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Virtual Machining Systems for CNC Milling and Turning Machine Tools: A Review

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ABSTRACT

Virtual manufacturing systems are developed by simulating real manufacturing processes in digital environments in order to increase accuracy as well as efficiency of part production. Accuracy of the produced parts can be increased by errors can also be analyzed and decreased by using virtual machining systems. Moreover, optimization methods can be applied to the simulated manufacturing processes in the virtual environments to improve efficiency of part production by using optimized cutting conditions. Elements of machine tools can be simulated, analyzed and modified by using virtual machining system. The simulated machining processes in virtual environments can be used in training monitoring and analyzing errors of simulated manufacturing processes in virtual environments. In order to boost accuracy of produced parts, effects of machining operation errors such as dimensional, geometrical, thermal and tool deflection programs without the need of shop floor testing. The most suitable methods of part production can be selected by applying process planning methodologies to the simulated manufacturing processes in the virtual environments. Furthermore, the parts can be analyzed in virtual environments using the Finite Element Method (FEM) to provide the error effects analysis. In this paper, a review of virtual machining systems for CNC milling as well as turning machine tools is presented and future research works are also suggested. As a result, it is hoped that the research filed can be moved forward by reviewing and analyzing recent achievements in the published papers.

Keywords: Virtual machining, CNC Machine Tools

Mathematics Subject Classification: 68M07, 74S05, 74P10

Journal of Economic Literature (JEL) Classification : L610, L630

1. INTRODUCTION

To increase accuracy as well as efficiency of part production, virtual manufacturing systems are presented by simulating real manufacturing processes in digital environments. Errors of manufacturing processes are mathematically modeled in order to be analyzed in virtual environments. To boost accuracy as well as efficiency of part manufacturing, actual machined parts can be created in virtual environments to be analyzed and processes modified if needed. Thus, efficiency of part manufacturing as well as reliability of produced parts can be increased. To increase efficiency of part production, optimized parameters of manufacturing processes can be calculated by applying optimization methods. As a result, more added value in part manufacturing can be achieved. Furthermore, structure of machine tools can be simulated, analyzed and modified. To increase the safety of machining processes, cutting tool paths can be analyzed and modified in terms of collision detection by using virtual machining system. The operators of machine tools can initially be trained by virtual machining environments. Process planning methodologies can be applied in virtual environments in order to select the most suitable methods of part production. To provide ability of error effect analysis, machined parts can be simulated and analyzed in virtual environments using the Finite Element Methods (FEM). Therefore, stress and strain of produced parts can be measured and analyzed in order to increase accuracy as well as reliability of part manufacturing.

Based on the authors' findings to date, it was determined that the review paper in the virtual machining systems for CNC milling and turning machine tools is insufficiently explored. Web-based virtual machine tool systems are considered by Kadir et al. (Kadir, Xu, and Hämmerle 2011) in order to present a review paper. In this paper, developed version of review article in virtual machining systems is presented by considering the all published papers in all research fields used by virtual technology including design, simulation, optimization, scheduling, process planning, monitoring systems, configuration for CNC milling and turning machine tools. In the research work, a review of virtual machining systems from the 173 published papers dated from 1995 to 2018 for CNC milling and turning machine tools is presented. Virtual machining systems and applications for CNC milling and turning machine tools are presented in the study by reviewing and analyzing recent achievements from published papers. As a result, new ideas in virtual machining systems are introduced to the researchers in order to push forward this interesting research field.

Section 2 presents a review from research works related to applications of virtual machining systems in simulation of cutting forces, dimensional, geometrical and tool deflection errors. Review of research works related to virtual machining systems for CNC milling machine tools is presented in section 3. A review of research works related to virtual machining systems for CNC turning machine tools is presented in section 4. Section 5 presents review of research works related to virtual machining systems for CNC turn-mill machine tools. Finally, conclusion of the research work as well as future studies in virtual machining systems are presented in the section 6 and 7 respectively.

2. REVIEW OF VIRTUAL MACHINING SYSTEMS IN SIMULATION OF CUTTING FORCES, DIMENSIONAL, GEOMETRICAL AND TOOL DEFLECTION ERRORS

This section covers research articles dated from 1995 to 2017 focusing on the methods used in the modeling of milling operations in virtual environments. The methodologies applied in modeling of cutting forces, dimensional and geometrical errors tool deflection error for CNC milling machine tools. Modeling methodologies of cutting forces, dimensional, geometrical and tool deflection errors are described in the section 2 which are used by the presented virtual machining systems in the sections 3 and 5.

2.1. Cutting force models

A virtual machining system is developed by Maekawa et al. (Maekawa, Shirakashi, and Obikawa 1995) to simulate and analyze chip flow, cutting forces, cutting temperature, fracture probability of cutting tool and tool wear of milling machines tools in virtual environments. The outlines of finite-element simulation theory and modeling and typical simulation results are presented in the study to develop machining simulation systems. In order to estimate tool wear as well as cutting forces in turning operations, a virtual cutting system using artificial neural networks is presented by Wang et al. (Wang et al. 2005). In this paper, a virtual cutting system is presented which can simulate turning process, estimate tool wear and cutting force using artificial neural network. This approach enables designers to evaluate and modify effective parameters of machining processes in order to increase accuracy and efficiency of part production.

Virtual simulation of three and five-axis milling operations is presented by Boz et al. (Boz, Erdim, and Lazoglu 2015) to develop prediction of cutting forces by different methods of cutter-workpiece engagement. In order to obtain desired surface quality and productivity, process parameters such as feed rate, spindle speed, and axial and radial depths of cut are appropriately selected by using the developed virtual milling system in the study. Tunç et al. (Tunç, Ozkirimli, and Budak 2016) presented a virtual machining system in order to develop machining strategy, based on process simulations in 5-axis milling machine tools. To obtain cutting parameters in machining operations, cutting forces are simulated through extended Z-mapping approach. To calculate the chatter stability in milling operations, stability diagrams are generated in frequency domain. Cutting torque, spindle power, tool deflection and surface roughness are considered to present dynamic programming for machining strategy.

Prediction of cutting forces in three and five-axis ball-end milling is presented by Tuysuz et al. (Tuysuz, Altintas, and Feng 2013). A methodology is presented by Lai (Lai 2000) in order to calculate cutting forces of milling operations in virtual environments. Effective parameters of cutting forces such as radial and axial depths of cut, cutting feed rate are considered in a study to present a modeling methodology for cutting forces. Simulation of cutting forces based on numerical methods in ball-end milling operations is presented by Milfelner and Cus (Milfelner and Cus 2003).

The cutting forces in ball-end milling operations of sculptured surfaces are calculated by Kim et al. (Kim, Cho, and Chu 2000) To determine engagement of cutting edge elements to the workpice in machining operations, the cutting edge elements are projected onto the cutter plane normal to the Z-axis. Then, cutting forces acting on the engaged elements of cutting edges are calculated by using empirical methods. As a result, the cutting forces are described in the study by mathematical concepts in order to be used in virtual simulation. Ferry et al. (Ferry and Altintas 2008a) developed a virtual machining system to predict cutting forces in five-axis machining operations.

A virtual machining system is developed by Yun et al. (Yun, Ko, Lee, et al. 2002) to simulate cutting processes in transient cuts in flat end-milling process. To simulate cutting processes, the cutting forces as well as surface errors are predicted in the study. Z-map calculation errors are developed in the study to calculate the cutting configuration for a given NC codes. The model can use edge nodes methodology in order to accurately describe each position of contact point between cutting tool as well as workpiece along machining paths. Thus, a virtual machining system is presented in the study to simulate cutting processes of multiple two-dimensional cutter paths which is a useful tool for process planners. Web-based virtual machining and measuring cell is developed by Yao et al. (Yao, Liu, and Li 2005) to predict cutting forces along machining paths in virtual environments. Predicted cutting forces, applied forces to cutting tool and calculated shape error due to tool deflection are considered by Dow et al. (Dow, Miller, and Garrard 2004) in order to present a technique in virtual environments to compensate deflection error of small milling tools.

A Virtual machining is presented by Uhlmann et al. (Uhlmann et al. 2017) in order to predict cutting forces as well as surface quality in micro-milling operations. Therefore, accuracy of produced parts in micro-milling operations can be analyzed and increased by using the developed system in the study.

To calculate the cutting forces in milling operations, a method is presented by Engin and Altintas . (Engin and Altintas 2001) Fig. 1 shows a typical milling operation with a general end mill (Engin and Altintas 2001).

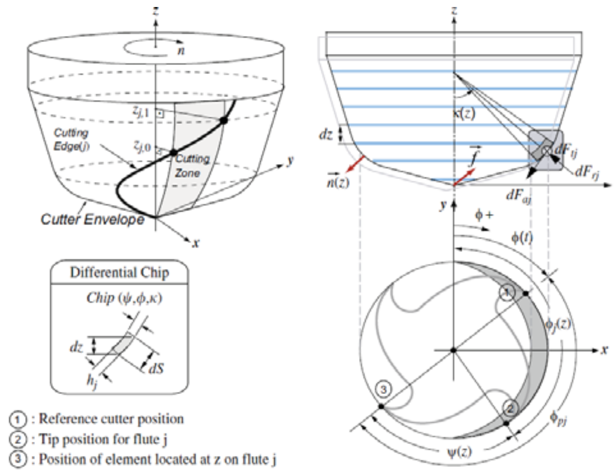

Fig. 1 Mechanics and kinematics of three-axis milling (Engin and Altintas 2001).

Where ϕ_{pj} is pitch angle of flute j, $\phi_j(z)$ is total angular rotation of flute j at level z on the XY plane, $\psi(z)$ is radial lag angle and $\kappa(z)$ is axial immersion angle. In the differential chip, dz is differential height of the chip segment, ds is the length of cutting edge and h_j is height of valid cutting edge from tool tip.

The differential tangential (dF_t), radial (dF_r) and axial (dF_a) cutting forces acting on an infinitesimal cutting edge segment are given in Eq. (1) (Engin and Altintas 2001).

$$\begin{cases} dF_t = K_{te}ds + K_{tc}h(\varphi_j, k)db \\ dF_r = K_{re}ds + K_{rc}h(\varphi_j, k)db \\ dF_a = K_{ae}ds + K_{ac}h(\varphi_j, k)db \end{cases} \tag{1}$$

Where $h(\phi_j, k)$ is the uncut chip thickness normal to the cutting edge and varies with the position of the cutting point and cutter rotation.

In flat end milling operation, the uncut chip thickness is presented by Erdim et al. (Erdim, Lazoglu, and Ozturk 2006) as is shown in Eq. (2).

$$h(\varphi_j, k) = S_{tj} Sin(\varphi_j) \tag{2}$$

Where S_{tj} and ϕ_j are feed per tooth and radial lag angle of tooth j respectively.

db is the projected length of an infinitesimal cutting flute in the direction along the cutting velocity which can be shown as Eq. (3) (Engin and Altintas 2001).

$$db = \frac{dz}{SinK} \tag{3}$$

Once the chip load is identified and cutting coefficients are evaluated for the local edge geometry, the cutting forces in cartesian coordinate system can be evaluated as Eq. (4) (Engin and Altintas 2001).

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_Z \end{bmatrix} = \begin{bmatrix} -\sin\varphi_j \sin\kappa & -\cos\varphi_j & -\sin\varphi_j \cos\kappa \\ -\cos\varphi_j \sin\kappa & \sin\varphi_j & -\cos\varphi_j \cos\kappa \\ \cos\kappa & 0 & -\sin\kappa \end{bmatrix} \begin{bmatrix} dF_r \\ dF_t \\ dF_a \end{bmatrix} \tag{4}$$

Finally, the total cutting forces for the rotational position ϕ_j can be found by integrating as Eq. (5) (Engin and Altintas 2001).

$$\begin{cases} F_x(\varphi_j) = \sum_{j=1}^{N_f} F_{xj}\left[\varphi_j(z)\right] = \sum_{j=1}^{N_f} \int_{Z_1}^{Z_2} \left[- dF_{rj} \sin\varphi_j \sin\kappa_j - dF_{tj} \cos\phi_j - dF_{aj} \sin\varphi_j \cos\kappa_j \right] dz \\ F_y(\varphi_j) = \sum_{j=1}^{N_f} F_{yj}\left[\varphi_j(z)\right] = \sum_{j=1}^{N_f} \int_{Z_1}^{Z_2} \left[- dF_{rj} \cos\varphi_j \sin\kappa_j + dF_{tj} \sin\varphi_j - dF_{aj} \cos\varphi_j \cos\kappa_j \right] dz \\ F_z(\varphi_j) = \sum_{j=1}^{N_f} F_{zj}\left[\varphi_j(z)\right] = \sum_{j=1}^{N_f} \int_{Z_1}^{Z_2} \left[dF_{rj} \cos\kappa_j - dF_{aj} \sin\kappa_j \right] dz \end{cases} \tag{5}$$

Where N_f is the number of flutes on the cutter, z_1 and z_2 are the contact boundaries of the flute which is in the cut and κ_j is axial immersion angle of flute j.

