Int J Adv Manuf Technol (2007) 35:55–65
DOI 10.1007/s00170-006-0700-6

ORIGINAL ARTICLE

# Machining simulation and system integration combining FE analysis and cutting mechanics modelling

**Svetan Ratchev · Shulong Liu · Wei Huang · Adib A. Becker**

Received: 15 December 2005 / Accepted: 13 June 2006 / Published online: 19 August 2006


**Abstract** In this paper, the machining process to produce the right surface profile in machining low-rigidity parts is studied by considering moving dynamic cutting forces that statically and dynamically excite the tool and part reducing the validity of these packages' output and leading to additional surface errors. The proposed approach is based on producing a simulation environment integrating a data model, an analytical force prediction model, a material removal model and an FE analysis commercial software package. This reported result focuses on the development of the simulation environment and the data model. The integrated environment provides a platform by which the FE analysis commercial package, ABAQUS, can exchange data with the proposed data model, force model and material removal model, to deliver new functionality for machining process simulation where there is force-induced part deflection. The data model includes complete mesh and analysis information for predicting part deflection and enables iterative data updating for multi-step simulation. The proposed simulation methodology has been experimentally validated.

**Keywords** Modelling and simulation · System integration · FE analysis

## 1 Introduction

To remain competitive manufacturers constantly seek to reduce machining costs and lead times by producing "right first time" components. The accuracy of the surface profile is one of the most important components of both dimensional and geometric accuracy and plays a significant role in achieving overall product quality because it is often directly related to the product's functional performance. Advanced computational methods and precision machining are also critically important in order to satisfy tight tolerances, eliminate hand-finishing processes and assure part-to-part accuracy.

Machining of low-rigidity parts is a key process in industries such as aerospace, marine engineering, and power engineering. Typical examples of such parts are propellers, bladed discs and turbine nozzles, which have thin-walled sections with length-thickness ratio greater than 10 resulting in deflection during machining induced by transverse forces in the thickness direction [1–3]. Producing the right profile in such parts increasingly depends on specialised CAD/CAE/CAM packages for defining appropriate cutting strategies and tool paths [4, 5]. 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. [6, 7]. In practice, the machining process is complicated by the cutting forces that statically and dynamically excite the tool and part reducing the validity of the CAD/CAE/CAM output and leading to additional machining errors that are difficult to predict and control [8]. The direct experimental approach to study the deflection-related machining errors is often expensive and time consuming.

An alternative approach is numerical simulation of the machining process, which usually involves a finite element (FE) method, force modelling techniques and material removal modelling [9]. FEA-based simulation models that consider physical factors, such as material properties, tool geometry etc., are required to accurately predict the part/

S. Ratchev · S. Liu (✉) · W. Huang · A. A. Becker
School of Mechanical, Materials, Manufacturing Engineering,
University of Nottingham,
Nottingham NG7 2RD, UK
e-mail: Shulong.liu@nottingham.ac.uk

tool deflection during machining. To compute the part/tool response to the cutting force, the continuous machining process was simulated by multi-step cutting processes [10, 11]. Spence et al. [10] developed a physical machining process simulation program based on a solid modelling kernel. A special sweep representation was used to update the part shape, and the FE mesh was periodically rebuilt. Tsai and Liao [11] developed an FE model along with an end milling cutting force model to analyse the surface dimensional errors in the peripheral milling of a thin-walled part. The cutting force distribution and the part deflection were solved by an iterative simulation algorithm. The dynamic effect during milling was not considered, and the tool and the workpiece were assumed to deform to their static equilibrium position at any milling instant.

While advanced and conventional shell theories have been considered for modelling deflecting structures during machining they appear to have limited applicability due to the level of complexity associated with modelling the part-tool behaviour during machining [1]. A number of FEA (finite element analysis) packages have been used to simulate manufacturing processes. These packages use mathematical theories and non-linear numerical algorithms to model plastic flow, heat conduction, thermo-mechanical coupling, dynamic behaviour and cutting mechanics [12]. Among commercial general-purpose FEA packages, ABAQUS [13] is widely used in academe and industry. Cho et al. [14] developed a static analysis FE model to simulate out-reactor fuel-string strength tests using ABAQUS. Zha and Moan [15] investigated the ultimate strength of stiffened aluminium panels with predominantly torsional failure modes by experimental and theoretical analysis.

The machining simulation research involves the development of the material removal model, part mesh and re-mesh model and force prediction model. A number of methods based on techniques such as Z-map, discrete vector and voxel-based representations were also used for cutting simulation and NC verification [16]. Spence et al. [10] indicated that most existing machining simulation techniques were geometric in nature and ignored the physical aspects of the process. Sagherian and Elbestawi [17] reported a dynamic cutting model that took into account the effect of material removal using an automatic mesh generation program. Jang et al. [18] developed a voxel-based simulator for multi-axis CNC machining. The voxel representation was used to efficiently model the machined workpiece, which was generated by successively subtracting tool swept volumes from the workpiece. Ratchev et al. [19] developed voxel-based material removal approaches by cutting through the voxels at the tool-part contact surface and replacing them with an equivalent set of mesh compliant volumetric elements.

