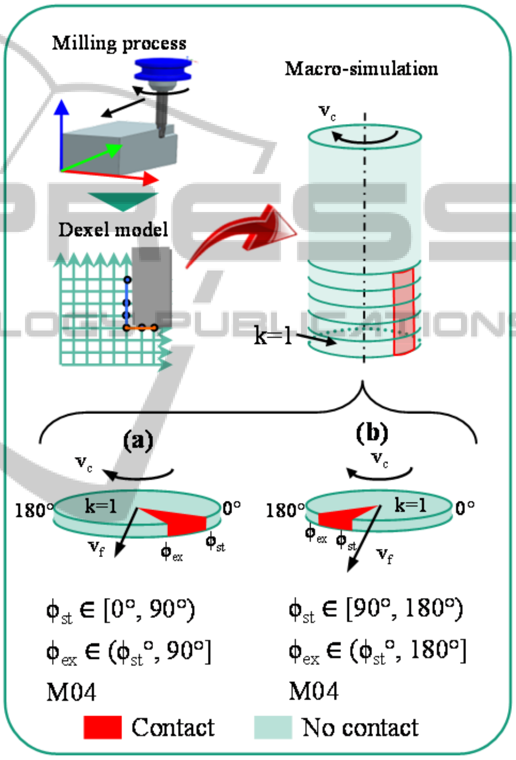

Figure 6: Definition of up-milling and down-milling in macro-simulation for counter-clockwise rotation.

The direction vectors of cutting velocity v_c and the feed velocity v_f are in opposite direction to each other in the engagement region in up-milling, and the direction vectors are parallel to each other in the engagement region in down-milling (Klocke, 2011). In the macro simulation, the values of the entry angle ϕ_{st} and the exit angle ϕ_{ex} are plotted on the surface envelope of the cutting tool model on each tool slice. The position for 0° and 180° is illustrated in Figure 6 and indicates the direction of measurement of angles. The tool slice is divided into four quadrants. The maximum possible contact angle ϕ_c is 180°. Hence the value of ϕ_{ex} cannot exceed 180° and the minimum value of ϕ_{st} is 0°.

Figure 6 illustrates the definition of up-milling (a) and down-milling (b) for a cutting tool rotating clockwise. The contact in up-milling is in the 1st quadrant, and for down-milling is in the 2nd quadrant. The sense of rotation in macro-simulation is recognized from the NC code, M03 for clockwise rotation (CW) and M04 for counter-clockwise (CCW) rotation. The engagement region between the cutting tool and the workpiece lies in the 1st quadrant. The entry angle ϕ_{st} can have the value 0°. The value of exit angle ϕ_{ex} should always be greater than the entry angle ϕ_{st}. The maximum allowable value of the exit angle for up-milling is 90°. Hence the value of the entry angle must be smaller than 90°. If the two values are equal then the contact angle is zero (refer Equation (1)). Equations (4)-(7) depict conditional definition for up-milling and down-milling in macro-simulation for CW and CCW rotations.

$$\phi_{st} \in (90°, 180°] \wedge \phi_{ex} \in (\phi_{st}°, 90°] \wedge \text{M03} \rightarrow \text{Up-milling} \tag{4}$$

$$\phi_{st} \in [0°, 90°) \wedge \phi_{ex} \in (\phi_{st}°, 90°] \wedge \text{M04} \rightarrow \text{Up-milling} \tag{5}$$

$$\phi_{st} \in [0°, 90°) \wedge \phi_{ex} \in (\phi_{st}°, 0°] \wedge \text{M03} \rightarrow \text{Down-milling} \tag{6}$$

$$\phi_{st} \in [90°, 180°) \wedge \phi_{ex} \in (\phi_{st}°, 180°] \wedge \text{M04} \rightarrow \text{Down-milling} \tag{7}$$

For a process designed as up-milling or down-milling, if the position of the entry angle and the exit angle are identified as $\phi_{st} \in [0°,90°)$ and $\phi_{ex} \in (90°,180°]$ respectively and CW rotation, then there is a transition in the cutting method from up-milling to down-milling. The identified cutting method due to such engagement condition is undefined, and hence should be avoided.