2.2. Dimensional and Geometrical errors and modeling methodology

Dimensional and Geometrical errors are mainly concerned with the errors in the structural elements of the machine tools. These errors affect the machine repeatability and kinematic accuracy which are inherent in the machine tool. For a 3-axis milling machine, there are 21 error components namely: 3 linear positioning errors, 6 straightness errors, 9 angular errors and 3 squareness errors. The errors can be applied to the nominal position of cutting tool by volumetric error vector. So, real positions of cutting tool along machining paths can be obtained.

Modeling methodology of dimensional and geometrical errors is described in order to be analyzed and compensated by the presented virtual machining systems in the section 3.

Okafor and Ertekin (Okafor and Ertekin 2000) presented an error model to obtain volumetric error vector for geometric errors of three-axis milling machines. Schematic of table and tool coordinate systems for a typical three-axis milling machine is shown in Fig. 2 (Okafor and Ertekin 2000).

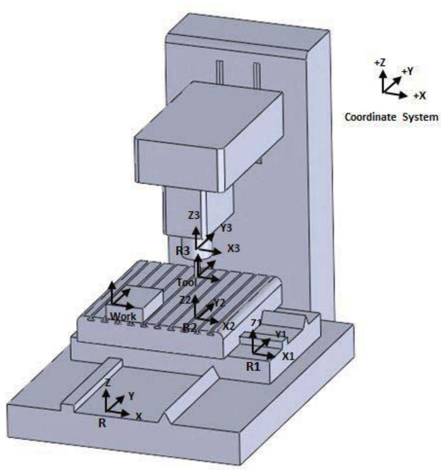

Fig. 2. Schematic of table and tool coordinate systems for 3 axis milling machines (Okafor and Ertekin 2000).

Where R is the base coordinate system of the machine, R2, R1 and R3 are coordinate systems of X, Y and Z directions respectively.
The actual position and orientation of the X-axis carriage in reference coordinate system is given as Eq. (6) (Okafor and Ertekin 2000).

$$\left[{}^{1}T_{2}\right]_{actual} = \begin{bmatrix} 1 & -\varepsilon_{z2}(x) & \varepsilon_{y2}(x) & x+\delta_{x2}(x)+a_2 \\ \varepsilon_{z2}(x) & 1 & -\varepsilon_{x2}(x) & \delta_{y2}(x)+b_2 \\ -\varepsilon_{y2}(x) & \varepsilon_{x2}(x) & 1 & \delta_{z2}(x)+c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

Where,

$\varepsilon_{x2}(x)$ Roll error of X-axis

$\varepsilon_{y2}(x)$ Pitch error of X-axis

$\varepsilon_{z2}(x)$ Yaw error of X-axis

a_2 Constant offset in X direction between R1 and R2

b_2 Constant offset in Y direction between R1 and R2

c_2 Constant offset in Z direction between R1 and R2

$\delta_{x2}(x)$ Linear displacement error of X axis

Linear displacement error of Y axis can be obtained by the Eq. (7) (Okafor and Ertekin 2000).

$$\delta_{y2}(x) = \delta'_{y2}(x) + \alpha_{xy} x \tag{7}$$

Linear displacement error of Z axis can be obtained by the Eq. (8) (Okafor and Ertekin 2000).

$$\delta_{z2}(x) = \delta'_{z2}(x) + \alpha_{xz} x \tag{8}$$

Where,

$\delta'_{y2}(x)$ Y straightness of X axis as it moves in X direction

$\delta'_{z2}(x)$ Z straightness of X axis as it moves in X direction

α_{xy} Squareness error between X and Y axes

α_{xz} Squareness error between X and Z axes

x Nominal X axis position which amplifies α_{xy} to yield and abbe error in Y direction in Eq. (7)

x Nominal X axis position which amplifies α_{xz} to yield and abbe error in Z direction in Eq. (8)

Position of work and tool can be shown as Eq. (9) and Eq. (10) (Okafor and Ertekin 2000).

$${}^{R}T_{Work} = {}^{R}T_{1}\,{}^{1}T_{2}\,{}^{2}T_{Work} \tag{9}$$

$${}^{R}T_{Tool} = {}^{R}T_{3}\,{}^{3}T_{Tool} \tag{10}$$

Where, the ${}^{2}T_{Work}$ can be presented in the Eq. (11) (Okafor and Ertekin 2000).

$$^{2}T_{Work} = \begin{bmatrix} W_x \\ W_y \\ W_z \\ 1 \end{bmatrix} \quad (11)$$

The $^{3}T_{Tool}$ can be presented in the Eq. (12) (Okafor and Ertekin 2000).

$$^{3}T_{Tool} = \begin{bmatrix} T_x \\ T_y \\ T_z \\ 1 \end{bmatrix} \quad (12)$$

Where W_x, W_y and W_z are the elements of work coordinates on the table and T_x, T_y and T_z are the elements of tool coordinates for X, Y and Z directions respectively, as shown in Fig. 2.

2.3. Tool deflection model

Because of tool deflection, cutter is deviated from the theoretical positions given in machining codes. So the cutter moves away for an amount of δ from the desired machining path. Different methods of tool defection error modeling are described in order to be analyzed and decreased by the presented virtual machining systems in the sections 3 and 5.

The tool deflection equation used by Rao and Rao (Rao and Rao 2006) and Law et al. (Law, Geddam, and Ostafiev 1999) is determined as Eq. (13).

$$\delta = \frac{F}{3EI}(L - 0.5a)^3 \quad (13)$$

Where a is the axial depth of cut, I is the equivalent moments of area. E is Young's module of elasticity and L is the length of tool that is out of spindle.

Kivanc and Budak (Kivanc and Budak 2004) presented another tool deflection model which is shown as Eq. (14).

$$deflection_{\max} = c\frac{F_x}{E}\left[\frac{L1^3}{D1^4} + \frac{(L2^3 - L1^3)}{D2^4}\right]^N \quad (14)$$

Where F_x is the applied force and E is the modulus of elasticity (MPa) of the tool material. The geometrical properties of the end mill are in mm. The constant c is 9.05, 8.30 and 7.93 and constant N is 0.950, 0.965 and 0.974 for 4-flute, 3-flute and 2-flute cutters, respectively.

Ryu et al. (Ryu, Lee, and Chu 2003) presented another method for calculation of the tool deflection error according to the tool rotational angle as well as the axial position of cutting tool along machining paths. Thus, the value of tool deflection error including the machine tool part deformation is shown in the Eq. (15) (Ryu, Lee, and Chu 2003).

$$\delta=\delta_t+\delta_c=\frac{F}{6EI}\left[-\left(L-L_f\right)^3+3\left(L-L_f\right)^2(L-z_f)\right]+\frac{F}{6EI_f}\left[\left(z_f-z\right)^3-\left(L_f-z\right)^3+3\left(L_f-z\right)^2\left(L_f-z_f\right)\right]$$
$$+\frac{F}{2EI}\left[-\left(L-L_f\right)^2+2\left(L-L_f\right)\left(L-z_f\right)\right]\left(L_f-z\right)+\frac{F\left(L-z_f\right)\left(L-z\right)}{K_2}+\frac{F}{K_1} \tag{15}$$

Dépincé and Hascoët (Dépincé and Hascoet 2006) presented a method for obtaining the simulated surfaces with the tool deflection error based on evolution of the contact points between the cutting tool and workpiece. To determine the milled surface in the study, the variation of the contact points between the workpiece as well as the cutting tool flute is considered. Then, the milled surfaces are obtained by applying linear interpolation between the obtained contact points of cutting tool and workpiece along machining paths. The simulated error surface obtained by using the method of contact points for three conditions of the deflected cutting tool is shown in Fig. 3 (Dépincé and Hascoet 2006).

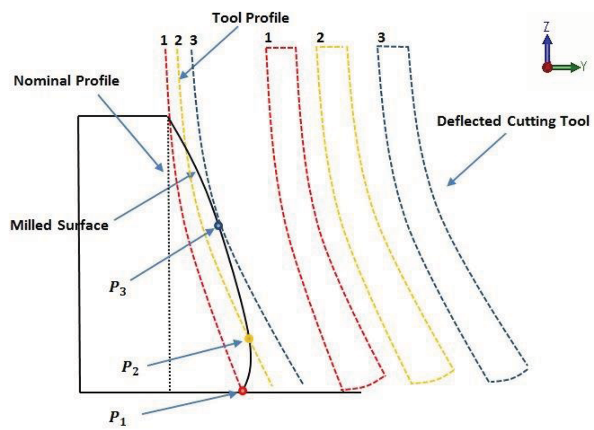

Fig. 3. The simulated error surface obtained by the method of contact points for three conditions of the deflected cutting tool (Dépincé and Hascoet 2006).

Tsai and Liao (Tsai and Liao 1999) presented a finite element model in order to analyze surface dimensional errors of thin- walled workpiece and cutting tool due to cutting forces. The helical fluted end mill is modeled in the study with the pre-twisted Timoshenko beam element. A virtual machining system is developed in the study by considering the geometry as well as thickness variations of the workpiece during peripheral milling operations. As a result, the surface dimensional errors of the workpiece are computed in virtual environments at each position of cutting tool along machining paths. Safar et al. (Saffar et al. 2008) presented prediction of cutting forces and tool deflection error by the Finite Element Method (FEM). In this paper, simulation of the end milling operation by finite element method, based on the Johnson–Cook theory, the cutting forces and tool deflection error are presented. A new CAD/CAM/CAE integration approach is presented by Wang and Chen (Wang and Chen 2014) to predict tool deflection of end mills by using the Finite Element Method (FEM). To calculate the tool deflection error by using the FEM, Wang and Chen (Wang and Chen 2014) presented the Eq. (14) via summing up the effects caused by the applied forces to the each node of the meshed CAD model of cutting tool.

$$dz = \sum_{i=1}^{M} d_i(z) \tag{16}$$

Where d_i is deflection of each node of cutting tool created by applying cutting forces for each position of cutting tool along machining paths. Then, amount of the tool deflection error due to applied cutting forces in milling operation can be calculated.

Zeroudi and Fontaine (Zeroudi and Fontaine 2015) presented prediction of tool deflection error and tool path compensation in ball-end milling by using the Finite Element Method (FEM). Cutting forces, surface form and roughness are predicted in the study to present an efficient optimization tool for industrial and complex milling operations.

3. Review of research works related to virtual machining systems for CNC milling machine tools

In this section, papers related to virtual machining systems for CNC milling machine tools dated from 1997 to 2018 are reviewed. To analyze and compensate the volumetric errors, milling operations of sculptured surfaces, creating actual machined parts in virtual environments, Internet-Based virtual CNC milling systems, feed rate scheduling systems, cutting tool paths optimization, machining parameters optimization, virtual process planning systems, machining operations of thin-wall structures, virtual training systems, analyzing and modifying machine tool elements, increasing accuracy of produced parts and collision detection systems, the papers are reviewed in the section 3.

3.1. Analyzing and compensating the volumetric errors

A virtual workpiece is presented by Lee and Nestler (Lee and Nestler 2012) in order to analyze and decrease geometric, kinematic and thermo-mechanical error effects of machining processes in actual machined parts. Application of virtual machining systems in feature recognition process is presented by Xú et al. (Shixin, Anwer, and Lihong 2015) to detect form errors of the machined features in milling operations. A virtual machining system is developed by Narita et al. (Narita et al. 2006) in order to simulate and analyze cutting forces and tool deflection error in virtual environments. A methodology in virtual environment is presented by Habibi et al. (Habibi, Arezoo, and Nojedeh 2011) to enhance accuracy of produced parts by compensating the geometrical and tool deflection errors. As a result, the presented algorithm in the study can provide an effective device using virtual machining system in order to increase accuracy of produced parts in milling operations.

A methodology in compensation of tool deflection errors is presented by Dépincé and Hascoët (Dépincé and Hascoët 2006) to achieve specific tolerances in milling operations. Furthermore, to compensate cutter radius in the finishing of ellipsoidal outer contour in ball end milling operations, virtual machining system is developed by Wang and Wang (Wang and Wang 2014). The corresponding amount of virtual cutting tool radius per layer is calculated by the system in order to be compensated in terms of NC codes modifications. Thus, accuracy of produced parts can be increase by using the presented virtual machining system in the study.

Geng et al. (Geng et al. 2013) presented a tool path correction and compensation algorithm for five-axis CNC machining operations. Modified versions of cutting tool paths are generated by the developed virtual machining system in the study in order to increase accuracy of part manufacturing. Smaoui et al. (Smaoui et al. 2011) developed a virtual machining system to correct and compensate cutting tool deflection in complex surface milling operations. Additionally, a virtual machining system is developed by Nojedeh et al. (Nojedeh, Habibi, and Arezoo 2011) in order to increase tool paths accuracy of CNC milling machine tools using method of geometrical error compensation.