Kline et al. [20] proposed a mechanistic model for cutting force prediction combined with a model for cutter and part deflections using FE analysis to model the part. A prediction model of cutting forces for flexible end milling systems was also reported by Sutherland and DeVor [21]. Budak and Altintas [22] considered the peripheral milling of a very flexible cantilever plate with slender end mills that incorporate a mechanistic force model and FE methods. Based on the mechanistic principles of metal cutting, Feng and Menq [23] developed a cutting force model taking into account the engaged cut geometry, the undeformed chip thickness distribution along the cutting edges and the effect of the cutter axis offset and tilt on the undeformed chip geometry. Based on the theoretical orthogonal cutting mechanics model [24], Budak et al. proposed an oblique cutting mechanics model [25, 26], in which the oblique cutting force components are obtained from orthogonal cutting force using an orthogonal to oblique cutting transformation method. The material-related and cutting condition-related parameters in orthogonal cutting of the workpiece-tool pair are calibrated using a standard routine published in [26]. The method can eliminate the need for experimental calibration for each milling tool geometry and can be applied to more complex tool designs, thus making it more generic and applicable. In general, the existing knowledge on cutting force can be clustered into two groups of studies: development of theoretical rigid force models and development of mechanistic force models considering the effect of tool/part deflection during machining. However, their applicability to force modelling in machining of low rigidity parts is limited due to the variability of material properties, cutting mechanics, non-linear dependency between the forces and the continuously changing tool immersion angle and chip thickness. For simulation of low-rigidity part machining, a general-purpose analytical force model is required.

Although commercial general-purpose FEA software, such as ABAQUS, was also used to simulate some manufacturing processes, it cannot be solely used to simulate multi-step cutting processes of low-rigidity parts. The main difficulty is that material removal and remeshing of part model cannot be automatically performed by the software for the multi-step processes and an appropriate theoretical force model for part/tool deflection prediction is not available. To simulate the machining of low-rigidity parts, varieties of models and software, including commercial tools and in-house programs, are involved, which have different data input and output requirements. There is a need to link the mainstream commercial FEA software with force prediction models and material removal models in order that data exchange among them can be achieved and the machining of low-rigidity parts can be simulated.

In this paper, the machining process to produce the right surface profile in machining low-rigidity parts is studied by considering moving dynamic cutting forces that statically and dynamically excite the tool and part reducing the validity of these packages' output and leading to additional surface errors. The proposed approach is based on producing a simulation environment integrating a data model, a flexible analytical force prediction model [5] that adopted the more generic oblique cutting mechanics model [25, 26], a material removal model [19] and an FE analysis commercial software package. This reported result focuses on the development of the simulation environment, the data model and the further development of the reported research achievement [6]. The integrated environment provides a platform by which FE analysis commercial packages, such as ABAQUS, can exchange data with the proposed data model, force model and material removal model, to deliver new functionality for machining process simulation where there is force-induced part deflection. The novel FEA-based data model includes complete mesh and analysis information for predicting part deflection and enables iterative data updating for multi-step simulation. The proposed simulation methodology has been experimentally validated.

## 2 An overview on the developing simulation environment

Further study based on the proposed prototype simulation environment [6] incorporates a variety of decision-making modules (Fig. 1), including cutting force modelling, component deflection modelling, and material removal modelling. There are several iterative levels within the environment. The first part includes force modelling and part deflection modelling to predict the feasible cutting force and the corresponding part deflection. The second part includes part deflection modelling and the third part, material removal modelling to simulate the material removal process. The environment integrates all the modules together to simulate the cutting processes. The predicted results are then analysed and compared with the experimental data to verify the developed methodology.

The main difficulty in developing the multi-step 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, 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 (Fig. 2). 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. An FE analysis tool uses the component data model as input to predict the part deflection, and then the force model [5] takes the deflected component model as input taking into account the effect of part deflection on the force prediction. The material removal model [19] is applied to cut 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.

## 3 Part data model

### 3.1 Flexible FE model

This research specifically focuses on low-rigidity parts deflected by the exerted cutting force during machining, and the deflection of the cutting tool is ignored. In the proposed model, the part deflection behaviour is predicted by FE analysis. A typical 3D FE mesh of a thin wall part is shown in Fig. 3. The part is meshed by using 8-node isoparametric quadratic (brick) elements with full-integration and there are total 60000 elements included. In this example, the eight vertices of the part are labelled A, B, C, D, E, F, G, and H. The origin of the global coordinate system is at point A. When the tool starts cutting, it contacts the part in the edge of FB and causes the part to deflect. The tool-part contact line is represented by FN in FB. The input to the FE analysis includes the mesh data of nodes and elements, cutting force, and other parameters describing material properties and boundary conditions etc.

During the machining simulation, the cutting force is provided by the theoretical force model and applied at different sampling points on the part along the tool path. At any position, the cutting force is applied on the tool-part intersection line, *FN* and distributed on the nodes along the line. The displacements of the nodes within the tool-part intersection area represent the deflection profile that is used in downstream decision-making modules for force prediction and material removal simulation.

In this study, ABAQUS is used to calculate the deflection caused by the cutting force at each sampling point through the following equation [13]

$$[K]\{U\} = \{F\}, \tag{1}$$

where $[K]$ is the stiffness matrix of the workpiece, $\{U\}$ and $\{F\}$ are nodal displacements of workpiece and the external cutting force acting on the tool-workpiece transient contact surface on workpiece, respectively. As the boundary