During multi-axis milling of turbine blades, contact on radially opposite sides on the cutting length of the cutting tool on different axial positions is possible. This phenomenon is illustrated in Figure 7. This leads to simultaneous up-milling and down-milling. Although the CAM planning software does not recognise this as an error, because contact is only in the cutting length region of the cutting tool, from a process technology point of view, it is a critical phenomenon. The result is unpredictable material removal and undefined mechanical load on the cutting tool. To identify this phenomenon, the cutting method on each of the tool slices in engagement is identified. If the cutting method on any pair of tool slices is inconsistent, i.e. different cutting methods are identified on the slices in the pair, simultaneous up-milling and down-milling is identified. Also, if any slice has two separate engagement regions, one in the up-milling and the other in down-milling region, then there is a case of simultaneous up- and down-milling.

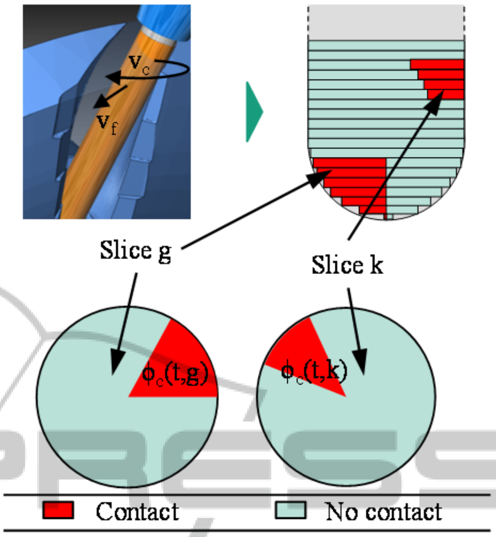

Figure 7: Simultaneous up- and down-milling.

The tip of the ball end mill in engagement during the process should be avoided (Ozturk, 2009). The cutting velocity on the ball end mill is increasing on the spherical part from a value 0 onwards due to increasing radius along the cutting tool axis. The zero cutting velocity at the tip results in no material removal, and a rubbing action when in contact, resulting in the increase in the temperature at the cutting tool interface due to friction. In the macro-simulation the engagement conditions are mapped on the surface envelope of the cutting tool geometry. Also the cutting tool is discretized into axial slices, thus the tip of the cutting tool is contained in the bottom-most tool slice (k=1). If the contact angle at the bottommost tool slice is greater than 0° i.e. ($\phi_c(1) > 0°$), the tip of the ball end mill is in engagement.

With the identification of the cutting method, undefined conditions such as transition of up-milling to down-milling and simultaneous up- and down milling can be identified during the CAM planning stage. Thus resulting in elimination of critical process conditions and increasing the process reliability.

3.2 Mapping of Cutting Edge Geometry in Macroscopic Engagement Simulation

The mapping of cutting edges in the

macro-simulation enables determination of engagement conditions for each individual cutting edge for e.g. the contact length ($l_{c,i}$) and the contact angle on individual cutting edges ($\phi_{c,i}$) (refer Figure 8).

In macro-simulation the engagement conditions are mapped on the surface envelope of the cutting tool. The information regarding the contact on the rake faces of the cutting tool is not derivable (refer **Figure 4**). For this reason the geometrical parameters of the cutting edges which cannot be mapped onto the surface envelope for e.g. rake angle, flank angle etc. are not considered. In order to map the cutting edges in the macro-simulation, two parameters regarding the cutting edges are necessary, namely the number of cutting edges Z, and the helix angle of the cutting edges λ. (refer Figure 8).

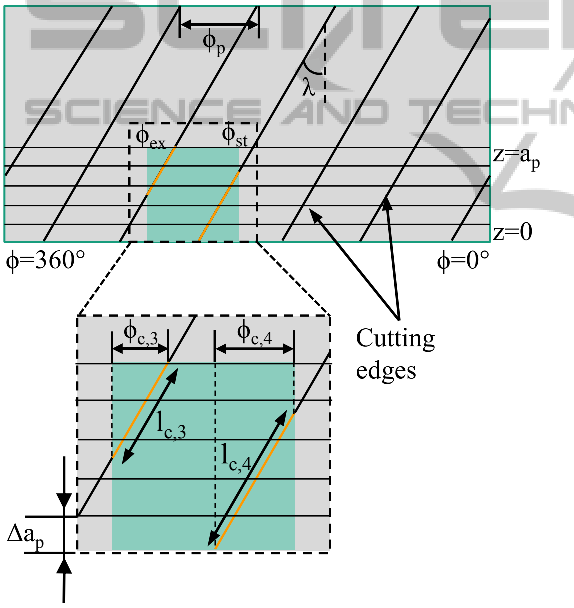

Figure 8: Engagement analysis for individual cutting edges in the macro simulation result.