Consequently, deviations of cutting tool along machining paths are eliminated by the presented virtual machining system in the study to increase accuracy of produced parts in milling operations.
An innovative error compensation methodology in virtual environment is presented by Eskandari et al. (Eskandari, Arezoo, and Abdullah 2013) to compensate the volumetric errors due to positional, geometrical and thermal errors of CNC milling machine. The thermal error is modeled by multiple linear regression model, ANN model and Fuzzy logic model to calculate error vectors for each position of cutting tool along machining paths. Then, NC codes are modified with regard to volumetric errors due to positional, geometrical and thermal errors of CNC milling machine. As a result, the system can improve accuracy of produced parts by compensating the errors in machining process. Moreover, in order to model and compensate geometric and thermal error in vertical machining centers, a virtual machining system is developed by Li et al. (Li et al. 2015). Therefore, accuracy of produced parts can be significantly improved by using the presented virtual machining system in this study.

3.2. Milling operations of sculptured surfaces

To simulate actual milling operations of complex surfaces by using ball-end milling cutting tools in virtual environments, Barbosa et al. (Barbosa, Osorio, and Nieto 2014) developed a virtual machining system. To simulate and analyze sculptured surfaces of actual machined parts in virtual environments, a virtual machining system is developed by Fountas et al. (Fountas et al. 2015b). As a result, accuracy as well as efficiency of part production can be increased by the presented system in the study. Likewise, material removal process and kinematics of milling machine axes are simulated in virtual environments by Bilalis et al. (Bilalis, Petousis, and Antoniadis 2009) in order to calculate effective parameters on roughness quality of a machined surface. Milling operations of sculptured surfaces are simulated in virtual environments by Chen and Cai (Chen and Cai 2008) in order to increase accuracy as well as efficiency of part production.

3.3. Creating actual machined parts in virtual environments

In order to create actual machined parts in virtual environments, Soori et al. (Soori, Arezoo, and Habibi 2013) presented a virtual machining system by considering dimensional and geometrical errors of a three axis CNC milling machine. 21 dimensional and geometrical error components of a three axis milling machine tool are applied to the nominal position of cutting tool by volumetric error vectors. Modified NC codes are generated by the virtual machining system to create actual machined parts in virtual environments. As a result, accuracy of actual machined parts can be increased by using the presented virtual machining system in the study. A virtual machining system in machining operations of shoe moulds is presented by Jimeno et al. (Jimeno, Chamizo, and Salas 2001) in order to be analyzed and modified in virtual environments. A tool-path generation algorithm is presented in this paper in order to calculate cost as well as accuracy of part production. Then, the process is modified by applying the optimisation process. Some computer architectures are also developed in the study to reduce the computational works. The proposed algorithm in the study is successfully implemented in a commercial CAD/CAM systems for shoe-production industries. To simulate and analyze three-axis milling operations in virtual environments, computational and graphical models are developed by Petousis et al. (Petousis, Bilalis, and Sapidis 2010).
A virtual machining system is presented by Soori et al. (Soori, Arezoo, and Habibi 2014) to create actual machined parts in virtual environments by considering dimensional, geometrical and tool deflection errors in three-axis CNC milling machines. Cutting forces for each position of cutting tool along machining paths are calculated by the presented virtual machining system in the study to obtain tool deflection error in milling process. Then, volumetric error vectors for each position of cutting tool

along machining paths with regard to dimensional, geometrical and tool deflection errors are generated by the system in order to modify the original NC codes. Actual machined parts are simulated in virtual environments by using the virtual machining system in order to increase accuracy and efficiency of part manufacturing. Flowchart and strategy of virtual machining system is shown in Fig. 4 (Soori, Arezoo, and Habibi 2014).

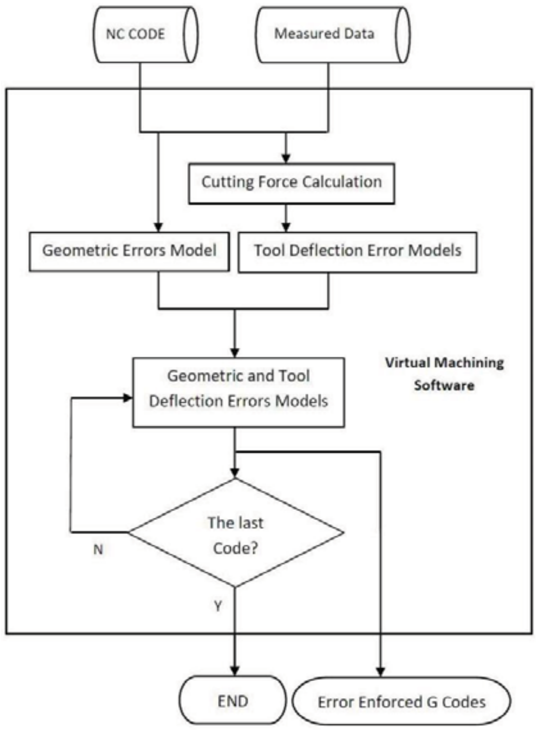

Fig. 4. Flowchart and strategy of virtual machining system (Soori, Arezoo, and Habibi 2014).

Lin et al. (Lin et al. 2017) presented a virtual machining system by considering CNC interpolation system, servo dynamics, friction and geometric errors in 5-Axis CNC machine tools. The sculpture of a human face is produced by modified machining codes in the study in order to be analyzed and modified in virtual environments. As a result, accuracy of part production can be increased.

3.4. Internet-Based virtual CNC milling systems

To analyze and optimize manufacturing processes in virtual environments, an Internet-Based virtual CNC milling system is presented by Ong et al. (Ong, Jiang, and Nee 2002). Resource support subsystem, CNC controller, user control interface and simulation of machining parameters are developed in the virtual machining system. They are connected together via the internet in order to create a web of knowledge in virtual machining system. The architecture of the web-based virtual CNC milling system is shown in Fig. 5 (Ong, Jiang, and Nee 2002). Different sections of the Internet-Based virtual CNC milling system as virtual libraries of material, fixture, cutter and machine tools are designed in the system. Personal database and knowledge base are considered in the system to provide necessary information for the machining operations. The section is connected to the CNC controller, user control interface, simulation service and environments and machining process parameters via internet in order to provide an Internet-Based virtual CNC milling system.

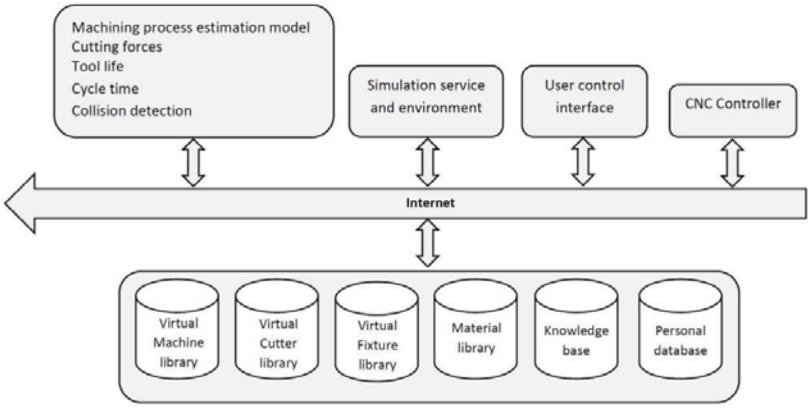

Fig. 5. Architecture of the web-based virtual CNC milling system (Ong, Jiang, and Nee 2002).

Real-time workpiece material removal rate, NC codes Interpreter, collision detection system, simulation of the machining parameters such as cutting forces, torque and power consumption and cutting tool life calculation models are functional applications of the presented virtual machining system in the study. As a result, machining conditions can be evaluated and optimized by using the developed virtual machining system in order to increase efficiency of part manufacturing.

A review paper is presented by Kadir et al. (Kadir, Xu, and Hämmerle 2011) considering Web-based virtual machine tool systems using mathematical modeling in order to take a more scientific approach to real behavior of machine tools and machining process. Virtual reality, web based techniques, mathematical modeling, hardware interactions and STEP-NC-based methodologies are considered in the study to present the developed virtual machine tool.

An Internet-based virtual machining system is presented by Kong et al. (Kong et al. 2002) which can apply virtual manufacturing technology to machining processes of CNC machining center. In order to transmit the NC codes to the related machining centers, the presented virtual machining system in the study is implemented with execute digital machining as well as verification devices. The research work proposes a developed virtual machining system which can monitor the status of cutting tool along machining paths by using the Internet. As a result, a virtual machining system is developed in the study to present a simple manipulation and monitoring system of machining centers in virtual environments by using information technology devices such as object-oriented method, middleware, Internet programming and client-server structure.

3.5. Feed rate scheduling systems

To increase efficiency of machining operations in five-axis CNC milling machines, feed rate scheduling strategy is presented by Zhang et al. (Zhang et al. 2009) by using virtual machining system. An intelligent feed rate scheduling system based on a virtual machining is presented by Lee and Cho (Lee and Cho 2003) in order to accurately predict cutting forces in general end milling operations. To present feed rate scheduling system, two steps are considered as calculation of an optimized feed rate based on a reference cutting and the modification of NC codes. An algorithm for the feed rate optimization is presented in the Fig. 6 (Lee and Cho 2003). As is shown in Fig. 6, feed rate optimization process is based on the calculated cutting forces for each position of cutting tool along machining paths.

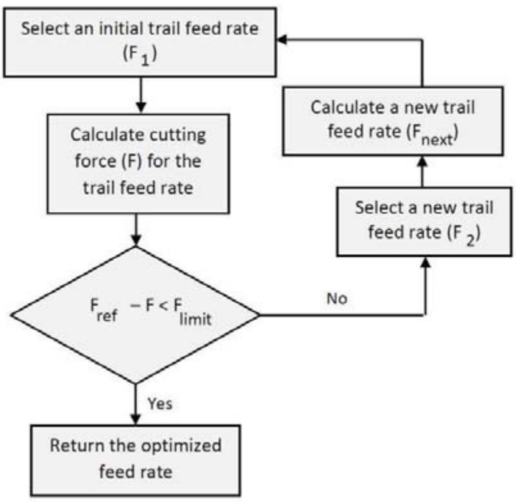

Fig. 6. An algorithm for the feed rate optimisation (Lee and Cho 2003).

The original NC codes are modified by applying the optimized feed rates for each position of cutting tool along machining paths. Therefore, a virtual machining system is presented in the study to predict the cutting forces in general milling operations. A virtual machining system is presented by Kurt and Bagci (Kurt and Bagci 2011) to optimize feed rate in machining operations of sculptured surface by using ball-end milling cutting tools in three-axis CNC milling machine tools.

Feed rate optimization for freeform milling operations is presented by Erkorkmaz et al. (Erkorkmaz et al. 2013) by considering constraints from the feed drive system as well as process mechanics. To simulate the cutting process in freeform milling operations, an algorithm is developed in the study to generate B-spline tool paths, time-optimized acceleration- and jerk-bounded axis trajectories by modifying the feed rates along machining paths. B-spline fitting and refinement and cutting tool engagement conditions along machining paths are generated from NC codes by using the presented virtual machining system in the study. Then, the B-spline tool paths are converted into cubic polynomials which are more suitable for interpolation process. Cutting forces as well as feed rates limitations due to cutting conditions are calculated in order to be used in feed rate optimization process. Limitations of the feed drive control system such as axis velocity, acceleration and jerk are considered in terms of feed rate optimization process. Feed rate optimization scheme is shown in Fig. 7 (Erkorkmaz et al. 2013). As is shown in Fig. 7, different steps as cutting process, tool path & drives and feed profiling & final trajectory are considered in terms of feed rate optimization process.

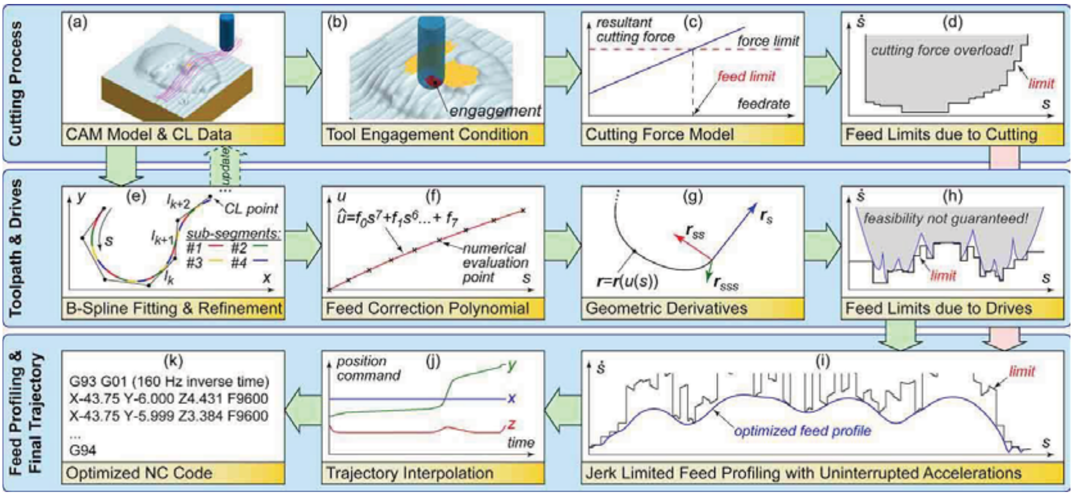

Fig. 7. Feed rate optimization scheme (Erkorkmaz et al. 2013).