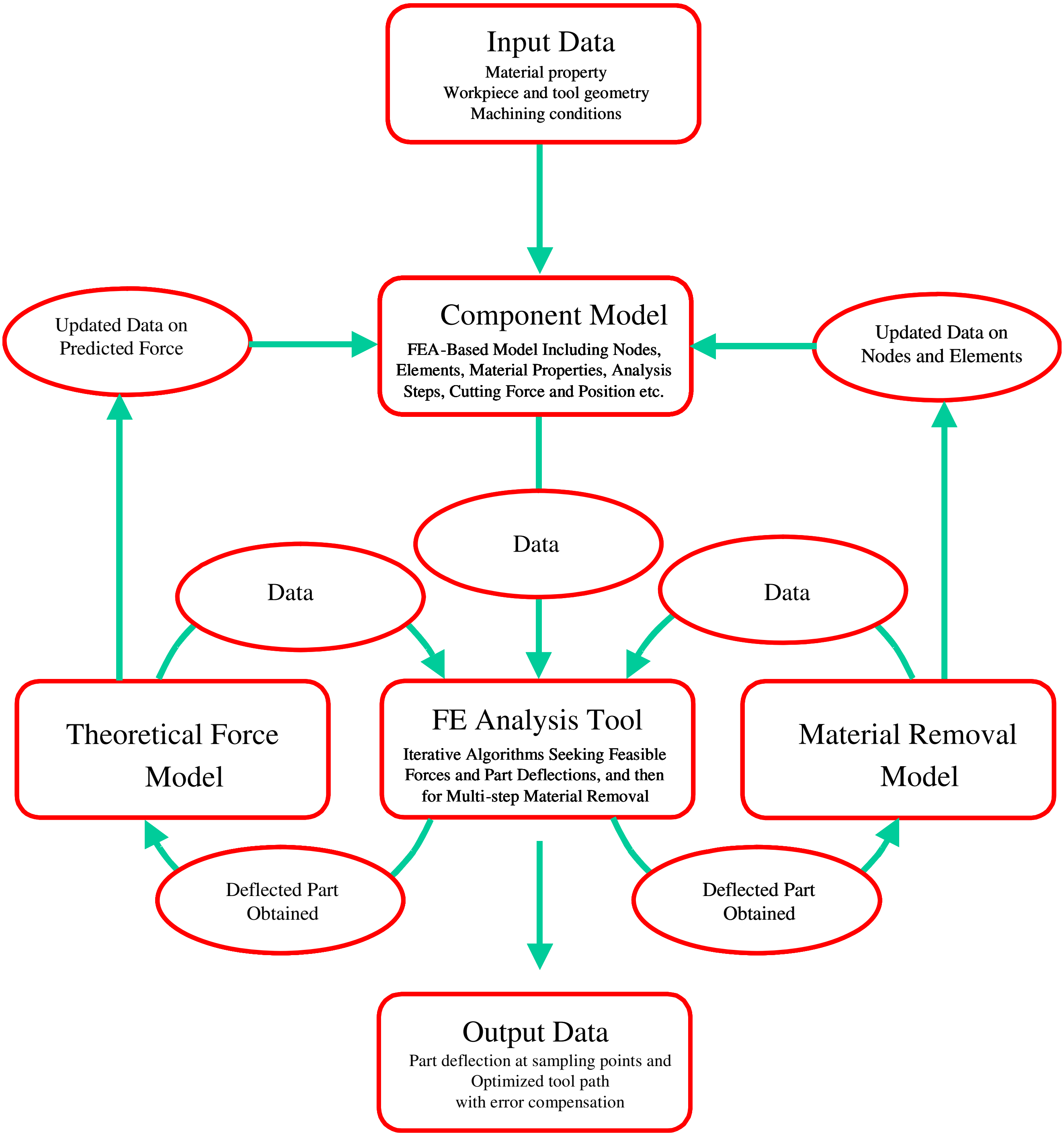


**Fig. 1** System integration within the simulation environment

conditions are specified, the nodal displacement can be obtained through solving the above equations.

However, the obtained part displacement (deflection) in a single FEA run may not be the feasible deflection for simulation of a cutting step. Due to part deflection, the cutting depth changes, which in turn affects the predicted force and deflection. The feasible force and deflection can be obtained by iteratively integrating the force model, component model, and the FEA tool until convergence to a required tolerance is achieved. Since the component model needs to be used iteratively during the whole simulation process, a component data model including the complete FE mesh and analysis information is required, which allows some data such as nodes, elements and force to be changed during the iterations.

