Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 16
ISSUE 1-2
May-June
2006

An advanced machining simulation environment employing workpiece structural analysis

S. Ratchev, S. Liu*, W. Huang, A.A. Becker
School of Mechanical, Materials, Manufacturing Engineering,
University of Nottingham, Nottingham, NG7 2RD, United Kingdom
* Corresponding author: E-mail address: shulong.liu@nottingham.ac.uk

Received 15.11.2005; accepted in revised form 15.04.2006

Analysis and modelling

ABSTRACT

Purpose: The study aims to reduce the surface dimensional error due to the part deflection during the machining of thin wall structures, thus, reduce machining costs and lead times by producing “right first time” components.
Design/methodology/approach: The proposed simulation environment involves a data model, an analytical force prediction model, a material removal model and an FE analysis commercial software package. It focuses on the development of the simulation environment with a multi-level machining error compensation approach.
Findings: The developed simulation environment can predict and reduce the form error, which is a limitation of the existing approaches.
Research limitations/implications: The energy consumption, temperature change and residual stress are not studied in this research.
Practical implications: The developed method provides a platform to deliver new functionality for machining process simulation. The convergence of the proposed integrated system can be achieved quickly after only a few iterations, which makes the methodology reliable and efficient.
Originality/value: The study offers an opportunity to satisfy tight tolerances, eliminate hand-finishing processes and assure part-to-part accuracy at the right first time, which is a limitation of previous approaches.
Keywords: CAD/CAM, Modelling and simulation; System integration, Structural analysis

1. Introduction

To remain competitive manufacturers constantly seek to reduce machining costs and lead times by producing “right first time” components. High precision machining of complex parts is one of the key processes in modern manufacturing. Machining of low-rigidity components is a key process in industries such as aerospace, marine engineering, and power engineering. Producing the right profile in such parts increasingly depends on specialised CAD/CAE/CAM packages for defining appropriate cutting strategies and tool paths. However, most of the existing techniques and models are based on idealised geometries and do not take into account factors such as variable cutting force, part/tool deflection etc. [1].

The surface dimensional error is induced mainly by the deflection of the tool and the workpiece during milling, which results in a deviation of the depth of cut. In the peripheral milling of a very flexible component, the deflection is significant. The process is further complicated by periodically varying milling forces, which statically and dynamically excite the tool and part structures, leading to significant and often unpredictable deflections. Advanced computational methods and numerical simulation of machining process that are often involved finite element (FE) methods offer the opportunity to satisfy tight tolerances, eliminate hand-finishing processes and assure part-to-part accuracy [2]. FEA-based simulation models that consider physical factors, such as material properties, tool geometry etc., are required to accurately predict the part/tool deflection during machining.

The resulting errors are normally compensated through a lengthy and expensive trial and error NC program validation process. Driven by the need to constantly reduce time and cost, manufacturers are looking for alternative techniques for NC program validation based on off-line surface error prediction and tool path compensation. Rahman et al [3] described two ways to modify NC programs including modelling and measurement of machine tools using a three-dimensional volumetric error model. Bohez [4] presented a general approach on how to compensate for the systematic errors based on the closed loop volumetric error relations. Wang et al [5] developed a static/quasi-static error compensation system composed of an interpolation algorithm, and a recursive software compensation procedure. Cho et al [6] proposed an integrated error compensation method based on an inspection database by using on-machine measurement in profile milling. Raksiri and Parnichkun [7] proposed an off line error compensation model in a 3-axis CNC milling machine.

Despite the significant developments in NC simulation and verification, there are still significant knowledge gaps in comparing the theoretically predicted surfaces and the measured surfaces due to the variation of the tool and part geometry that is not interpreted by the existing software systems. The decision on how to efficiently and accurately compare the machined surface to the initial CAD model is of critical importance in achieving high quality machining of complex sculpted surfaces. There is still a knowledge gap in identifying the impact of deflection on the process of metal removal and hence there is a lack of systematic approaches to modelling, prediction and compensation of the component errors in machining process and machining simulation subject to force-induced deflection.