Finally, original NC codes are modified by optimized feed rate calculated in the system in order to increase efficiency of part manufacturing. A virtual machining system is developed by Ferry and Altintas (Ferry and Altintas 2008b) to optimize feed rate in five-axis milling operations of jet engine impellers. Likewise, to optimize feed rate in 3-axis milling operations, a virtual simulation as well as optimization system is developed by Li et al. (Li et al. 2003). Similarly, Benardos and Vosniakos (Benardos and Vosniakos 2014) developed a virtual machining system to optimize feed rate as well as spindle speed in three-axis machining operations of sculptured surfaces. Furthermore, to increase efficiency of part manufacturing, Merdol and Altintas (Merdol and Altintas 2008b) developed a virtual machining system in order to schedule and optimize feed rate in milling operations. Cutting speed, feed rate, depth and width of cut are optimized by the presented system in order to maximize the material removal rate.

To optimize feed rate and cutting speed in milling operations, a virtual machining system is presented by Epureanu and Teodor (Epureanu and Virgil 2006). Cutting forces in milling operations are calculated in the study by using the simulated chip areas in virtual environments. Workpiece geometry, cutting tool specifications, measured blank in real profile, allowed geometrical roughness and allowed chip area are identified as input to the virtual machining system. Cutting forces are monitored during the milling operations in order to be verified with assumed process limitations. Then, uncut chip section areas in milling operations are analyzed and modified by considering the limitations of cutting process. Vibrations of cutting tool in the machining operations are also monitored in order be used in analyzing and modifying the cutting speed along machining paths. Consequently, the new inputs are generated by the presented system in the study to optimize feed rate as well as cutting speed in milling operations. The procedure of the virtual machining system is presented in the Fig. 8 (Epureanu and Virgil 2006). As is shown in Fig. 8, the virtual machining system can obtain cutting forces as well as vibration of machine tool from actual machining to correct cutting speed and chip area in milling operation.

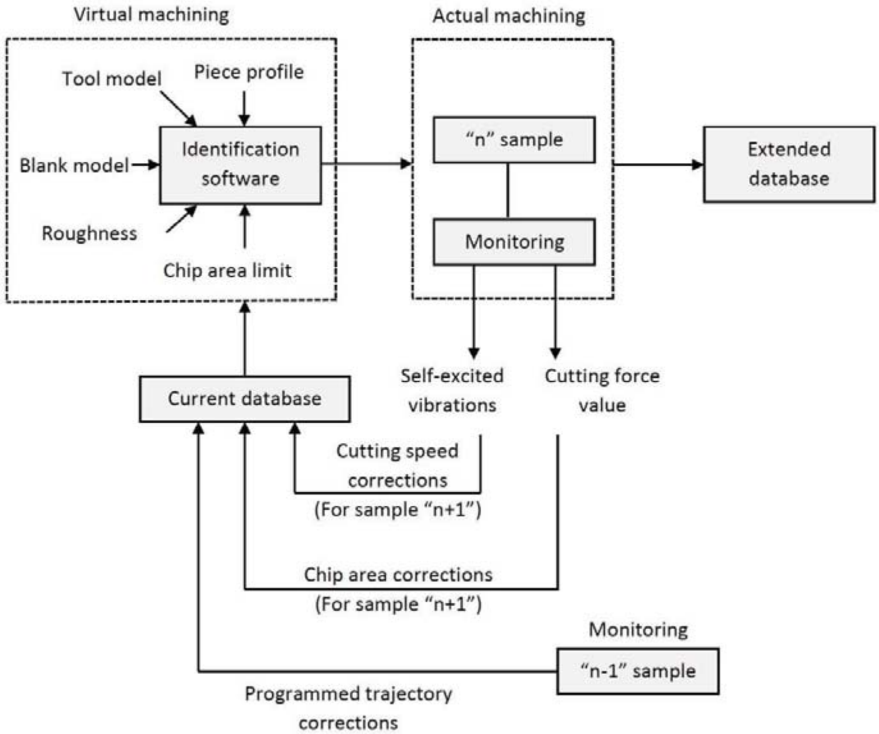

Fig. 8. Procedure of the virtual machining system (Epureanu and Virgil 2006).

To schedule off-line feed rate based on an evaluation of cutting tool performances in milling operations, a virtual machining system is presented by Ko et al. (Ko, Yun, and Cho 2003). In order to evaluate cutting tool performance, the cutting tool configuration should be calculated based on the cutting tool geometry, workpiece geometry for each position of cutting tool along machining paths. Then, uncut chip thickness based on the cutting forces can be calculated in machining paths. Thus, machined surfaces errors can be calculated by using the presented virtual machining system in the study. To analyze the cutting forces as well as machined surface errors along machining paths, optimized techniques can be applied to the simulated machining process in virtual environments. Finally, modified NC codes are generated by the system to increase accuracy as well as efficiency of the part manufacturing.

Structure of the virtual machining system is shown the Fig. 9 (Ko, Yun, and Cho 2003). As is shown in Fig. 9, machining parameters are entered to the virtual machining system in order to generate optimized NC codes by controlling cutting forces as well as machining surface error.

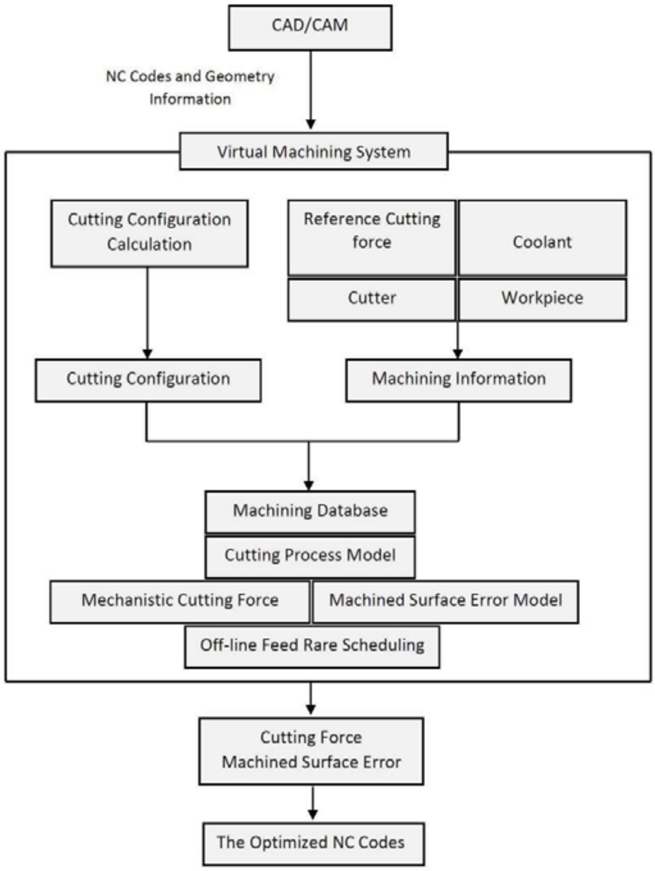

Fig. 9. Structure of the virtual machining system (Ko, Yun, and Cho 2003).

Application of virtual machining system for high speed machining operations of hardened steels is presented by Majerik and Jambor (Majerik and Jambor 2015) in order to be analyzed and optimized in virtual environments. A new methodology is presented in the study to determine the global optimum cutting tool paths for machining operations of free form surfaces. Then, modified NC codes are generated by the presented system with regard to calculated optimal tool path for each position of cutting tool along machining paths. Thus, time and cost of accurate production in high speed machining of hardened steels can be decreased by the presented methodology in the study.

3.6. Cutting tool paths optimization

A virtual machining system is developed by Lacalle et al. (De Lacalle et al. 2007) to optimize cutting tool paths by minimizing the tool defection error in milling operations. It is based on the calculation of the minimum cutting force components by selecting the optimal tool paths on complex surfaces. Therefore, accuracy of produced parts can be increased by using the presented virtual machining system in the study. A virtual machining system is developed by Fountas et al. (Fountas et al. 2015a) in order to optimize cutting tool paths for both 3- and 5-axis machining operations of sculptured surfaces. Therefore, the system can generate uniform tool paths with low geometric machining error distribution as well as high efficiency in part manufacturing.

To optimize cutting tool paths in milling operations of five-axis milling machine tools, a virtual machining system is developed by Moodleah and Makhanov (Moodleah and Makhanov 2015).The maximum material removal rate is considered in terms of optimization process in order to reduce the machining time. Furthermore, Wang et al. (Wang et al. 2017) developed a virtual machining system to generate optimized cutting tool paths in blade machining operations. To improve efficiency of machining operations, a finite element method (FEM) based on the numerical method is proposed in the study by considering smoothness as well as evenness of tool paths.

Optimization of cutting tool paths based on adaptable geometric pattern in five-axis milling machine tools is presented by Makhanov (Makhanov 2010). To optimize the positions and orientations of cutting tool along machining paths, adaptation is performed in the presented system by using certain criteria in quality of cutting tool paths such as kinematic errors, scallops, possible undercuts or overcuts and the continuity of the paths. In order to optimize cutting tools paths in five-axis CNC milling machine tools, a virtual machining system is developed by Cai et al. (Cai et al. 2012). Therefore, accuracy as well as efficiency of part production can be increased using the presented virtual machining system in the study. Similarly, a virtual machining system is developed by Lin et al. (Lin, Lee, and Bohez 2009) to increase accuracy of produced parts by using optimized cutting tool paths in five axis-machining operations.

To optimize cutting tool paths in five-axis machining operations, a virtual machining system is developed by Bohez et al. (Bohez, Makhanov, and Sonthipermpoon 2000). The method of adaptive curvilinear tool paths is used by Moodleah et al. (Moodleah, Bohez, and Makhanov 2016) to optimize cutting tool paths in five-axis machining operations. A virtual machining system is presented by Rauch and Hascoët (Rauch and Hascoët 2012) to generate optimized cutting tool paths in complex surfaces machining. A virtual machining system is developed by Fountas et al. (Fountas et al. 2017) to optimize cutting tool paths in machining operations of sculptured surfaces by using 5-axis milling machine tools. To optimize cutting tool paths of sculptured surface, the genetic algorithm is used by considering surface machining error, machining time and number of cutter location points along machining paths as objective functions. Moreover, Fountas et al. (Fountas et al. 2014) developed a virtual machining system in order to optimize cutting tool paths in machining operations of sculptured surfaces. The genetic algorithm is used to present an optimization procedure in order to obtain optimized parameters in machining operation of sculptured surfaces.

Application of virtual machining system in high speed contouring operations is presented by Erkorkmaz et al. (Erkorkmaz, Yeung, and Altintas 2006). Accurate estimation of the contour error is presented in the study in order to improve accuracy of high speed contouring operations. The nearest reference segment method is used in the study to estimate the contour error of machining paths without any restriction to the type of tool path geometries such as linear, circular or spline. An algorithm is also developed in the study to produce parts with smoothed sharp corners and spline fitting. The presented method in the study allows corners of machining paths to be turned while a continuous feed rate profile is maintained. Thus, a series of reference knots with a series of fifth-order polynomial segments in quantic spline tool paths is generated by using the presented virtual machining system in the study. Moreover, parameterization as well as interpolation steps are considered in the generation process of spline tool paths. Then, the add-in splines are parameterized and cornering feed rates along the tool paths of add-in splines are calculated. Finally, modified corners in optimized machining paths are generated by the virtual machining system with regard to minimum machining time as well as tool path tolerances. Therefore, tool positioning accuracy in corner machining applications can be increased by using the presented virtual machining system in the study. Heo et al. (Heo et al. 2017) developed a virtual machining system in order to monitor and analyze the cutting tool conditions in milling operations.

3.7. Machining parameters optimization

Application of virtual machining systems in monitoring and minimizing the tool deflection error of three axis CNC milling machines is presented by Soori et al. (Soori, Arezoo, and Habibi 2016). The tool deflection errors along machining paths are monitored to present a useful methodology in controlling the produced parts with regard to desired tolerances. A methodology based on the genetic algorithm is developed to optimize the machining parameters with regard to objective functions such as minimizing unnecessary cutting forces, machining times, surface roughness and maximizing tool life. As is shown in Fig. 10 (Soori, Arezoo, and Habibi 2016), the system can receive geometry of cutting tool, measured cutting forces, desired amount of population size, chromosome length, probability of crossover and probability of mutation as input. As a result, they are converted to binary codes using either zeros or ones. Then, fitness functions based on the presented objective functions are constructed. The fitness functions are used in order to evaluate and rank the chromosomes in the population to select the chromosomes with higher fitness values. To produce new offspring, the operator of crossover is used. Then, mutation is applied after the crossover in order to provide a quicker convergence. Finally, the obtained results are compared in order to select the most appropriate outputs of objective functions. The process will be repeated in order to achieve the most appropriate outputs for machining parameters as feed rate as well as spindle speed. Flowchart and strategy of machining parameters optimization by genetic algorithm is shown in Fig. 10 [74]. As a result, accuracy and efficiency of part manufacturing can be increased using the presented virtual machining system by monitoring and minimizing the tool deflection error.