The number of cutting edges is given by Z and the cutting edges are distributed with a constant offset between consecutive cutting edges, this offset is called as the angular pitch (ϕ_p).it is calculated using equation (8).

$$\phi_p = \frac{2\pi}{Z} \tag{8}$$

The progression of the helix angle (λ) of the cutting edges needs to be considered while mapping of parameters in the macro simulation. The progression of the helix angle is dependent on the tool shape. The helix angle of the cutting edges of the cylindrical end mill is constant along the axis of the cutting tool, and thus on a 2D developed surface model for the cylindrical end mill, the cutting edges are linear (refer Figure 8). The diameter on the spherical part of the ball end mill is variable along the tool axis, hence the helix angle of the cutting edge in case of a ball end mill is not constant along the tool axis, but defined by a function (Lazoglu, 2000).

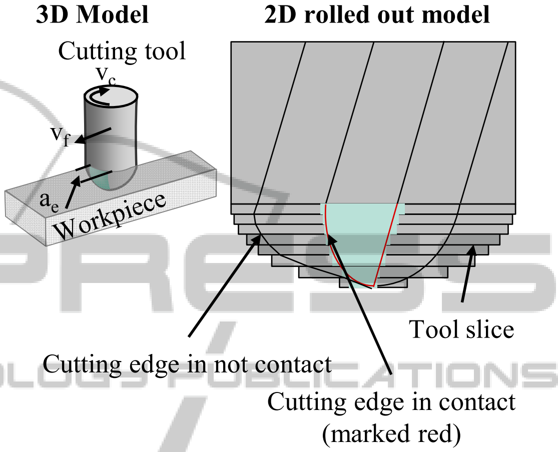

Figure 9: Mapping of cutting edges on a 2D rolled out model of ball end mill.

The spherical part is divided into slices of constant diameter and the circumference of each tool slice is mapped in the 2D rolled out model of a ball end mill. Also the cutting edges for ball end mill start on the tip of the ball end mill as illustrated in **Figure 9**. The contact angle is assumed to be constant for each tool slice. The helix angle is calculated for each tool slice as a function of its axial position, and is considered to be constant for each tool slice Δa_p. Hence the cutting edge is mapped as a straight line on every tool slice. During mapping, the cutting edges which are in contact can be marked as seen in **Figure 9**.

The process condition illustrated in Figure 9 is an elementary case of engagement between the cutting tool and the workpiece. This engagement area can be formally defined and mapped on the surface envelope of the cutting tool. As illustrated in Figure 10, the engagement area for a 5-axis milling case of an impeller is mapped. It can be seen from the figure that the engagement area is distorted and cannot be defined formally. Also the contact on individual cutting edges also cannot be defined formally. To enable the mapping of the contact for individual cutting edges, the contact angle calculated for each tool slice is essential. The contact angle is

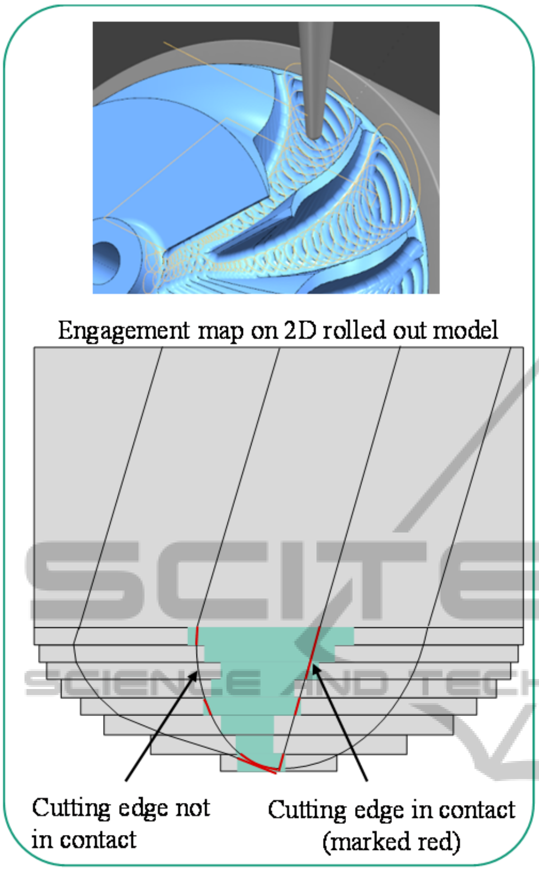

Figure 10: Mapping of microscopic parameters reflecting contact conditions on a 2D rolled out model of ball end mill.

then mapped on the tool surface envelope. The position of the cutting edges mapped in the 2D rolled out model of a cutting tool is considered to be constant. Thus comparing the peripheral position of the cutting edges and the contact angle for each tool slice, the exact engagement for individual cutting edge for every position along the cutting tool axis is determined.