The proposed simulation environment involves a data model [10], an analytical force prediction model [8] [15], a material removal model [9] and an FE analysis commercial software package [13]. This reported result focuses on the development of the simulation environment with a multi-level machining error compensation approach focused on force-induced errors in machining of thin-wall structures. It is the further development on the reported research achievement [10] [11] [16]. The integrated environment provides a platform to deliver new functionality for machining process simulation where there is force-induced part deflection. The prediction algorithm takes into account the deflection of the part at sampling points on the tool path. The machining conditions are modified at each step when the cutting force and deflection achieve a local equilibrium. The results from part structural FE analysis are used but not discussed in this report. The error compensation scheme is simulated using an NC simulation package VERICUT [12] and is experimentally verified.

2. The proposed simulation environment

Further study based on the proposed prototype simulation environment [10] incorporates a variety of decision-making modules (Figure 1), including cutting force modelling [8], component deflection modelling, and material removal modelling [9]. The main difficulty in developing the simulation environment is caused by the need for data exchange between a variety of models and software modules. The environment includes commercial FEA packages, such as ABAQUS [13], and in-house programs for force modelling and material removal modelling with different data input and output requirements. The integration requires using a component data model as a common data exchange medium. This data model includes the complete FE mesh and analysis information such as nodes, elements, material properties, analysis procedure, boundary conditions, force, and output control to predict the deflection of a low-rigidity part during machining. A FE analysis tool uses the component data model as input to predict the part deflection, and then the force model takes the deflected component model as input taking into account the effect of part deflection on the force prediction. The material removal model is applied to remove material from the deflected component model and return the updated data on nodes and elements. The updated data on new nodes, elements, and force are then used to modify the component data model for next step simulation.

In machining simulation, the nominal cutting path is given in a form of NC code at selected sampling points. The compensation software identifies the coordinates of the cutting trajectory and uses them as the inputs for error predictions. As soon as the milling error is obtained, the error compensation can be achieved through optimising the tool path by comparing the nominal (control) surface and the predicted surface. The cutting trajectory is then automatically modified according to the predicted part deflection. An algorithmic approach is proposed for generating corrective actions by recalculating the tool path. A modified NC code is then generated and issued to the machine's CNC controller. Further to the force-induced errors, the methodology can be extended to include other types of errors into the compensation algorithm. The approach aims to utilise the available company specific knowledge and priorities in selecting processing alternatives and deflection compensation strategies.

In more detail, the data model structure of the simulation environment is developed in C++. The component data model used in the simulation environment is developed based on both the FEA principles and the object-oriented principles. It includes several key object classes: component, node, element and force described with their attributes and associated methods.

The object class "Component" is the main part of the data model. It holds the complete information for the FE analysis. The attribute of "Heading" includes the title of the component to be machined. "Nodes" and "Elements" hold the mesh information of the component. There is no limit on what element types the FE model can have and also no limit on how many nodes an element can include. After material is removed from a component, the machined surface can be represented accurately by replacing the "old" elements with any type and number of new elements. "Loads" holds the positions (in terms of node numbers and degrees of freedom) and magnitudes of the cutting force. The attribute of "Constants" represents some unchanged data during the iterative procedure e.g. the material property including material type, Young's modulus and Poisson's ratio etc. "Output Control" determines what FEA results will be output that are used for the next iteration. For example, the nodal displacements are normally required to indicate the part deflection and will then be used to update the model to be a deflected model.

The attributes of "Component" class include objects (at least one object) of other classes such as "Node", "Element" and "Force", which have their own methods to modify the related data during the iterative procedure. A meshed component may include hundreds and thousands of nodes and each of them is represented by one object of the "Node" class within the data model. The attributes of each "Node" object include the reference number of the node, the nodal coordinates and the displacements caused by the cutting force. Thousands of elements may also be included within a meshed part and each element is also represented by an object of "Element" class. The attributes of each "Element" object include the reference number, the type and those nodes forming this element. The objects of "Force", called Loads, hold force information provided by the theoretical force model. Since the force is distributed on the nodes within the tool-part contact zone, these data are stored in terms of nodal number, degree of freedom, and the force magnitudes.