In order to decrease the tool deflection error in milling operations, an enhanced machining simulator with tool deflection error analysis is presented by Dugas et al. (Dugas, Lee, and Hascoët 2002). To reduce the error in terms of machining operations, an optimization algorithm is developed in the study by comparing a simulated model to original geometry model. So, amount of the tool deflection error for each position of cutting tool along machining paths can be predicted and decreased by the presented virtual machining system in order to increase accuracy of part manufacturing. A virtual machining system in five-axis milling machine tools is developed by Munlin et al. (Munlin, Makhanov, and Bohez 2004) in order to minimize kinematics errors near the stationary points of the machined surfaces. An optimization algorithm based on the iterative scheme of shortest machining path is developed in the study to minimize the kinematic errors with regard to feasible angles performed in vicinity of stationary points. Consequently, the system can increase accuracy of machining operations in rough machining operations with large angular steps in five-axis milling machine tools.

Milfelner et al. (Milfelner, Cus, and Balic 2005) developed a condition monitoring system using genetic optimization in order to design a signal processing system as well as a detector of fault conditions in milling operations. A virtual machining system is developed by Mudcharoen and Makhanov (Mudcharoen and Makhanov 2011) to optimize axis rotations in six-axis machining milling machine tools.

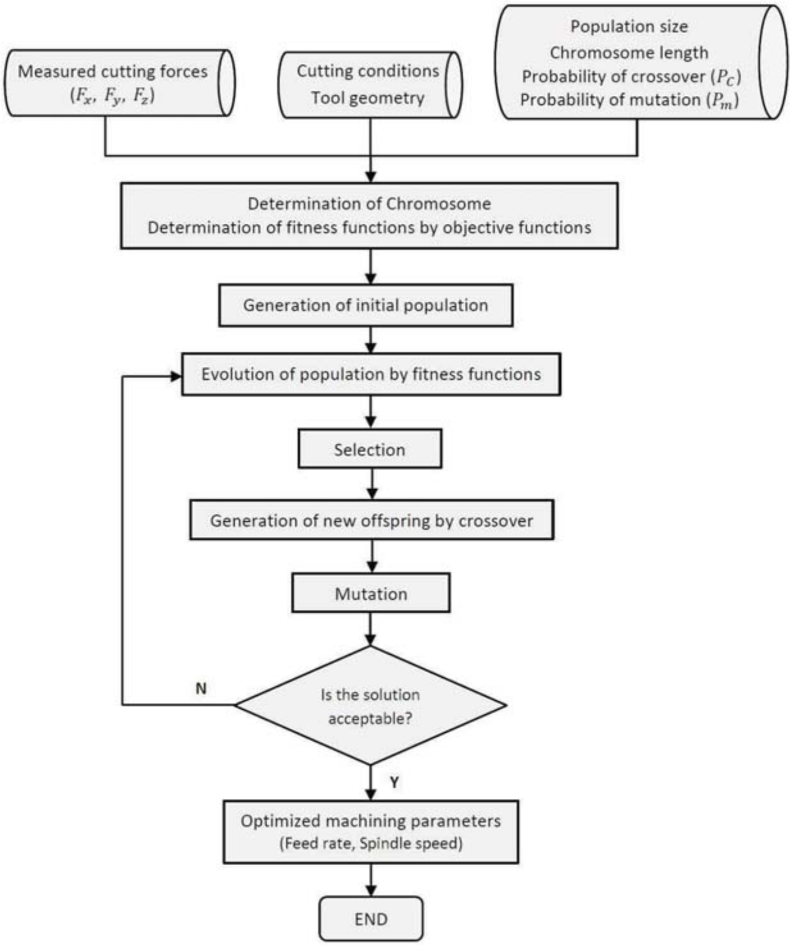

Fig. 10. Flowchart and strategy of machining parameters optimization by genetic algorithm (Soori, Arezoo, and Habibi 2016).

The shortest path strategy and method of using additional axis are applied in the presented system to optimize two rotation axes on the table and one additional rotation axis on the cutting tool. As a result, accuracy and efficiency of part production can be increased by the developed virtual machining system in the study. Moreover, a virtual machining system is developed by Altintas et al. (Altintas et al. 2005) to analyze and optimize elements of machine tools using finite element models. Integrated design of modern virtual machine tool elements are described in the study by using computer aided design and kinematics studies, Finite Element Analysis (FEA), coupled flexible Multi-Body-Simulation and calibration of the simulation models. The kinematic performances of machine tools elements are optimized to obtain optimum dimensions of platform as well as position of joints at machine tool bed. In order to obtain optimized elements of machine tool such as columns as well as spindle, structural behavior analysis by using the FEA is evaluated in the study. Static, dynamic and thermal loads with minimum structure mass and highest machining precision are considered in the analysis to calculate optimized elements of machine tool. The topology optimization procedure is used to define the best material distribution in a given design space. Moreover, the parameter optimization technique is used to optimize more detailed designs of machine tool elements such as wall thickness of machine beds as well as columns. The parameter optimization tools are used to obtain optimum sets of structural parameters for moving parts of machine tools by using the FEA. In addition, coupled simulation of structural dynamics as well as control loops of machine tools are studied in the research work to meet high static and dynamic stiffness, high dynamic properties of the feed drives and low path deflection during the chip removal processes. Finally, the obtained results are used in designing and modifying machine tool components in order to increase accuracy as well as efficiency of part production. Methods of structural optimization are shown in Fig. 11 (Altintas et al. 2005). As is shown in Fig. 11, topology optimization, parameter optimization, topography optimization and shape optimization are the main methods of structural optimization of machine tools elements.

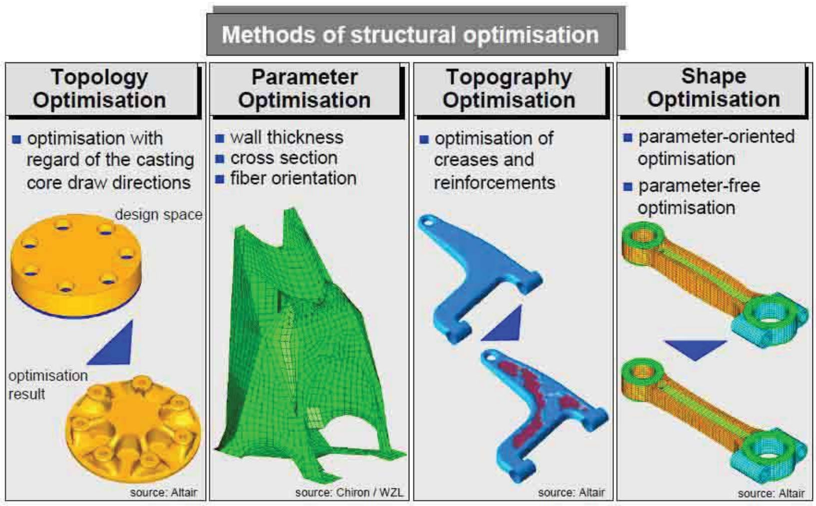

Fig. 11. Methods of structural optimization (Altintas et al. 2005).

A virtual machining system is developed by Madhavan et al. (Madhavan, Chandrasekar, and Farris 2000) to simulate and predict trends of machining operation in virtual environments using finite element analysis. A virtual machining system is also developed by Hung et al. (Hung et al. 2013) to evaluate the machining stability of a vertical milling system under the interactive influence of the spindle unit and the machine frame structure. Stability analysis of milling machine tools is presented in the study by considering the effects of machine frame structure as well as spindle bearing functions using the finite element method. Optimization of workpiece setup for continuous five-axis milling operations is presented by Pessoles et al. (Pessoles et al. 2013).To obtain optimum position of workpiece setup, workpiece orientation as well as workpiece position in translation are considered as effective parameters. The distances covered by the machine axes are also considered as objective function in optimization process. So, machining time can be decreased by the presented system in the study to increase efficiency of part manufacturing.

A developed virtual machining system is presented by Ko et al. (Ko et al. 2002) to evaluate and optimize cutting performances in milling operations. A new methodology is presented in the study to predict cutting forces in milling operations for a wide range of cutting conditions by calculating cutting-condition-independent coefficients. A systematic procedure is presented in the study as is shown in the Fig. 12 (Ko et al. 2002) in order to determine cutting coefficients in the empirical equations for workpiece as well as cutting tool regardless of cutting conditions such as width of cut, depth of cut and feed rate. This is due to using the instantaneous cutting forces as well as uncut chip thickness in coefficients determination process. So, they are generated by using the infinitesimal helical edges of cutting tool engaged to the workpiece in milling operations. Extraction of the cutting forces generated by one helical edge of a single disk element is shown in the Fig. 12 (Ko et al. 2002).

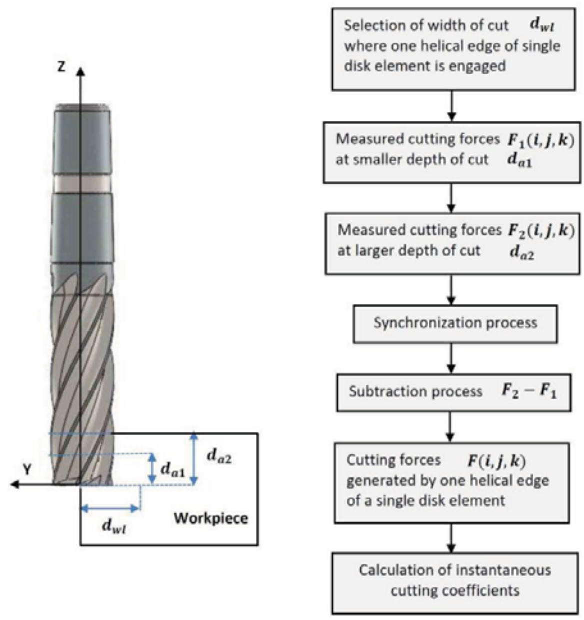

Fig. 12. Extraction of the cutting forces generated by one helical edge of a single disk element (Ko et al. 2002).

Therefore, cutting forces in milling operations can be accurately predicted by using the direct application of instantaneous cutting coefficient with regard to dimensions of cutting tool. A virtual machining system is developed by Chaves-Jacob et al. (Chaves-Jacob, Poulachon, and Duc 2012) to optimize finishing strategies in machining operations of impeller blades using 5-axis CNC machine tools.

Off-line optimization on CNC machine tool using virtual machining system is presented by Li et al. (Li et al. 2008) to evaluate and optimize the actual machining processes in virtual environments. Virtual machining, cutting parameters optimization, error prediction and compensation are studied to present efficiency of off-line optimization for different purposes. Furthermore, to simulate and optimize machining operations in virtual environments, Rao (Rao 2011) developed a virtual machining system. Therefore, a better product quality in machining operations can be achieved by using presented virtual machining system in the study. A generalized process simulation as well as optimization strategies using a virtual milling system is presented by Merdol and Altintas (Merdol and Altintas 2008a) to predict and improve the performance of three-axis milling operations. Cutting forces for each position of cutting tool along machining tool paths are calculated in the study to simulate milling process. Then, the machining parameters are optimized to maximize the material removal rate by calculating acceptable levels of feed rate in milling operation. Finally, modified NC codes are generated by the presented system in the study to provide more accuracy as well as efficacy in part production. Likewise, Palanisamy et al. (Palanisamy, Rajendran, and Shanmugasundaram 2007) presented a developed computer algorithm in order to optimize the cutting parameters of end milling operations by using the genetic algorithm. Merdol and Altintas (Merdol and Altintas 2008c) presented a virtual simulation and optimization system to optimize effective parameters in milling operations. Chip load, torque and cutting force s are analyzed and optimized by the presented system to increase efficiency of part production. To monitor and optimize cutting process of ball end milling operations, an intelligent system using genetic algorithms is also developed by Cus et al. (Cus, Milfelner, and Balic 2006). Moreover, optimization of machining parameters for alumina based ceramic cutting tools by using the genetic algorithm is presented by Kumar et al. (Kumar et al. 2006). So, material removal rates as well as productivity of milling operation are increased by using optimized parameters of machining operation.

A virtual machining system is also presented by Park et al. (Park et al. 2018) in order to obtain optimized feed rates by minimizing machining times. As a result, modified NC codes in the study can increase efficiency of part manufacturing. Application of virtual machining system in machining operations of aerospace industries is presented by Wiederkehr and Siebrecht (Wiederkehr and Siebrecht 2016). Optimized machining parameters are obtained in the study to decrease errors of thin-walled workpieces as well as thermo-mechanical deformations. Moreover, a generalized process simulation as well as optimization strategy for two 1/2-axis milling machines is presented by Altintas and Merdol (Altintas and Merdol 2007) to increase material removal rate in milling operations.