3.2.1 Derivable Microscopic Geometric Parameters from Macroscopic Engagement Analysis

With the information regarding the exact contact conditions on individual cutting edges, geometric quantities, such as the number of cutting edges in contact, the contact length (L_{sp}) and the uncut chip geometry parameters such as the chip thickness (h_{sp}), the and the chip cross section area (A_{sp}) can thus be derived using the result of the macro simulation. This is achieved by the extension of the macro simulation as illustrated in Figure 11.

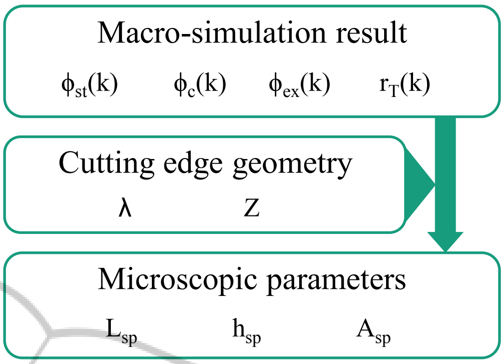

Figure 11: Determination of microscopic parameters in the macro-simulation.

For a given contact angle ϕ_c the contact length on every tool slice is determined using the equation (9) where r_T is the cutting tool radius.

$$dl_s(k)=\frac{r_T(\phi_{ex}(k)-\phi_{st}(k))}{\sin(\lambda(k))} \tag{9}$$

Six possibilities of contact on the cutting edge (Altintas, 2012). are illustrated in Figure 12 for tool slices, where $\phi_{1,1}$ and $\phi_{1,2}$ are the angular positions of the cutting edges on the cutting tool periphery, the part of the cutting edge in contact is coloured orange, and the part not in contact is coloured black. The exact contact length for each individual cutting edge on each tool slice $dl_s(t,k)$ for every point on the toolpath can be determined. The contact length $l_s(t)$ for one cutting edge summed over all the tool slices n is calculated using Equation (10):

$$l_s(t)=\sum_{k=1}^{n} dl_s(t,k) \tag{10}$$

The total contact length for all cutting edges $L_s(t)$ at every point on the toolpath is calculated using the equation (11), where Z is the number of cutting edges.

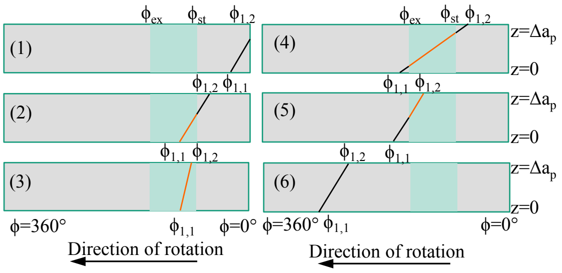

Figure 12: Cutting edge contact length for each tool slice.

$$L_s(t)=\sum_{j=1}^{z} l_{s,j}(t) \tag{11}$$

Figure (13) (a) illustrates a case of blisk machining with a ball end milling cutter, (b) shows the engagement field mapped on the tool surface envelope. The contact angle is variable along the cutting tool axis. The progression of the chip thickness is illustrated in part (c) for a tool slice k. The chip thickness according to Fischer's approach is calculated using equation (12). The chip thickness h_{sp} depends not only on the contact angle ϕ_c but also on the position of ϕ_{st} and ϕ_{ex} on the tool periphery. The chip cross section area (A_{sp}) also depends on the ϕ_{st} and ϕ_{ex}. The chip cross-section area can be determined using equation (13) (Meinecke, 2009) respectively.

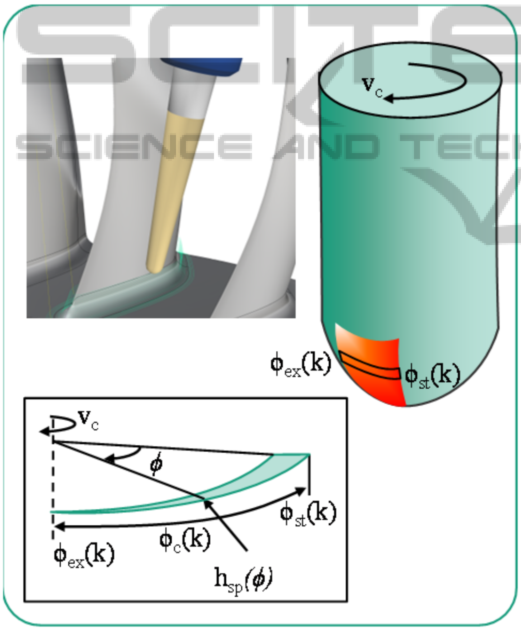

Figure 13: Progression of chip thickness over the contact angle.