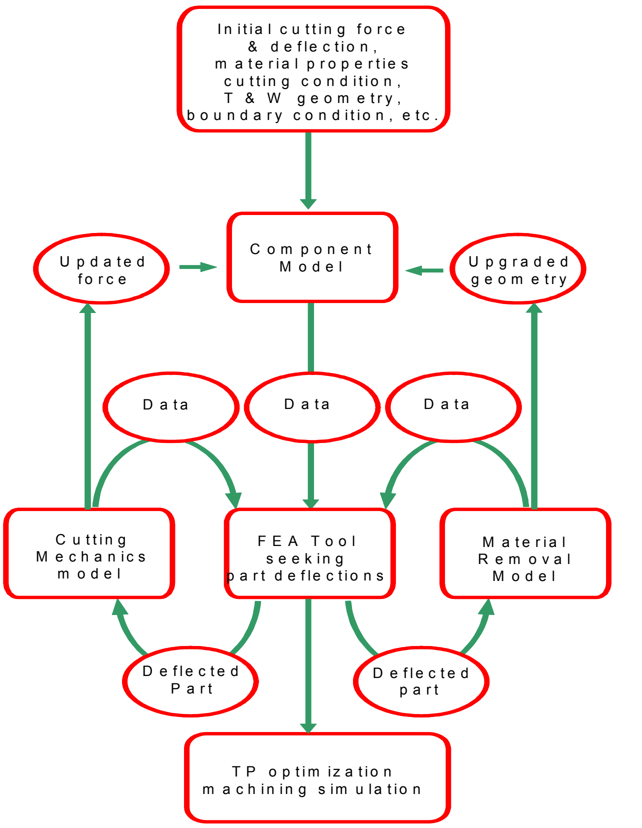

Fig. 1. System integration scheme for the machining simulation environment

The methods within the class "Component" are used to control the data change with the other external models and commercial FEA package. The methods under "Input Data for FEA" create the input data for FE analysis and manage the data exchanges with the FEA package. During each iteration, these methods extract the displacements of those appropriate nodes within tool-part contact zone from the FE analysis results and then update the corresponding data within the component data model to create the updated input files for the next FEA run. The methods under "Nodes & Elements" manage the data exchanges with the material removal model and update the mesh information within the component data model. The methods under "Force" control the data exchanges with the force model.

The developed simulation environment allows the integration of mainstream FEA packages and specialist cutting simulation programs. The incorporation of ABAQUS, a mainstream FEA commercial package within the developed simulation environment, has been achieved as a proof of concept. However, the proposed methodology and the developed programs are generic by nature and can be easily integrated with other FEA packages due to the object-oriented implementation environment that allows easy and quick change.

3. Multi - level error compensation scheme

A tool path can be considered as a sequence of cutter locations represented at sampling points. At each cutter location (sampling point), the cutting position on both the tool and workpiece consists of two meanings - the 'nominal' tool contact point and the actual contact point after the deflection of the part. The 'nominal' tool position is known while the actual contact point is obtained using a flexible force and part deflection model. The multi-level error compensation scheme for force induced error compensation can be described as follows [11]:

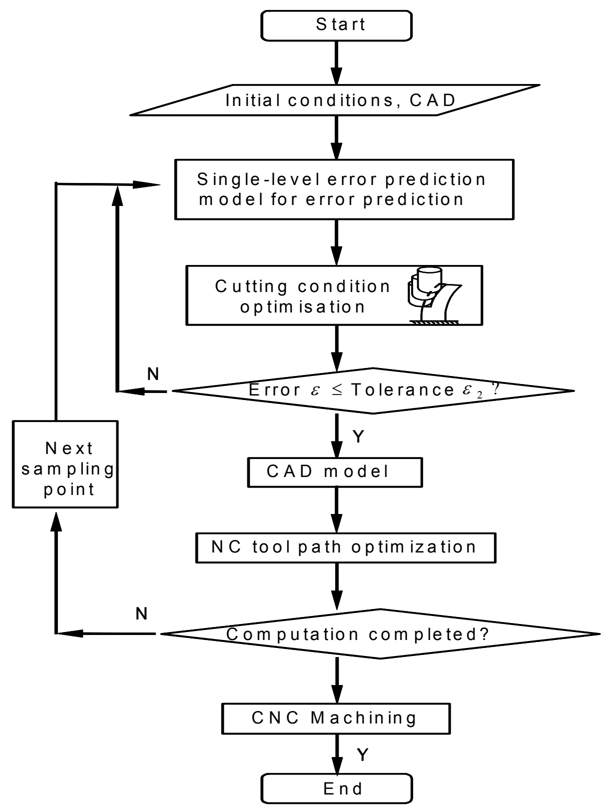

Fig. 2. Flowchart of the multi-level error prediction and compensation scheme

At any sampling point, j, along the workpiece length, under the designed cutting conditions, the workpiece deflection, $[u_1, v_1, w_1]$, is obtained from the equilibrium state of the flexible cutting force and workpiece deflection through an iterative procedure, the so called primary level or single level error prediction. Due to the workpiece deflection, the cutting depth and cutting force changes, therefore, the cutter and the workpiece will be in an equilibrium state at the different position. Thus, if the error is compensated in a single step, the tool tip will still not reach the desired cutting position. Under the cutting conditions with the tool path compensated to [x_1, y_1, z_1] by [u_1, v_1, w_1], a new workpiece deflection, [u_2, v_2, w_2], can be found, and so on.