3.8. Virtual process planning systems

In order to evaluate the machining operation in the process planning stages, a virtual machining simulator is developed by Narita et al. (Narita et al. 2000). As is shown in the Fig. 13 (Narita et al. 2000), NC codes simulator, geometric simulator and physical simulator are designed in the system to present optimal condition of machining process for process planners. The cutting tool locations along machining paths, time of machining operation and cutting conditions such as feed rate and spindle speed are calculated by NC codes simulator. Cutting conditions such as depths of cut as well as metal removal rate are also calculated in the study by using geometric simulator. Then, cutting forces in machining process as well as machining errors due to cutting conditions are generated by using presented physical simulator in the study. Finally, the system presents an optimized condition of machining operations in order increase accuracy as well as efficiency of part manufacturing by process planners. Procedure of the virtual machining simulator is shown in the Fig. 13 (Narita et al. 2000).

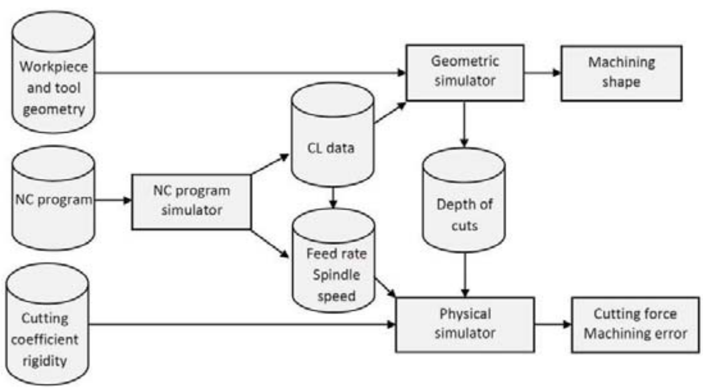

Fig. 13. Procedure of the virtual machining simulator (Narita et al. 2000).

To meet desired geometric tolerances in milling operations, application of tool deflection knowledge in process planning using selecting optimal feed rates is presented by Ong and Hinds (Ong and Hinds

2003). Also, application of virtual machining system in process planning of part manufacturing is presented by Sormaz et al. (Sormaz, Arumugam, and Ganduri 2007). The workpiece geometries, cutting tools and tolerances are considered in the system to generate machining strategies with regard to desired quality for produced parts. So, efficiency of part production can be increased using presented virtual machining system in the study. Moreover, application of virtual machining system in process planning is presented by Kim and Woo (Kim and Woo 2013) to determine the maximum cutter sizes in milling operations. In order to produce a feature in a shorter period of time, the system can detect virtual corners to calculate the maximum cutter sizes in machining paths. The energy consumption of machine tools is simulated in virtual environments by Brecher et al. (Brecher, Bäumler, and Triebs 2013) to increase energy efficiency aspects in process planning of part production. The presented virtual machining system in study can analyze and reduce required power of machine tools in order to increase efficiency of part manufacturing.

Applications of genetic algorithms in process planning of 2.5-axis pocket machining operations are presented by Ahmad et al. (Ahmad, Rahmani, and D'Souza 2010). A new virtual machining system is developed in the study to select optimal sequence of cutting tools in 2.5-axis pocket machining operations by considering given pocket geometry, a database for cutting tools, cutting parameters and tool holder geometry. Prediction of machining accuracy based on geometrical errors in five-axis peripheral milling operations is presented by Ding et al. (Ding et al. 2014) in order to develop a process planning system in virtual environments.

To explain inputs and outputs of the virtual machining models for sustainable machining operations, a virtual machining system is presented by Shao et al. (Shao, Kibira, and Lyons 2010). Environmental impacts of machining process based on life cycle assessment are analyzed in virtual environments in order to improve sustainable performances of machining systems. Proposed virtual machining model with environmental impacts analysis is presented in the Fig. 14 (Shao, Kibira, and Lyons 2010).

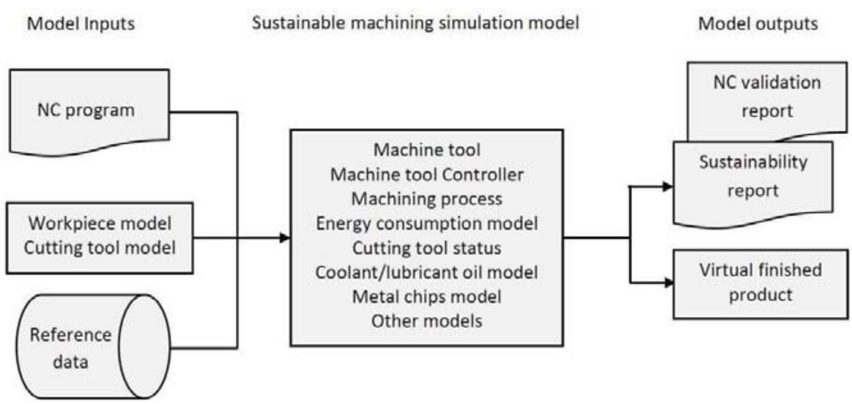

Fig. 14. Proposed virtual machining model with environmental impacts analysis (Shao, Kibira, and Lyons 2010).

The study can provide a better understanding for machining strategy, scheduling, process planning, and configurations through analysis of the environmental impact in machining process. As a result, time and cost of accurate production can be decreased by using the presented process planning system in the study.

In order to predict part machining cycle times in machining operations, a virtual machining system is developed by Altintas and Tulsyan (Altintas and Tulsyan 2015). The part machining cycle time in machining process is obtained by using the trajectory module of the CNC machine tools influenced by the velocity, acceleration and jerk profiles. To predict the part machining times in the study, trajectory profiling parameters and sharp corner contouring strategies are also extracted. The process is without the demand of filtering as well as interpolation strategies embedded into the software and hardware modules of commercial CNC systems. Accuracy of the presented methodology is influenced by quality of trajectory generation as well as smoothing and cornering strategies. Thus, suitable machine tool elements as well as efficient procedures of process planning in part production can be accurately selected by the presented virtual machining system in the study.

3.9. Machining operations of thin-wall structures

Error compensation strategy in milling operation of flexible thin-wall parts is presented by Ratchev et al. (Ratchev, Liu, and Becker 2005).To increase accuracy of produced parts in the study, force-induced errors in machining of thin-wall structures are predicted and compensated in virtual environments. In order to increase accuracy of part production, a virtual machining system is developed by Altintas et al. (Altintas et al. 2018) to predict and compensate the deflection error in machining operations of flexible turbine blades. Frequency domain updating of thin-walled workpiece dynamics using reduced order substructuring method in machining operations is also presented by Tuysuz and Altintas (Tuysuz and Altintas 2017).

Machining simulation environment is presented by Rai and Xirouchakis (Rai and Xirouchakis 2008) in order to analyze deflection error in milling operations of thin-walled components. Modeling and simulation environment for machining operations of low-rigidity components is also presented by Ratchev et al. (Ratchev, Huang, et al. 2004). To analyze deflection error in machining operation of low-rigidity components, a finite element analysis is developed in the study.

To increase accuracy of part production, Arnaud et al. (Arnaud et al. 2011) simulated machining operations of low rigidity parts with thin-walled structures in virtual environments. Numerical simulation is used to obtain optimal cutting conditions for the precision of produced parts as well as the desired surface finish. A dynamic mechanistic model with time domain simulation is applied to simulate the milling operations. As a result, thin-walled workpiece chatter in milling operations are simulated in order to be analysed. Prediction and compensation of workpiece deflection error in milling operation of low-rigid parts is presented by Ratchev et al. (Ratchev, Liu, et al. 2004). Finite element analysis is used in the study to predict tool deflection error of low-rigidity components in machining operations. A new analytical flexible force model is developed in the study to increase geometric accuracy of produced parts by considering the impact of the machining forces on the deflection of thin-wall structures.

Ratchev et al. (Ratchev, Nikov, and Moualek 2004) simulated material removal rate in peripheral milling operation of thin wall low-rigidity structures by using finite element analysis. A new voxel-transformation model and algorithm are developed in the study to simulate and analyze the material removal rate in milling operations. Prediction and compensation of workpiece deformation error in multilayer milling operation of thin-walled parts is presented by Chen et al. (Chen et al. 2009). A dynamical model is developed in the study to predict the deformation in multilayer machining a thin-walled part. The coupling relation between cutting force and machining deformation are considered by using the iterative computation. As a result, workpiece deformation error can be predicted and compensated using the presented virtual machining system in the study. To increase accuracy of part production, finite element analysis and calculation of deformation error in machining operation of thin-walled components is presented by Ning et al. (Ning et al. 2003). This paper applies the finite element method to the quantitative analysis of thin-walled structure deformation in the process of machining operations.

Ratchev et al. (Ratchev et al. 2003) presented force and workpiece deflection error modeling in milling operations of low-rigidity complex parts. The proposed approach in the study is based on modelling and analyzing of part deflection as well as material removal rates in milling operations of low-rigidity complex parts. To increase accuracy of part production, workpiece deflection error in machining operation of aerospace thin-walled parts due to original residual stress is simulated in virtual environments by Wei and Wang (Wei and Wang 2007). In this paper, finite element model of original residual stress is used to analyze the deflection error in machining operation of aerospace thin-walled parts. Study on workpiece deformation error in milling operation of titanium thin-walled parts using finite element models is also presented by Gang (Gang 2009). In this paper, the three-dimensional finite element models of a helical cutting tool and a thin-walled part are presented in order to simulate and analyze the milling operations.

3.10. Virtual training systems

Web-based virtual operating of CNC milling machine tools is presented by Hanwu and Yueming (Hanwu and Yueming 2009) in order to provide operational training system for milling process. Main components of the CNC milling machine tool such as bed, workbench, saddle, lifting table, spindle workpiece and fixture are simulated in the virtual environments to create a virtual CNC milling machine tool. Also, a virtual CNC control panel is designed for the presented system in order to monitor and translate NC codes to the virtual machine tool. Hardware and software environments as well as performance test of milling operations are the main simulated sections of the presented virtual machine tool in the study. G-Code Editor Interface, cutting tool addition, reference tools addition and workpiece set up are also designed in the operation interface section. Z-Map structure model algorithm is considered to simulate material removal rate in cutting simulation process. As a result, actual milling operations are simulated in the virtual environments in order to be used in training process of machining operators without the need of shop floor testing. Fig. 15 shows virtual CNC milling machine tool (Hanwu and Yueming 2009).

Fig. 15. Virtual CNC milling machine tool (Hanwu and Yueming 2009).

A developed machining simulation system is presented by Zhang et al. (Zhang, Ong, and Nee 2012) in order to be used in training process of novice operators. Collision between cutting tool and fixture in machining operations can be detected by the presented system in order to be prevented. To model the machining operation in virtual environment, material removal rate is simulated by calculating cutting forces using calculated cross-sectional area of machined surfaces during full intersection period of machining process. Then, linear square fitting method is applied to the calculated cutting forces in order to be analyzed and calibrated. Therefore, useful virtual machining system in training process is presented in the study to improve experiences of novice operators in machining operations. A virtual machining system in industrial training purposes is developed by Lin et al. (Lin et al. 2002) to provide a useful device in training of machining operators. To generate appropriate training task according to training goals, several modules are designed in the presented system such as training task-planning, performance evaluation and instruction and interference. An automatic monitoring as well as data collection system is designed in performance evaluation module of the presented system in order to recognize and modify the situation of training programs. Finally, the most suitable training program is presented by using modified interference modules. So, the presented system in the study can be used in improving experiences of CNC machine tools operators in order to increase efficiency of part manufacturing.

Lin and Fu (Lin and Fu 2006) developed a Virtual Machine tool Structural Modeler (VMSM) by an interface system to present a machine tool in a virtual reality environment. Several modules such as component modules, module shape library, combination rule library and structure library are presented as architecture of the system. The developed virtual machine tool in the study can be efficiently used for industry training as well as machine leaning and operating.

Virtual simulation system of CNC milling machine tools is presented by Sun et al. (Sun et al. 2008) in order to be used in training programs. Virtual scene mapping and model optimization system, NC codes compiler process and simulator of machine tool moving axis are investigated in the study in order to simulate actual machining process in virtual environments. A virtual CNC training system in high speed and ultra-precision machining operations is presented by Liu and Zhu (Liu and Zhu 2014). So, efficiency of machine tool learning for operators can be increased by using the presented virtual machining system in the study.

3.11. Analyzing and modifying machine tool elements

Virtual simulation model of realistic and modular CNC machine tools is presented by Yeung et al. (Yeung, Altintas, and Erkorkmaz 2006). The procedures of the developed virtual CNC systems are described in the study to predict the performance of a real CNC system during part machining operations. Dynamic model of feed drive is also simulated in virtual environment in order to predict and evaluate performance of machine tools elements. Thus, realistic simulation of the drive's high speed contouring capability and auto-tuning of sophisticated axis are presented in the study to analyze real behavior of machine tools elements in virtual environments.