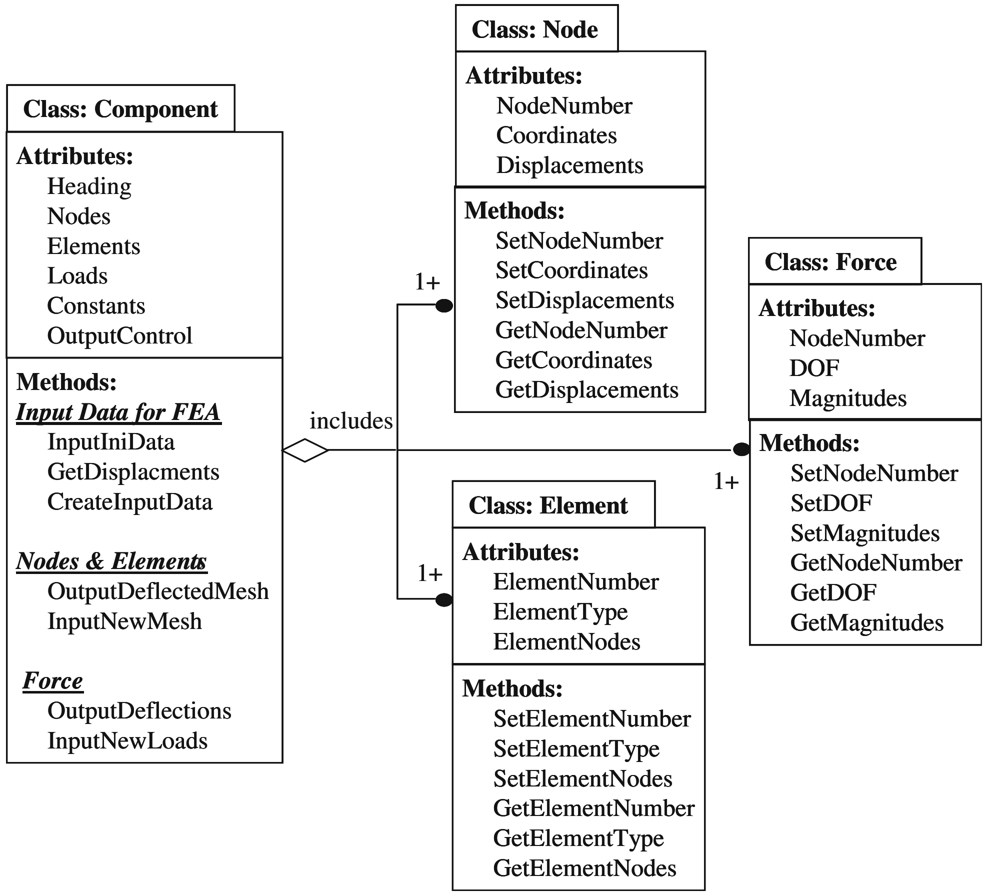


**Fig. 2** Object diagram for FEA-based data model

## 3.2 Data model structure

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. A complete object diagram for the data model of low-rigidity parts in machining simulation is developed and illustrated in Fig. 2. 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

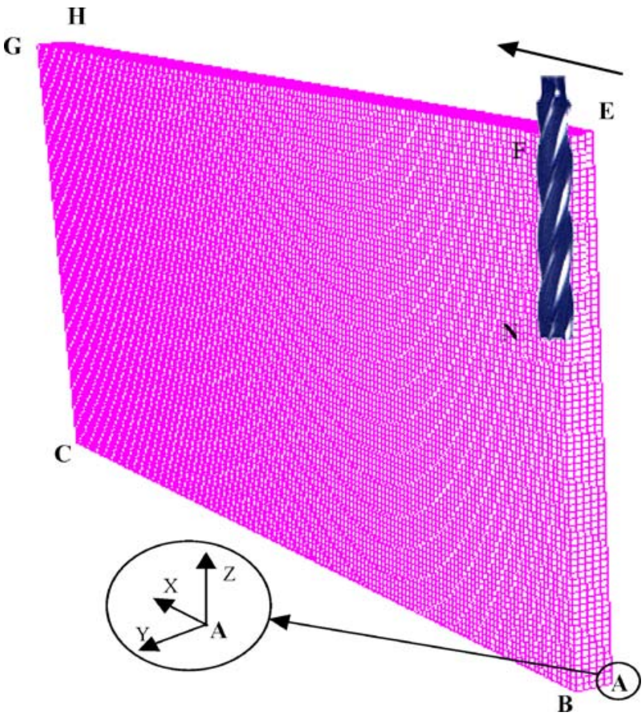


**Fig. 3** Machining geometry in machining thin wall part at the initial cutting position

stored in terms of nodal number, degree of freedom, and the force magnitudes.

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 simulation 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 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.

## 4 Cutting mechanics model

The proposed model is based on an extended perfect plastic layer model (card model) [5, 24–26] integrated with an FE model for prediction of part deflection [13]. In the perfect plastic layer model, the cutter cutting edge is assumed to be perfectly sharp. Where the cutting edge travels, a thin layer of material is sheared off on the shear plane in the shear zone; thus, the tertiary deformation process 'ploughing' or 'rubbing' at the flank of the cutting edge, the tangential $F_{te}$ and feed $F_{fe}$ rubbing force are zero. The specific cutting pressure is a function of the yield shear stress of the workpiece material during cutting and the friction angle between the tool and chip, etc. The friction angle depends on the lubrication used, the tool-chip contact area, and the tool and the workpiece material. If the shear plane is assumed to be a thick zone, which is more realistic than having a thin shear plane, there will be a work hardening. The temperature variation in the shear and friction zones will also affect the hardening of the workpiece material. Hence the cutting force varies with the cutting conditions.

Under this consideration, the theoretical differential orthogonal cutting force is modified to include the edge force, which can be expressed in the forms of [5, 26]

$$\begin{aligned} dF_t &= \left(\tau_s \frac{\cos(\beta_a - \alpha_r)}{\sin \text{Ø}_c \cos(\text{Ø}_c + \beta_a - \alpha_r)} h + k_{te}\right) ds, \\ dF_f &= \left(\pi_s \frac{\sin(\beta_a - \alpha_r)}{\sin \text{Ø}_c \cos(\text{Ø}_c + \beta_a - \alpha_r)} h + k_{fe}\right) ds, \end{aligned} \qquad (2)$$

where $\tau_s$, $h$ and $ds$ are the shear strength, uncut chip thickness and the differential width of cut, correspondingly, while $\phi_c$, $\beta_a$ and $\alpha_n$ are shear angle of shear plane, friction angle and rake angle, respectively. $k_{te}$ and $k_{fe}$ are the tangential and feed edge force coefficients that can be calibrated directly from metal cutting experiment such as turning for a tool-workpiece pair [26].