In the iteration step i, the deflection [u_i, v_i, w_i] is predicted, the tool tip cutting position compensated to [x_i, y_i, z_i]. A new deflection error value [$u_{i+1}, v_{i+1}, w_{i+1}$], is computed and the new deflected position of the designed cutting position on the workpiece is found. The newly predicted workpiece deflection error, is again used for the next tool path compensation from position [x_i, y_i, z_i] to [$x_{i+1}, y_{i+1}, z_{i+1}$]. The difference between the successive two compensated tool positions, $i+1$ and i, is expressed as [$\Delta x_i, \Delta y_i, \Delta z_i$].

The summation of the predicted cumulated total amount for altering tool path in the multi-level iteration is

$$\begin{bmatrix}\Delta x & \Delta y & \Delta z\end{bmatrix} = \begin{bmatrix}\sum_i \Delta x_i & \sum_i \Delta y_i & \sum_i \Delta z_i\end{bmatrix} \quad (1)$$

with disregarding to the tool rotation. The correction of the tool path from the designed cutting position [x_d, y_d, z_d] to the optimised actual cutting position [x_c, y_c, z_c] is therefore:

$$\begin{bmatrix}x_c & y_c & z_c\end{bmatrix} = \begin{bmatrix}x_d & y_d & z_d\end{bmatrix} + \begin{bmatrix}\Delta x & \Delta y & \Delta z\end{bmatrix} \quad (2)$$

The primary level iteration will be terminated as the tolerance, ε_1, is satisfied, i.e. the difference of the workpiece deflection between two successive iterations, ($k+1$) and k, under specific cutting conditions of the step i,

$$Max\left(ABS\begin{bmatrix}\Delta u_k & \Delta v_k & \Delta w_k\end{bmatrix}\right) = Max\left\{ABS\left(\begin{bmatrix}u_{j,i,k+1} & v_{j,i,k+1} & w_{j,i,k+1}\end{bmatrix} - \begin{bmatrix}u_{j,i,k} & v_{j,i,k} & w_{j,i,k}\end{bmatrix}\right)\right\} \le \varepsilon_1 \quad (3)$$

Then the predicted error in the primary level iteration will be used for optimising cutting conditions. As the cutting condition changes, a new iteration is needed to find the new possible error caused by the changes in the cutting conditions. Therefore a multi-level iteration is needed. The tolerance, ε_2, for terminating the multi-level iteration and moving machine tool from one sampling point to the next one is based on the difference of the workpiece deflection between two successive tool path compensations ($i+1$) and i, implied in the cutting depth in the axial cutting direction h_r, at the sampling point j,

$$Max\left(ABS\begin{bmatrix}\Delta x_i & \Delta y_i & \Delta z_i\end{bmatrix}\right) = Max\left\{ABS\left(\begin{bmatrix}u_{j,i+1} & v_{j,i+1} & w_{j,i+1}\end{bmatrix} - \begin{bmatrix}u_{j,i} & v_{j,i} & w_{j,i}\end{bmatrix}\right)\right\} \le \varepsilon_2 \quad (4)$$

As the difference of the predicted amount for altering tool path between two successive iterations satisfies the given tolerance in the multi-level iteration, the computational algorithm will move on to the next sampling point, $j+1$.

4. Results and discussion

There are a number of commercial packages for NC part programme verification which simulate the tool movement and resulting part shape. Using such tools allows the cost of NC data verification to be reduced and the efficiency of the material removal process to be improved by optimising the feed and speed values. A major drawback of all NC verification packages is that they do not take into account the dynamic state of the machined part, and therefore cannot predict surface errors due to deflection. In this study, the machining process simulation tool, Third Wave AdvantEdge [14] and the NC simulation, verification tool VERICUT [12] have been used to simulate the machining process. The optimised tool path used for CNC machining and simulation tool, VERICUT, is generated using a CAD/CAM package. The workpiece model fed in VERICUT uses a surface model that includes node coordinates before workpiece deflection (x_0, y_0 and z_0) and the workpiece deflection at the corresponding nodes (dx, dy and dz). A quasi-static illustration is compromised due to VERICUT being originally designed to deal only with rigid part models.