A virtual machine tool is presented by Gomez et al. (Gomez, Castiblanco, and Osorio 2017) to simulate elements of the Hartford SMC5 machining centre in virtual environments. Virtual controller and postprocessor are also designed in the presented system to control and optimize the moving axis of machine tools. As a result, the elements of machining centre can be analysed and modified by using presented virtual machining system in the study. Machine tool elements such as main spindle and feeding motors of milling machine tools are modelled and simulated in virtual environments by Shin et al. (Shin et al. 2006) to increase efficiency of part production. Likewise, machine tool elements are simulated in virtual environments by Coffignal et al. (Coffignal et al. 1997) to predict vibrations of machine tool elements in cutting process as well as the interaction between cutting tool and workpiece in milling operations. A virtual machining system is developed by Tani et al. (Tani et al. 2007) in order to simulate vertical z axis of five axis machining centers in virtual environments. Then, the finite element method is used to analyze and modify the simulated elements of machine tools in virtual environments. So, the system can be used in modifying machine tool design in order to increase efficiency of part manufacturing.

Air cooling systems of CNC milling machine tools are simulated in virtual environments by Perri et al. (Perri et al. 2016) in order to be analyzed and modified. To predict the temperature field as well as the displacements of the cutting tool due to the thermal effects, a simulation model is developed in virtual environments. As a result, errors of machining operation can be corrected in order to increase accuracy of part manufacturing by using simulated air-cooled milling machine tools in virtual environments.

Machine tool elements are simulated in virtual environments by Marin et al. (Marin et al. 2015) in order to analyze and modify machine tool configuration. So, the system can help machine tool designers by providing appropriate reconfiguration methods in order to make better decisions in designing process of machine tool elements.

A virtual machining system is presented by Cao and Altintas (Cao and Altintas 2007) to model spindle-bearing as well as machine tool elements. Rotating shaft, tool holder, angular contact ball bearings, housing and the machine tool mounting are also simulated in the virtual machining system to create virtual cutting from actual machining process. The system can predict bearing stiffness, mode shapes, frequency response function, static and dynamic deflections along the cutter and spindle shaft and contact forces on the bearings using calculated cutting forces in virtual environments. Finite element models of spindle-bearing as well as machine tool system are also presented in virtual environments to accurately analyze effects of forces to the elements of cutting tool, holder, shaft and spindle. Elastic model of the bearing elements such as housing, outer ring, inner ring and balls under dynamic forces are presented in the study to simulate spindle bearing in the system. As a result, stability of the machine tool as well as chatter can be predicted and prevented by using the virtual machining system in order to increase accuracy of part manufacturing.

Shneor et al. (Shneor, Chapsky, and Shapiro 2018) presented application of virtual machining system in virtual inspection of produced parts by 5-axis CNC machine tools in order to verify machine tool accuracy performances. So, accuracy of machine tools can be analyzed and increased by using the presented virtual machining system in the study.

A virtual machining system is developed by Yanwei et al. (Yanwei et al. 2008) in order to simulate spiral bevel gear of milling machine tools in virtual environments. So, an improvement in designing procedures of the machine tool elements can be achieved in order to increase efficiency of part manufacturing. Modeling and simulation of Z axis in a five axis machining center for high-speed milling operations is presented by Tani et al. (Tani et al. 2005). The modeling procedures such as finite element method, modeling of the mechanical structure, a concentrated parameter model of the kinematics of the axis, a set of algebraic and logical relations to represent the loop CNC-Z feed drive, an equation set to represent the functioning of the pneumatic system and a specific analytical model of the friction phenomena occurring between sliding and rotating mechanical components are used in the study to present the dynamic behavior of the entire Z axis. As a result, the simulated element of machine tools in virtual environments can improve designing procedures of machine tool elements in order to improve efficiency of part manufacturing.

Functional accuracy of work-holding rotary axes in five-axis CNC machine tools is investigated by Nojedeh and Arezoo (Nojehdeh and Arezoo 2016). Cycling error motions of work-holding rotary axes in radial fixed sensitive direction setup is considered in the study in order to present possible error patterns. A virtual cutting module equipped with an error-mapping model is also presented in the study to simulate the cutting process in vicinity of different error motion scenarios. So, the errors are simulated and studied in virtual environment to increase accuracy of part production using five-axis CNC machine tools.

3.12. Increasing accuracy of produced parts

A voxel-based simulator for five-axis CNC machine tools using virtual machining system is presented by Jang et al. (Jang, Kim, and Jung 2000) in order to accurately calculate material removal rate in milling operations. The voxel representation is used in the study to simulate five-axis milling operations in virtual environment. So, volume of computational works for regularized Boolean set operations as well as material removal rates are reduced by using the developed system in the study. The feed rate along machining paths can be adaptively adjusted by using the presented material removal rate based on number of removed voxels in machining operations. Consequently, an advanced virtual machining system in five axis machine tools is presented in order to increase efficiency of part manufacturing.

To predict and analyze errors of machined surfaces in peripheral end milling process, a virtual machining system is developed by Yun et al. (Yun, Ko, Cho, et al. 2002). To obtain error maps of machined surfaces, uncut chip thickness for each position of cutting tool along machining paths are calculated by using estimated cutting forces in virtual environments. Peak and valley values of the cutting force component normal to the machined surface are also obtained to analyze machined surface errors. Thus, errors of machined surfaces can be accurately predicted by using the presented virtual machining system in the study to decrease time and cost of accurate production.

In order to integrate machine tool error models in machining process of sculptured surfaces, a virtual machining system is developed by Lin and Shen (Lin and Shen 2004). The machine tool geometric errors are also predicted in the study from the simulated model of machine tool in virtual environments. To translate machine geometric errors into part geometry errors for sculptured surfaces of machined parts, the solid modeling approach as well as the surface modeling approach are used in the study. Thus, the final part geometry errors are obtained by subtracting the tool swept volume from the stock geometric model using the solid modeling approach. The actual cutter contact points by calculating the cutting tool motions and geometries are obtained by using the surface modeling approach. As a result, part geometry errors in sculptured surface of machined parts can be effectively predicted and modeled by using presented virtual machining system in order to be analyzed and eliminated.

An advanced virtual machining system is developed by Ratchev et al. (Ratchev et al. 2003) in order to predict and compensate surface errors due to deflection error in machining of low-rigidity components. The proposed approach is based on modeling of material removal process in virtual environment in order to predict and correct the part deflection.

An application for virtual machining system is developed by Soori et al. (Soori, Arezoo, and Habibi 2017) in order to analyze accuracy of tool deflection error modeling in prediction of milled surfaces. A comparison for different methods of tool deflection error such as cantilever beam model of the cutting tool, Finite Element Method (FEM) of the cutting tool and workpiece and geometrical model of the cutting tool effects on the workpiece is presented to show accuracy as well as reliability of the methods in prediction of milled surfaces. As a result, capabilities and difficulties of the different methods in the error modeling are presented by using a virtual machining system to increase accuracy as well as efficiency of part manufacturing.

3.13. Collision detection systems

A collision detection methodology based on dynamic graph structures is developed by Luo et al. (Luo et al. 2002) to improve efficiency of collision detection systems in milling operations. In order to create a real time dynamic workpiece, the system is defined as a graph with categorized vertices as well as dynamic edges. To decrease volume of computational works for collision checks, all virtual objects are approximated as cylindrical and cubic descriptions. Then, they are initially categorized into three kinds of virtual objects as dynamic, motion and static to be analyzed and modified. In order to present a virtual workpiece, material removal rate in machining operations is considered as an effective parameter to the raw material of the workpice. To present dynamic workpiece, dimensions of workpiece for each position of cutting tools along machining paths influenced by removed materials are calculated for each machining axis of machine tool. Fig. 16 shows representation of a dynamic workpiece in milling process (Luo et al. 2002).

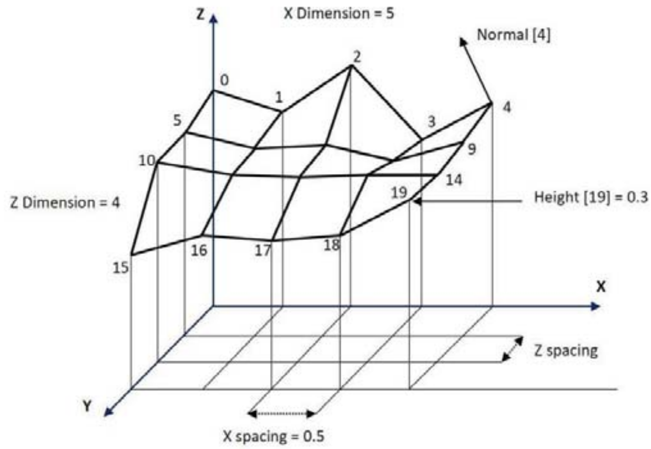

Fig. 16. Representation of a dynamic workpiece in milling process (Luo et al. 2002).

Therefore, a useful method in process of collision detection is presented in the study in order to increase safety of machining operations. Moreover, a virtual workpiece based on the material removal rate in milling operations is presented in the study to increase accuracy of part production.

A 3D vision system for simulation of machining setups in virtual environments is developed by Zhang et al. (Zhang, Tian, and Yamazaki 2010) to present a collision detection system. As a result, 2D edge feature detection algorithm is designed in the system in order to extract the edges of the machined part by processing the real and virtual images. Then, a stereo vision system is developed to obtain the three-dimensional (3D) edge data of the workpiece in order to determine the contacts of cutting tool and workpiece. As a result, an advanced collision detection system using virtual machining is presented in the study.

A virtual machining system for automatic checking of machining setup is developed by Karabagli et al. (Karabagli, Simon, and Orteu 2016) to present a collision detection system. This computer vision system utilizes a single camera to automatically check actual machining set-up with the desired 3D CAD model before the start of machining operation. Thus, a virtual machining system is presented to detect collision between tool and machining set-up components.

Mei and Lee (Mei and Lee 2016) developed a virtual machining system to increase efficiency of the collusion detection process in milling operations as well as robot arms. Lee and Ren (Lee and Ren 2011) developed a virtual machining system to simulate and evaluate cutting tool paths in term of collision detection process. To develop collision detection process in multi-axis milling machining operations, a virtual machining system is developed by Ilushin et al. (Ilushin et al. 2005). A virtual machining system is presented by Lee and Lee (Lee and Lee 2001) to develop a collision detection system in five axis milling operations. Additionally, in order to develop collision detection systems in milling operations, geometric modeling of material removal processes in virtual environments is presented by Chiou (Chiou 2007).

4. REVIEW OF RESEARCH WORKS RELATED TO VIRTUAL MACHINING SYSTEMS FOR CNC TURNING MACHINE TOOLS

In this section, papers related to virtual machining systems for CNC turning machine tools dated from 1997 to 2013 are reviewed. Due to capabilities of milling operations, sophisticated parts with different complexities can be produced by the part production method. As a result, more research works are presented in the milling operations in comparison to the turning operations. To create precision optic devices, creating actual machined parts in virtual environments, machining parameters optimization, virtual inspection systems and virtual training systems, the papers are reviewed in the section 4.

A virtual machining and inspection system in turning operations is presented by Cheung and Lee (Cheung and Lee 2001) to create precision optic devices in virtual environments. To optimize functional performances of optic devices such as surface roughness and form accuracy, different modules such as Information, optics design and optimization, virtual machining, virtual inspection, analysis and decision-making and performance evaluation and monitoring are designed in the presented system. A tool path generator is designed in the virtual machining module to generate original NC codes for machining operations of optic devices. To obtain errors of machining process in virtual environments, modules of error generation, workpiece and cutting tool and surface topology are created. Thus, a useful devise in manufacturing of precision optics devices by turning operations is presented using virtual machining system to increase accuracy of produced parts.

To create actual machined parts in virtual environments, a virtual turning system is developed by Li et al. (Li et al. 2005). To simulate workpiece in virtual environments, polygons are generated by non-linear curves instead of linear segments with regard to a given accuracy which are called Generator Polygon (GP). The method of using GP to represent a revolution workpiece is called Generator Polygon Representation (GP_Rep) which is simple and flexible method to simulate workipece in virtual environments. So, volumes of computational works in terms of workpiece simulation are decreased by using the method of transforming complex 3D solid into simple 2D polygon. To simulate machining process in virtual environments, material removal rate is simulated by using method of 2D clipping operations between polygons. Fig. 17 shows algorithm of material removal simulation (Li et al. 2005).

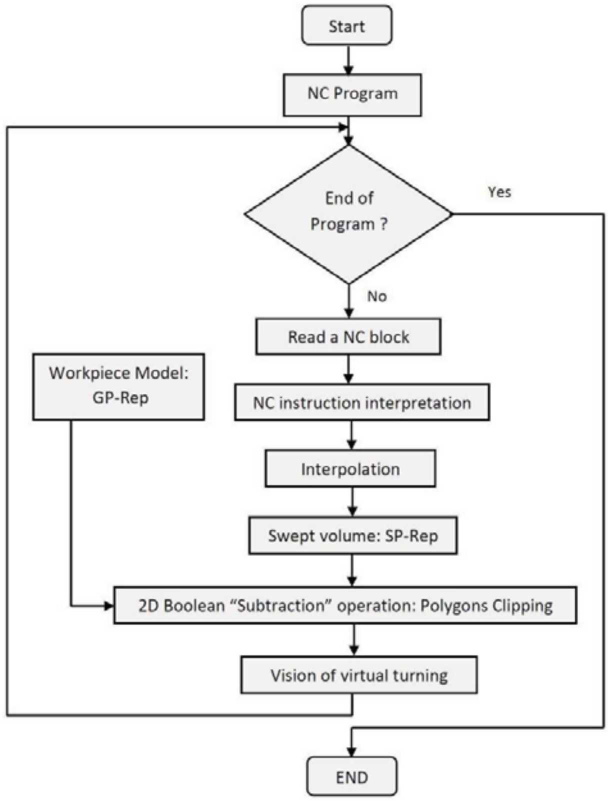

Fig. 17. Algorithm of material removal simulation (Li et al. 2005).