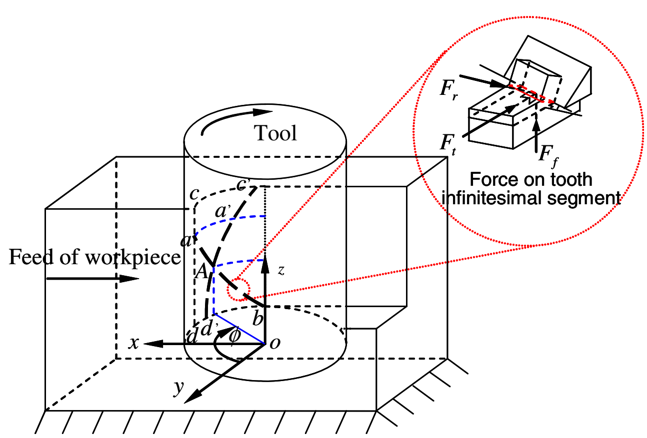


**Fig. 4** Cutting geometry with part deflection

In milling, the material removal process at any infinitesimal segment of the cutter teeth is considered as oblique cutting (Fig. 4). The oblique cutting forces are obtained from orthogonal cutting [5, 25, 26]. Once the local oblique cutting forces, $F_t(\phi)$, $F_r(\phi)$ and $F_a(\phi)$, are determined theoretically, three force components $F_x(\phi)$, $F_y(\phi)$ and $F_z(\phi)$ acting on the cutter in the reference Cartesian coordinate system can be obtained through a transformation matrix $T$

$$T = \begin{bmatrix} -\cos Ø & -\sin Ø & 0 \\ \sin Ø & -\cos Ø & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

as

$$\begin{Bmatrix} F_x(Ø) \\ F_y(Ø) \\ F_z(Ø) \end{Bmatrix} = T \begin{Bmatrix} F_t(Ø) \\ F_r(Ø) \\ F_a(Ø) \end{Bmatrix} \quad (4)$$

In milling a flexible thin wall part, the differential cutting force on the engaged infinitesimal tool cutting edge varies with the cutting depth that is the function of the immersion angle determined by part deflection (Fig. 5). The force is calculated by taking into account the changes of the immersion angle, $\phi$, of the engaged teeth. As soon as the deflection, $u_y$, at time, $t$, and the coordinate ($x$, $y$, $z$) of point, $a$, are known (Fig. 4), the instant immersion angle $\varphi$ in down milling after deflection can be calculated using

$$Ø(t, z) = \cos^{-1}\frac{R - \left(h_r(z, t) - u_y(z, t)\right)}{R} \quad (5)$$

where $R$ is the cutter radius, and $h_r$ is the designed milling depth in the workpiece thickness direction, while $u_y$ is the deflection in the corresponding point predicted through FE analysis.

In more detail, as the cutter is engaged, the tool-part intersection line *c-a-d* deflects to the line c'-a'-A-d'

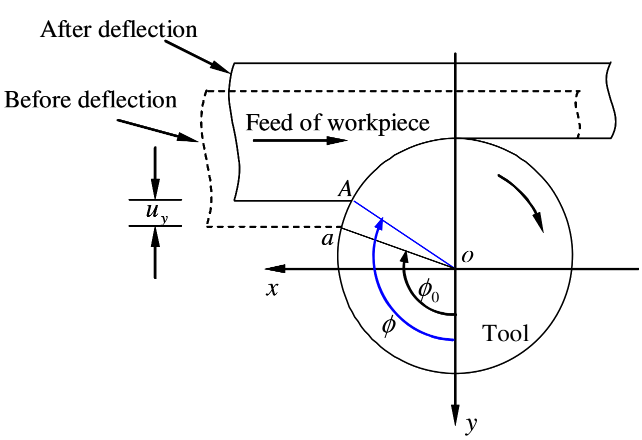


**Fig. 5** Part deflection in milling a low-rigidity part-view along the cutter axis

(Fig. 4). The point $a$ on the workpiece deflects to the new position $a'$, which is no longer an instant cutting point. The same point $a$ on the tooth moves to $A$ along the tooth edge $ab$. Therefore the immersion angle and coordinate have been changed after this movement. As soon as the immersion angle is known, the new coordinate $z$ of $a$, i.e., $A$, after part deflection can be determined through the equation

$$z = \left[Ø_0 + jØ_p + \omega t - Ø(t, z)\right]/k_\beta \quad (6)$$

where $\phi_0$ is the reference tooth starting angle at time $t$=0, $\phi_p$ is flute pitch angle, $\omega$ is the cutter angular speed, and $k_\beta$ is the tooth lag angle. As the coordinate $z$ of $a$ is determined, the deflection of the new position will be used to re-calculate the immersion angle. The final immersion angle $\phi$ of point $A$ after deflection at a certain cutting position can be obtained by solving a set of simultaneous equations (Equations 1 and 2).

In order to integrate the models with FE analysis, the $N$-flute helical fluted end mill is sliced into segments sliced into ($M$-1) segments with $M$ nodes numbered from 1 to $M$. The differential cutting forces $DF_k(i, j, t)$ ($k$=$x$, $y$, $z$) on the $i$th tooth segment of the tooth $j$ in the Cartesian Coordinate system are obtained through integration along its in-cut segment. Summing up the cutting forces for each axial segment engaged, one can obtain the instantaneous cutting forces acting on the whole end mill as follows:

$$F_x = \sum_{i=1}^{M-1}\sum_{j=1}^{N} DF_x(i, j\,t) \quad (7a)$$

$$F_y = \sum_{i=1}^{M-1}\sum_{j=1}^{N} DF_y(i, j, t) \quad (7b)$$

$$F_z = \sum_{i=1}^{M-1}\sum_{j=1}^{N} DF_z(i, j, t) \quad (7c)$$

Since the focus of the study is on prediction of the surface errors due to part deflection, the instantaneous dynamic cutting force is replaced by a quasi-static cutting force. The quasi-static cutting force is treated as a moving-distributed load acting on the part-tool contact zone in the cutting process, which is derived from the dynamic cutting force of nodes $i$ ($i$=1, 2, ..., M). The force applied on the part and the cutter is in a form of summation and obtained from the nodes force density, $F_x(\phi_i)$, $F_y(\phi_i)$, $F_z(\phi_i)$:

$$F_x = \frac{h_a N \tan\beta}{M\pi D}\sum_{i=1}^{M} F_x(Ø_i) \quad (8a)$$

$$F_y = \frac{h_a N \tan\beta}{M\pi D}\sum_{i=1}^{M} F_y(\text{Ø}_i) \tag{8b}$$

$$F_z = \frac{h_a N \tan\beta}{M\pi D}\sum_{i=1}^{M} F_z(\text{Ø}_i) \tag{8c}$$

where the geometric parameters $h_a$, $N$, $\beta$ and $D$ are axial milling depth, number of flutes, helical angle and diameter of the milling cutter. $\phi_i$ is the immersion angle, $\phi$, as the tooth passes the position $i$. For convenience, the tool-part intersection line and the immersion entry angle on this line are used to describe the determination procedure of the immersion angle at any time and any point within the tool-part contact zone.