$$h_{sp}=\int_{\phi_{st}}^{\phi_{ex}} f_z \sin(\phi)d\phi \tag{12}$$

$$A_{sp}=\frac{D}{\sin\lambda}\sum_{j=1}^{z}\int_{\phi_{1,j}}^{\phi_{2,j}} h_c(\phi)d\phi \tag{13}$$

Where, D is the cutting tool diameter, $\phi_{1,j}$ and $\phi_{2,j}$ are the angular positions of the entry angle and the exit angle of the cutting edges. And ϕ is the tool rotation angle as depicted in Figure 13. From the contact angle calculated for every tool slice and the cutting edge helix angle, the progression of the chip thickness and chip cross section area for each tool slice can be calculated. This enables determination of local uncut chip geometry parameters.

The cutting edges enter and leave the engagement area due to the rotation of the cutting tool, resulting in the variation of the contact length and chip cross section area. The rotation of the tool can be simulated by iterating the values of ϕ_{st} and ϕ_{ex} from 0° to 360°, and thus the variation in contact length of the tool and the chip cross section area at a point on the tool path can be analysed. This variation in the values of the geometrical microscopic parameters can be used for characterization of NC machining processes based on process technology values. Moreover, it can be evaluated if the instantaneous values of the process technology parameters are exceeding the minimum and the maximum values decided during process design.

3.3 Process Characterization

Parameter based process characterization

The microscopic geometric quantities related to the uncut chip determined on the basis of macroscopic parameters (refer **subsection 3.2.1**), have direct co-relation to process technology parameters. Due to which, the magnitude of the microscopic geometric parameters is indicative of the magnitude of the process technology parameters for e.g. cutting force F_c, facilitating the parameter based characterization of NC machining processes.

The cutting forces F_c can be determined using equation (14):

$$F_c=\frac{r_T \times K_c}{\tan\lambda}\sum_{j=1}^{Z}\int_{\phi_{st,j}}^{\phi_{ex,j}} h_{sp}(\phi)d\phi \tag{14}$$

where K_c is an empirical constant calculated experimentally and ϕ is the tool rotation angle. Considering a case of a mould machining process designed for a constant axial depth of cut, i.e. for constant tool load, the complex toolpath geometry results in varying engagement conditions along the toolpath and thus varying loads. The relation between the cutting forces and the chip thickness enables process characterization based on chip thickness. During process design, an optimal value of the chip thickness is decided considering the tool load. On one hand, exceeding of this set optimal value results in tool overload. Thus the maximum allowable feed $f_{z,max}$ per cutting edge for a point on the tool path depends on the instantaneous contact angle, which is dynamically changing. On the other hand, during chip formation, if the value of feed per cutting edge f_z is too low for the instantaneous contact angle, then a chip is never formed, and there is ploughing effect due to rubbing action between the cutting tool and workpiece, due to the friction the temperature at the cutting tool workpiece interface increases, leading to tool wear (Klocke, 2011). This phenomenon can be identified in the macro simulation. The minimum allowable value of feed per tooth, is the one which allows for formation of chip, i.e. the cutting edge radius (Degner, 1973). Thus, the value of minimum chip thickness is constant throughout the process, whereas the value of minimum feed per tooth $f_{z,min}$ is variable along the toolpath, due to dynamic nature of the changing contact angle. Any value of the feed per tooth between $f_{z,min}$ and $f_{z,max}$ is acceptable but there is loss in productivity. The conditional equation for evaluation of processes based on feed per tooth as a characterization parameter is shown in equations (15)-(17).