For simplification the part is assumed to be a thin-wall rectangular workpiece. The idealised machined profile is a vertical flat surface. During the milling process, the workpiece deflection in workpiece thickness direction that is perpendicular to the machined surface, has a most significant impact on forming the surface profile error. Errors predicted in other two directions are negligibly small and are not considered in machining simulation. The force components are measured using an eight-channel Kistler dynamometer. The part deflection is measured on-line by monitoring the displacements of the part during machining using inductive displacement sensors mounted at the back of the workpiece [8]. Displacements at two points, a and b, are measured where the measuring point, a, is located at 6 mm below the top of the workpiece and b is at the bottom of the cutter. In these trials, the axial cutting depth is 30mm. The radial cutting depth is 2mm. The feed rate is 0.25 mm/rev-tooth.

The proposed algorithm was applied to find the converged displacements. The tolerance for iteration termination is 0.1% in the y-direction that dominates the part deflection of low-rigidity parts during machining. It takes five iterations to converge to a feasible cutting force and the corresponding deflections for the chosen set of the variable initial values. The measured and predicted displacement at point a in workpiece thickness direction, u_y, are plotted against each other in Figure 3. while the measured and predicted resultant forces are illustrated in Figure 4. In Figures 3 and 4, it shows that convergence is robust and fast down to the given tolerances.

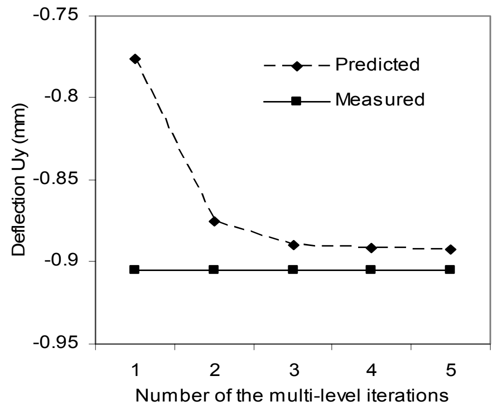

Fig. 3. Convergence of displacement u_y at point a and x =0

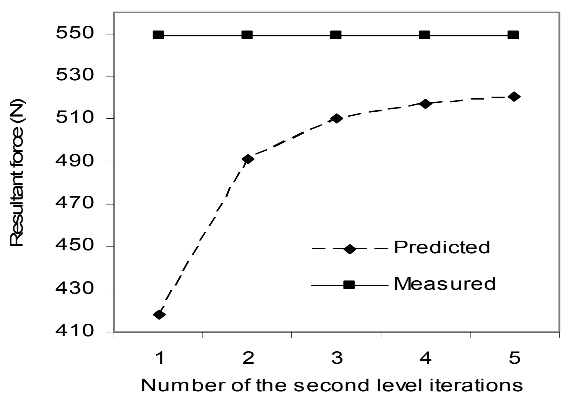

Fig. 4. Convergence of resultant force F at point a and x =0

The displacement at points, a and b, the force component in workpiece thickness direction, F_y, and resultant force, are shown in Table 1. Values at x = 0, 60 and 150 mm along the workpiece length are presented. The agreement between the predicted and measured values is adopted to show the efficiency and speed of proposed integration environment and is defined as,

Agreement%=ABS(Predicted value / Measured value) *% (5)

It can be observed that the predicted and measured values are very close. The agreement values are all larger than 81%. It is worth noting that the predicted values can converge to the measured counterparts from either side and the speed of convergence depends on the choices of the variable initial values.