## 5 Integrated simulation algorithm

An integrated simulation algorithm was developed to achieve the central loop of the proposed simulation environment by integrating all decision-making modules together to simulate the multi-levelled iterative cutting processes [7]. This algorithm was produced by combining two small-range algorithms that were developed for force predication [5] and material removal simulation, respectively [19].

The purpose of this algorithm is to predict the cutting force, part deflection and material removal for every cutting simulation step. The modules include the component data model, FE analysis tool, theoretical force model [5], and material removal model (Fig. 1). The input data of the integrated environment includes element (node number) information; initial node information: nodal cutting force and nodal coordinate; workpiece material properties: Young's module, Poisson's ratio; workpiece-tool pair material property-related parameters: shear strength, shear angle of the shear plane, friction angle; tool geometry: diameter, rake angle, helical angle, number of tooth; workpiece dimensions: length, height, thickness and orientation angles; milling conditions: radial milling depth, axial milling depth, feed rate, spindle speed, etc.

A multi-level iteration is performed in the proposed methodology. The procedure of the single-level algorithm, which is used in the multi-level iteration, is described as follows [7]:

1. Create an FEA-based data model to represent the low-rigidity part under machining.
2. Calculate an initial cutting force using the force model and set it as the current cutting force for a cutting step.
3. Predict the part deflection [6] caused by the current cutting force using an FE analysis tool.
4. Calculate the new cutting force [5] taking into account the changed cutting depth due to the part deflection.
5. Compare the two part deflection (or resultant force) values obtained from the consecutive iterations. If the difference of the two values is less than a given tolerance provided by the user, e.g., 0.1%, the force has converged to an appropriate value. If it exceeds the tolerance, the two consecutive deflection (or force) values are then weighted for robust convergence. The corresponding value in the component data model is updated. The procedure goes back to Step 4.
6. Material removal model [19] is used to remove the material from the deflected component model, i.e., to determine what nodes and elements are removed and what new nodes and elements are needed to represent the machined part.
7. The nodal and element data in the component data model are updated to represent the machined part.
8. The procedure goes to Step 2 for the next step cutting simulation unless the total cutting length of part is reached.

## 6 Results and discussion

The proposed FEA-based simulation environment has been validated by comparing the predicted and measured part deflections for a set of cutting trials. A practical case of down milling a thin wall part is shown in Fig. 3. 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. Two sensors are placed vertically along the cutter axis and move with the cutter during machining. The first measuring point (*a*) is located at 6 mm below the top of the workpiece and the second one (*b*) is at the bottom of the cutter. In this case, the measured force and deflection are both treated as authentic and correlated, i.e., if the measured force is applied on the part, it will generate the corresponding measured value for part deflection and vice versa. The validity of the proposed approach is assessed by comparing the predicted and experimentally identified deflections.

The cutting tool material is HSS 8% Co. and the workpiece material is Aluminium alloy 6082 H30 (Elastic modulus: 69000 MPa, Poisson's ratio: 0.33, Brinell hardness HB=100). The cutting trials were based on clamped-free-free-free cantilever plates and a four-flute milling cutter with a 30° helical angle, a rake angle of 14° and a clearance angle of 10°. To maximise the deflection of the workpiece and minimise the deflection of the tool, a 20 mm diameter milling cutter and a 150 mm long thin wall part (5 mm thickness and 80 mm height) were used. The force components were measured using an eight-channel Kistler dynamometer type 9255B. In the measurement range of 0 to 2 kN, the sensor sensitivity in the dynamometer horizontal plane is 7.85 pC/N, while the one in vertical direction is 3.86 pC/N (pico Couloms per Newton). The linearity is less or equal to 0.1% FSO (full scale output signal). The crosstalks between channels are less than 0.9%. The tests were repeated and the average of measured force and deflection were used for data processing.

The cutting geometry at the initial cutting position is shown in Fig. 3. The axial cutting depth represented by the tool-part intersection line *FN* in *z*-direction is 30 mm and the radial cutting depth in *y*-direction is 2 mm. The machine table feed rate is 0.25 mm/rev-tooth while the flat head milling cutter spindle speed is 500 revolutions per minute.

For FE analysis, the part is meshed by using 8-node isoparametric quadratic (brick) elements with full-integration and there are total 60000 elements included. The force model is calibrated using orthogonal cutting (turning) [26]. &&10 The tangential and feed edge force coefficients, $k_{te}$ and $k_{fe}$, in orthogonal cutting (turning) are 29.358 N/mm and 23.009 N/mm, respectively.