$$f_z(t) < f_{z,min}(t) \lor f_z(t) > f_{z,max}(t) \rightarrow \text{Unacceptable chip thickness} \tag{15}$$

$$f_{z,min}(t) < f_z(t) < f_{z,max}(t) \rightarrow \text{Acceptable chip thickness} \tag{16}$$

$$f_z(t) = f_{z,max}(t) \rightarrow \text{Optimal chip thickness} \tag{17}$$

During NC machining, multiple cutting edges are in contact with the workpiece. Due to the rotation of the cutting tool, the cutting edges enter and leave the contact region, resulting in the fluctuation of load on the cutting tool. When a cutting edge exits contact and at the same moment, another cutting edge enters contact, there is low fluctuation of cutting forces. This condition is defined as Uniformity. Engagement conditions leading to a low fluctuation in the cutting load are preferred, since this helps in an optimal process design. Uniformity is defined in equation (18) (Kronenberg, 1969)

$$U = n\left(\frac{l_{arc}}{\phi_p}\right) \tag{18}$$

where n is an integer, l_{arc} the contact arc length and ϕ_p the angular pitch of the cutting tool. C. Gey conducted experiments and concluded that when U=1 there is a local reduction in the cutting forces (Gey, 2002). There is no variation in the value of chip cross section area and the contact length. Uniformity can be used for NC machining process characterization, as fluctuation in load on cutting tool is reflected by fluctuation in value of microscopic geometric parameters. The variation in chip cross section area (A_{sp}) due to tool rotation can be used as a metric to measure U, given by equation (19) (Meinecke, 2009).

$$U = \frac{\min\{A_{sp}\}}{\max\{A_{sp}\}} \tag{19}$$

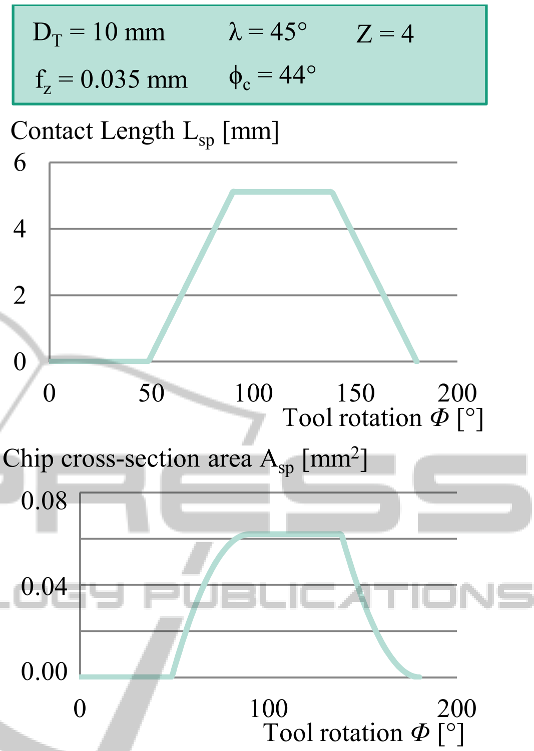

Figure 14: Progression of A_{sp}, L_{sp} for one cutting edge with tool rotation.

During milling, when the contact angle for an individual cutting edge increases as the cutting tool rotates, the contact length increases linearly, whereas the increase in chip cross section area is digressive (refer Figure 14). Thus the contact length can also be used to measure Uniformity, and to derive information regarding the process dynamics. For a cutting tool with multiple cutting edges in engagement, for one complete rotation, due to the individual cutting edges entering and exiting the contact area, the total contact length L_s. Thus equation (20) depicts Uniformity measured on the basis of the total contact length.

$$U = \frac{\min\{L_s\}}{\max\{L_s\}} \tag{20}$$

4 CONCLUSION

The high manufacturing costs involved in the multi-axis machining of components having free form surfaces makes it imperative to meet the highest quality with minimum effort. Moreover, a short product life cycle leads to frequent design changes. This increases the challenge on the process designers to setup fault free processes the first time right. The macro simulation tool provides an opportunity to analyse and optimize the machining processes.

In the macro simulation, the macroscopic engagement is calculated on the discrete points of the toolpath. Using these calculated macroscopic engagement conditions, interpretations regarding the real process conditions can be deduced. With an extension of the macroscopic simulation, even microscopic geometric process characteristics are derived. Thus NC machining processes can be characterized based on purely macroscopic and microscopic geometrical parameters which are derived using the macroscopic engagement parameters. Further this process analysis is independent of empirical process data.

Prediction of the critical sections on the toolpath, where the process technology values can exceed the allowable limits set during process design, is possible. Through the proactive identification of the critical process sections, their elimination at the process design phase is possible before the machining processes are executed, thereby reducing potential expensive damages and machine downtime. Moreover there is improvement in the process reliability. Thus there is optimization in the productivity of the NC machining processes.

ACKNOWLEDGEMENTS

The authors would like to thank the German Research Foundation DFG for the support of the depicted research within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries".

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