Table 1.
Comparison of the predicted and measured values

	x (mm)	Predicted	Measured	Agreement
	0	-0.892	-0.905	98.6%
Uya (mm)	60	-0.607	-0.738	82.3%
	150	-1.120	-1.014	89.5%
	0	-0.615	-0.544	87.0%
Uyb (mm)	60	-0.386	-0.427	90.4%
	150	-0.644	-0.569	86.9%
	0	-344.1	-315.9	91.1%
Fy (N)	60	-428.8	-361.4	81.3%
	150	-303.5	-307.4	98.7%
	0	520.5	549.2	94.8%
F (N)	60	629.5	615.1	97.7%
	150	463.1	535.2	86.5%

a. measuring point located at 6 mm below the top of the workpiece
b. measuring point located at the bottom level of the cutter

5. Conclusions

This paper reports part of the achievements based on the general error compensation strategy [9] and, by focusing on the machining simulation and system integration, aims to improve the accuracy and reduce the cost of machining of low-rigidity components. It is achieved by integrating a number of innovative developments including analytical force modelling, part deflection prediction modelling and material removal modelling in a multi-level iterative scheme.

The proposed integration environment including a multi-step simulation of cutting processes of low-rigidity components has been experimentally tested and validated. The results demonstrate that the proposed approach is a practical way to integrate in-house programs for force modelling with complete FE mesh and analysis information using mainstream FEA packages to predict part deflection during machining simulation.

The results of the experimental verification of the proposed routines indicate at least 81% of the total error can be captured through the developed error compensation methodology. The results show that convergence of the proposed integrated system can be achieved quickly after only a few iterations, which makes the methodology reliable and efficient.

Acknowledgements

The reported research is part of the project “Adaptive Planning for Machining of Complex Low-Rigidity Components” funded by the UK EPSRC (GR/R13098/01), the support of which is gratefully acknowledged.

References

[1] T. S. Suneel, S. S. Pande, Intelligent tool path correction for improving profile accuracy in CNC turning. International Journal of Production Research 2000;38(14):3181-3202.

[2] J. Mackerle, Finite-element analysis and simulation of machining: a bibliography (1976-1996). Journal of Materials Processing Technology 1999;86:17-44.

[3] M. Rahman, J. Heikkala, K. Lappalainen, Modeling, measurement and error compensation of multi-axis machine tools. Part I: theory, International Journal of Machine Tools and Manufacture, 40 (2000) 1535-1546.

[4] E.L.J. Bohez, Compensation for systematic errors in 5-axis NC machining, Computer-Aided Design 34 (2002) 391-403.

[5] S.M. Wang, Y.L. Liu, Y. Kang, An efficient error compensation system for CNC multi-axis machines, International Journal of Machine Tools and Manufacture 42 (2002) 1235-1245.

[6] M. Cho, T. Seo, H. Kwon, Integrated error compensation method using OMM system for profile milling operation, Journal of Materials Processing Technology 136 (2003) 88-99.

[7] C. Raksiri, M. Parnichkun, Geometric and force errors compensation in a 3-axis CNC milling machine, International Journal of Machine Tools and Manufacture 44 (2004) 1283-1291.

[8] S. Ratchev, S. Liu, W. Huang, and A. A. Becker, Milling error prediction and compensation in machining of low-rigidity parts, International Journal of Machine Tools and Manufacture, 44 (2004) 1629-1641.

[9] S. Ratchev, S. Nikov, I. Moualek. Material removal simulation of peripheral milling of thin wall low-rigidity structure using FEA. Proceedings of the 35th CIRP international seminar on manufacturing systems, Seoul, Korea, 13-15 May 2002. p. 371-377.

[10] S. Ratchev, W. Huang, S. Liu, and A. A. Becker, Modelling and simulation environment for machining of low-rigidity components, Journal of Materials Processing Technology 153-154 (2004) 67-73.

[11] S. Ratchev, S. Liu, W. Huang, and A. A. Becker, An advanced FEA based force induced error compensation strategy in milling, International Journal of Machine Tools and Manufacture (In press).

[12] VERICUT 5.2 User Manual, www.cgtech.com, Irvine, CA92618, 2002.

[13] ABAQUS/Standard User’s Manual 6.1, Hibbitt, Karlsson and Sorensen, Inc., Pawtucket, RI 02860-4847, USA, 2000.

[14] Third Wave AdvantEdge, Third Wave Systems, Inc., USA., 2003

[15] S. Ratchev, S. Liu, W. Huang and A. A. Becker, A flexible force model for end milling of low-rigidity parts, Journal of Materials Processing Technology 153-154 (2004) 134-138.

[16] S. Ratchev, S. Liu, W. Huang and A. A. Becker, Error compensation strategy in milling flexible thin wall parts, Proceedings of the Advanced Materials & Processing Technologies 2005, Poland, 499-502.