The FEA-based simulation approach was applied to predict the cutting forces and part deflections, where the nodal displacements of *FN* is used. The proposed algorithm was applied to find the converged displacements. One of the inputs to the algorithm is the tolerance of the part, which is design driven and product specific that is used to determine the termination tolerance value (the percentage difference between two consecutive computation steps) of the iterative process, Here, to demonstrate the convergence of the proposed approach the termination value for the error in the *y*-direction is set to 0.1%. The predicted cutting forces on *FN* and the predicted part deflections in the *y* direction at the two concerning points, obtained during each simulation iteration, are presented in Table 1. It takes five iterations to converge to a feasible deflection. The converged predicted forces and displacements have been compared with the measured forces and displacements. It can be observed that the predicted and measured displacements are very close at the upper measuring point and the predicted displacement (absolute value) is slightly less than the measured one. The displacement difference at the bottom measuring point is larger but still reasonable. At this point, the predicted displacement (absolute value) is larger than the measured one. It can also been observed that the predicted and measured forces are also reasonably close, and especially the difference of force in *y* direction, $F_y$ is very small. The small prediction force error in this direction can cause the small prediction error of part deflection.

During the machining process, the milling cutter moves along *x* direction (Fig. 3). The part deflections are predicted at 11 evenly spaced sampling points along the workpiece length. The measured and predicted displacements of point (*a*) at the 11 sampling points is plotted in Fig. 6, while the one at point (b) is illustrated in Fig. 7. It can be found that the predicted displacements are reasonably close to the experimental ones, and especially at the bottom measuring point, point-*b*, and the predicted displacements are nearly the same as the measured values in some cutting positions. In most cutting positions, the displacement difference at the bottom measuring point is smaller than the corresponding one at the upper point, point-*a*.

The experimental results indicate a general trend that the predicted and measured part deflections at the part ends are larger than the corresponding ones in the middle of the parts, and the part deflections at the starting end are smaller than those at the finishing end. It is also identified that the predicted displacements are usually smaller than the measured values except at both ends of a part. This may be explained by the fact that at both ends of a part either the tool starts cutting the part or the tool is about to leave the part, causing unstable cutting force and displacements, whereas more stable data are obtained in middle range of a

**Table 1** Convergence and comparison of the predicted and measured forces and displacements at the initial cutting position

| | Iteration Number | $U_{ya}$ (mm) | $U_{yb}$ (mm) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) |
|---|---|---|---|---|---|---|
| Predicted | 1 | −0.7765 | −0.5349 | −276.074 | −300.760 | 91.2804 |
| | 2 | −0.8749 | −0.6029 | −339.324 | −338.333 | 106.986 |
| | 3 | −0.8894 | −0.6131 | −360.440 | −343.533 | 111.041 |
| | 4 | −0.8916 | −0.6146 | −369.424 | −344.141 | 112.508 |
| | 5 | −0.8919 | −0.6149 | −373.679 | −344.146 | 113.157 |
| Measured | | −0.905 | −0.544 | −436.4 | −315.9 | 106.65 |
| Difference% | | −1.45% | 13.03% | −14.37% | 8.94% | 6.10% |

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

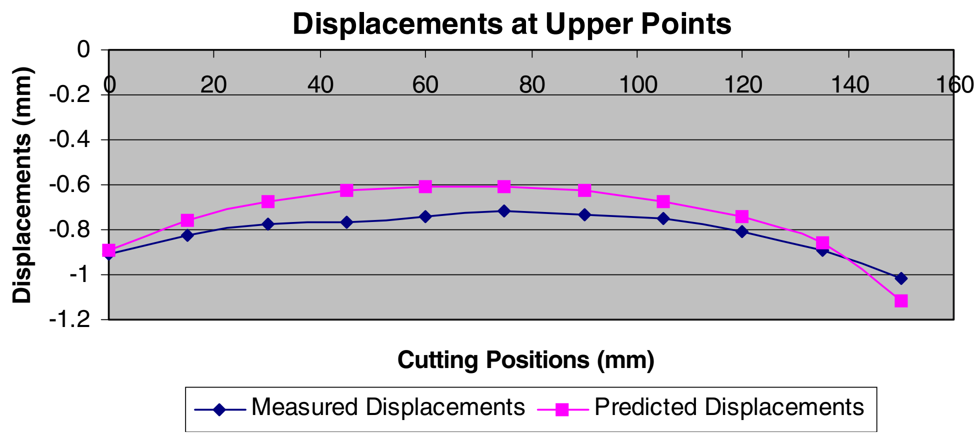


**Fig. 6** Comparison of the measured and predicted displacements at point a

part during the machining process. The measured data in the middle region show that the prediction is quite accurate, thus demonstrating the feasibility of the proposed simulation methodology.

Although the predicted part deflections are reasonably close to the measured data, there are differences between them. A number of factors may cause these differences. Some of them are from the theoretical prediction environment including the force model, component data model, material removal model and the integration process. Assumptions are made within each model that may not be exactly suitable to every individual case. For example, in the theoretical analysis, it is assumed that machining is chatter-free. However, there is an unavoidable vibration of the workpiece that affects the part deflections and thus distorts the readings of the inductive displacement sensors. Experimental work may also introduce errors. The on-line workpiece deflection is measured through inductive sensors placed in the cutter plane but at the rear side of the workpiece. It is assumed that the possible errors caused by the plastic deformation across the workpiece resulting from the cutting force and part deflection would be very small compared with the part deflection, and can be ignored.

## 7 Conclusions

The reported research is the further study of the reported achievement [6], and focused on the system integration and data model development. It is a part of the reported machining planning [5–7, 9] that 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. The integration requirement is addressed by using a novel component data model as a common data exchange medium.

The proposed modelling methodology and integration environment for multi-step simulation of cutting processes of low-rigidity components have been experimentally tested and validated. The results demonstrate that the proposed

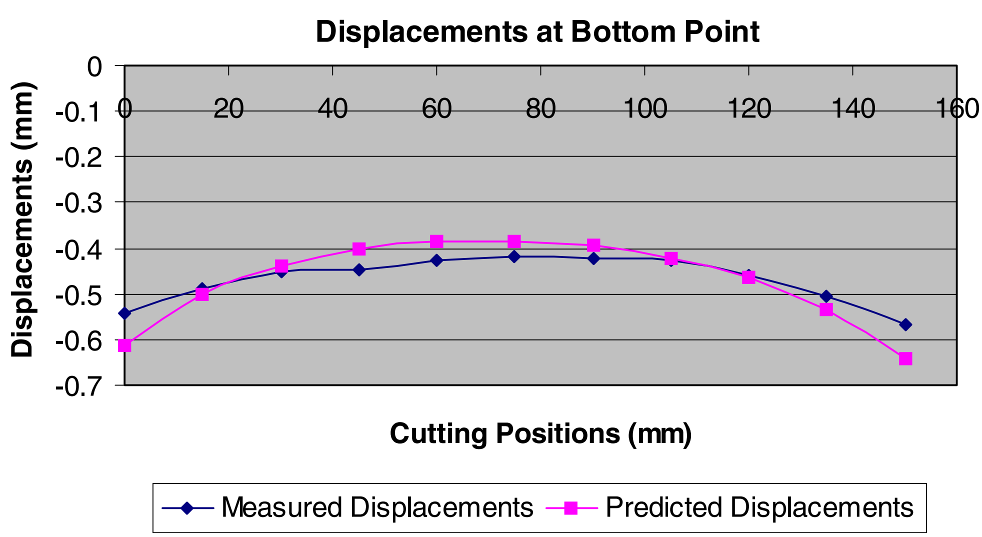


**Fig. 7** Comparison of the measured and predicted displacements at point b

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.

**Acknowledgement** 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. Liu S, Soldatos KP (2002) On the improvement of transverse stress distributions in cross-ply laminated beams: advanced versus conventional beam theories. Int J Mech Sci 44:287–304
2. Herranz1 S, Campa FJ, Lo'pez de Lacalle LN, Rivero1 A, Lamikiz A, Ukar1 E, Sa'nchez JA, Bravo U (2005) The milling of airframe components with low rigidity: a general approach to avoid static and dynamic problems. Proc I MECH E Part B J Eng Manuf 219(B11):789–802
3. Tsai J, Liao C (1999) Finite-element modelling of static surface errors in the peripheral milling of thin-walled workpiece. J Mater Process Technol 94:235–246
4. Ratchev S, Nikov S, Moualek I (2002) 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 pp 371–377
5. Ratchev S, Liu S, Huang W, Becker AA (2004) Milling error prediction and compensation in machining of low-rigidity parts. Int J Mach Tools Manuf 44:1629–1641
6. Ratchev S, Huang W, Liu S, Becker AA (2004) Modelling and simulation environment for machining of low-rigidity components. J Mater Process Technol 153–154:67–73
7. Ratchev S, Liu S, Huang W, Becker AA (2006) An advanced FEA based force induced error compensation strategy in milling. Int J Mach Tools Manuf 46:542–551
8. Suneel TS, Pande SS (2000) Intelligent tool path correction for improving profile accuracy in CNC turning. Int J Prod Res 38 (14):3181–3202
9. Mackerle J (1999) Finite-element analysis and simulation of machining: a bibliography (1976–1996). J Mater Process Technol 86:17–44
10. Spence AD, Abrari F, Elbestawi MA (2000). Integrated solid modeller based solutions for machining. Comput Aided Des 32:553–568
11. Tsai J, Liao C (1999) Finite-element modelling of static surface errors in the peripheral milling of thin-walled workpiece. J Mater Process Technol 94:235–246
12. Marusich TD, Ortiz M (1995) Modelling and simulation of high speed machining. Int J Numer Methods in Eng 38:3675–3694
13. ABAQUS 6.3. ABAQUS Inc, 1080 Main Street, Pawtucket, Rhode Island, 02860-4847, USA. http://www.abaqus.com
14. Cho MS, Sim KS, Suk HC, Chang SK (2000) Static strength analysis of CANDU-6 reactor fuel bundle. Nucl Eng Des 200:407–419
15. Zha Y, Moan T (2001) Ultimate strength of stiffened aluminium panels with predominantly torsional failure modes. Thin-Walled Struct 39:631–648
16. Choi BK, Jerard RB (1998) Sculptured surface machining: theory and applications. Kluwer Academic, Dordrecht
17. Sagherian R, Elbestawi M (1990) A simulation system for improving machining accuracy in milling. Comput Ind 14: 293–305
18. Jang D, Kim K, Jung J (2000) Voxel-based virtual multi-axis machining. Int J Adv Manuf Technol 16:709–713
19. Ratchev S, Nikov S, Moualek I (2002) 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 pp 371–377
20. Kline WA, DeVor RE, Shareef IA (1982) The prediction of surface accuracy in end milling. J Eng Ind 104:272–278
21. Sutherland JW, DeVor RE (1986) An improved method for cutting force and surface error prediction in flexible end milling systems. J Eng Ind (Transaction of the ASME) 108:269–279
22. Budak E, Altintas Y (1995) Modelling and avoidance of static form errors in peripheral milling of plates. Int J Mach Tools Manuf 35(3):476–495
23. Feng HY, Menq C (1994) Prediction of cutting forces in the ball-end milling process-I: model formulation and model building procedure. Int J Mach Tools Manuf 34(5):697–710
24. Merchant ME (1944) Basic mechanics of the metal citing process. ASME J Appl Mech A-168–175
25. Budak E, Altinrtas Y, Armarego EJA (1996) Prediction of milling force coefficients from orthogonal cutting data. ASME J Eng Ind 118:216–224
26. Altintas Y (2000) Manufacturing automation. Cambridge University Press, 2000