Geometrical, kinematic, thermal and spindle errors are considered to create actual machined parts in virtual environment. A surface topography simulation model is designed in the presented virtual machining system to simulate and analyze profiles of actual machined parts. Consequently, a developed virtual machining system is presented to improve accuracy of part manufacturing by simulating actual machined parts in virtual environments.

To create virtual workpiece with machining errors in virtual environments, a virtual machining system in turning operations is presented by Yao et al. (Yao et al. 2006). Trajectory and attitude errors of cutting tool in turning operation such as kinematic errors along Z axis are calculated in the system to analyze effects of the errors to the workpiece. Also, a surface topography simulator is designed in virtual environments to generate surface finish profiles after turning operations. As a result, the virtual machining system in turning operations can simulate actual machined workipece in virtual environment to increase accuracy of part manufacturing.

Computer-integrated optics design and tool path generation in turning operations using a virtual machining of aspheric surfaces is presented by Lee et al. (Lee et al. 2003). Computer aided optics design system in virtual environments is presented in the study to simulate, evaluate and optimize performances of the optical devices. To increase accuracy of produced optical devices, optimized design as well as machining parameters can be calculated. Finally, NC codes of machining operation are modified by the presented system in the study to achieve more accuracy as well as efficiency in manufacturing process of optical devices. An optimization paradigm based on genetic algorithms for the determination of the cutting parameters in turning process is proposed by D'Addona and Teti (D'addona and Teti 2013).The genetic algorithm is used in the study in order to obtain optimal cutting parameters in turning operations. A review in applications of the genetic algorithm in virtual machining systems is developed by Jameel et al. (Jameel, Minhat, and Nizam 2013) to optimize the machining parameters in turning operation. To optimize process parameters in turning operations, a virtual machining and inspection system is developed by Lee et al. (Lee et al. 2007).

In order to increase efficiency of part production, Arif et al. (Arif, Stroud, and Akten 2014) developed a virtual machining system to optimize effective parameters in turning operations. Online machining optimization with continuous learning using a virtual machining system in turning operations is presented by Chandrasekaran et al. (Chandrasekaran et al. 2012). To minimize cost of machining operation, a fuzzy optimization method is used in the study in order to determine optimum process parameters. As a result, efficiency of part production can be increased by the presented virtual machining system in the study.

To create profiles of actual machined parts in virtual environment, a virtual machining and inspection system in turning operations is presented by Ramaswami (Ramaswami 2010). Effects of the errors in a turning machine tool such as static errors inherent in turning center, the error in spindle motion, machine vibrations, tool geometry, process parameters and tool wear on the profiles of machined parts are modeled and analyzed in the system. Then, to determine portion of each error in accuracy of produced parts, various dimensional as well as geometrical parameters of modeled surfaces such as form error, size, run out and orientation tolerances are analyzed and modified. Various inspection strategies such as number of sample points, sampling method and location of part on the CMM table are analyzed and modified using the developed virtual inspection system. Thus, a useful device in accuracy analysis of produced parts in turning operations using virtual machining system is presented in the study.

The procedures of the virtual machining and inspection systems are shown in the Fig. 18 and Fig. 19 respectively (Ramaswami 2010).

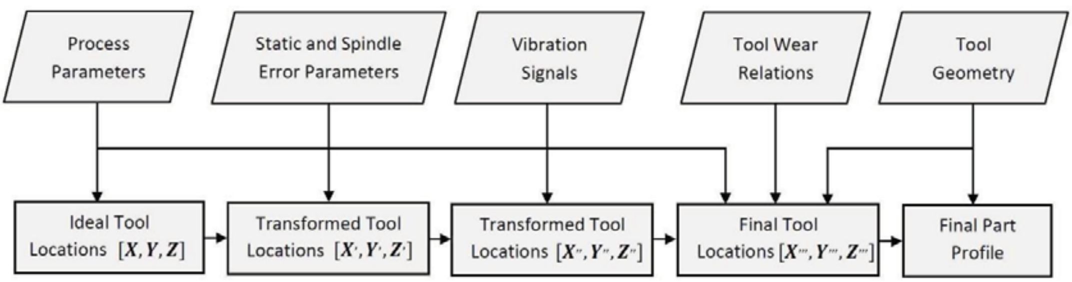

Fig. 18. Procedure of the virtual machining system (Ramaswami 2010).

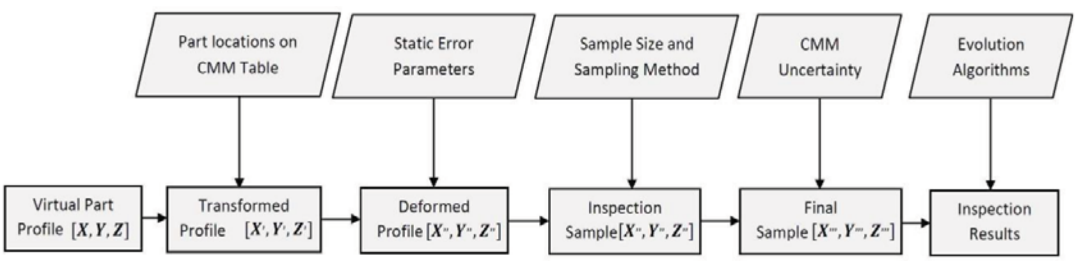

Fig. 19. Procedure of the virtual inspection system (Ramaswami 2010).

Boer et al. (Boer et al. 1997) presented an integrated virtual machining system for education as well as training programs in turning operation. A virtual machining system is developed by Chang (Chang 2010) in order to be used in training programs of turning operations. Thus, machining experiences of novice operators can be increased by the presented system in the study without the need of shop floor testing.

5. REVIEW OF RESEARCH WORKS RELATED TO VIRTUAL MACHINING SYSTEMS FOR CNC TURN-MILL MACHINE TOOLS

In this section, papers related to virtual machining systems for CNC turn-mill machine tools dated from 1998 to 2016 are reviewed. Other methods of part production such as grinding and boring are also presented in this section. To optimize machining parameters, possibility of chatter along cutting tool paths, analyzing and modifying machine tool elements, virtual process planning systems, Internet-Based virtual CNC milling systems, virtual training systems virtual inspection systems and collision detection systems, the papers are reviewed in the section 5.

Virtual process systems for part machining and grinding operations are presented by Altintas et al. (Altintas et al. 2014). To simulate machining operation in virtual environments, several algorithms of tool–workpiece-engagement such as solid-model-based systems, wire-frame-based systems, voxel-, dexel-, and Z-buffer-based systems, Point-based methods and analytical methods are discussed with regard to accuracy of the obtained results as well as computational works. Metal cutting process models such as mechanics of orthogonal cutting as well as oblique cutting are investigated in the study to simulate material removal process in virtual machining system. Then, effective parameters to chip thickness in material removal process such as a function of feed, tool geometry, kinematics of machining operation and relative vibrations between cutting tool and workpiece are also calculated in turning, boring, drilling and milling operations. Metal cutting process in grinding operations is simulated in virtual environments by calculating cutting forces for engagement sections of grinding well and workpiece along machining paths. To model dynamics of the machine tool elements, the rigid body kinematics, CNC system and structural dynamics of the multi-axis machine system are simulated. Possibility of chatter along cutting tool paths are studied in order to be decreased by selecting optimized machining parameters such as depth of cut, width of cut and spindle speed. To improve efficiency as well as accuracy in part production, an optimization strategy based on the process physics is proposed in the study to determine the most efficient machining parameters such as speeds, feed rates and depths of cut. Then, modified NC codes according to optimized parameters of machining are generated by the presented system. Thus, a developed virtual machining system is presented in the study to analyze and optimize machining process in virtual environment. A digital machining system is presented by Li and shin (Li and Shin 2009) to simulate dynamic machining process in milling, turning, boring and grinding operations. Probability of chatter in machining operations.is evaluated in the system in order to be decreased.

An overview of parts digital machining in virtual environment is presented by Altintas (Altintas 2016). Several different modules such as Cutter-workpiece engagement, CNC and machine tool definition, cutting tool definition, work material data base, process simulation engine and process optimization engine are designed in the system to simulate machining process in virtual environment. Consequently, a useful devise is presented in the study to the process planners in order to increase accuracy as well as efficiency of part manufacturing by using virtual machining system. Also, milling and turning operations are simulated in virtual environments by Dubovska et al. (Dubovska, Jambor, and Majerik 2014) in order to be analyzed and optimized. So, efficiency of part production can be increased by the presented virtual machining system in the study. To increase efficiency of part manufacturing, a virtual machining system is developed by Pelliccia et al. (Pelliccia et al. 2016) to optimize energy consumption of milling and turning machine tools.

To provide an optimized procedure in machine tool design, virtual design of machining centers is presented by Fortunato and Ascari (Fortunato and Ascari 2013). Kinematics of machine tools elements such as linear and rotational controlled axis as well as ball screw are modeled by differential equations with regard to degrees of freedom in moving paths. Then, an input – output interface is designed in presented system to select proper design parameters such as total inertia, torsional stiffness of screw, toothed belt stiffness, preload of the nut and bearings and friction coefficients. Finally, simulated elements of machine tools are optimized in the system in order to present optimized techniques in machine tool design.

An advanced axis control system in CNC machine tools using virtual simulation is presented by Susanu and Dumur (Susanu and Dumur 2004). So, a generalized predictive control system for machine tool feed drive is designed in virtual environment to be analyzed and modified. Different axis control strategies of CNC machine tools are compared in the study to present capabilities and difficulties of the methods in controlling of machine tool axis. Thus, a useful device in axis control systems of CNC machine tools is presented in the study using virtual machining system.

An integrated haptic virtual machining environment for automatic generation of process plans is developed by Fletcher et al. (Fletcher et al. 2013). A haptic virtual process planning system is presented in the study to simulate combined machining processes for 2.5D-axis milling machine tools, center lathe and pillar drill machine tools. Loading billet of a predefined size, workpiece clamping in position, carrying out a sequence of cutting operations in real time, workpiece clamping and log in for a new machining process are also designed in the automatic process planning system. So, an advanced device in process planning of part manufacturing is presented in the study to increase efficiency of part manufacturing.

A web-based virtual CNC turn-milling system is developed by Zhu et al. (Zhu et al. 2015) in order to enable process planners to accurately generate NC codes in milling and turning machine tools. Material removal function, tool trajectory planning function, numerical control (NC) code inputting and compiling function are designed in the system to increase accuracy as well as efficiency of process planning in part manufacturing.

A virtual machining based training system for CNC machine tools is presented by Yao et al. (Yao, Li, and Liu 2007). Practical skills as well as problem troubleshooting techniques are used in the study to improve quality of training programs. To simulate actual machining process in virtual environments, procedures as well as algorithms of the training virtual machining system are described. Finally, several digital NC machining training systems are developed in the study to prepare an advanced virtual training system for novice operators.

Dynamic models of a CNC machine tools and cutting process in machining operations are simulated in virtual environments by Ebrahimi and Whalley (Ebrahimi and Whalley 1998). Simulated elements of machine tools are analyzed and modified by using the FEM method as well as dynamic simulator programs. To calculate cutting forces, cutting process is simulated as the interacting phenomena between the spindle and feed axes by considering dynamic deflection of the elastic parts. Then, computer aided control system design, computer aided multi–body dynamic and finite element modeling are applied to the simulated machine tools elements in virtual environments to be analyzed and modified. As a result, an advanced design of machine tool elements can be obtained by using presented virtual machining system in the study.

To increase efficiency of part manufacturing, virtual inspection system in machining operations is presented by Siemiatkowski and Przybylski (Siemiatkowski and Przybylski 2006).
To develop a collision detection system by generating safe and intelligent cutting tool paths for multi axis milling and turning machine tool operations, a virtual machining system is developed by Ahmad et al. (Ahmad, Tichadou, and Hascoet 2016). A web-based virtual system is developed by Yu et al. (Yu et al. 2013) to analyze material removal rate, NC codes compiling and collision detection in turning and milling machine tools.

6. CONCLUSION

This paper presents a review for virtual machining systems from published papers dated from 1995 to 2018 for CNC milling and turning machine tools. So, recent achievements from published papers are presented as a review paper to provide new ideas for future research works in the field of study. To simulate cutting processes in virtual environments, cutting forces are modeled by using mathematical concepts. Dimensional and geometrical errors as well as tool deflection error of cutting tool are modeled in order to be simulated in virtual environments.
Errors of actual machined parts are simulated in virtual environments to be analyzed and corrected. The simulated errors in virtual environments are compensated in order to increase accuracy of part manufacturing. Surfaces of simulated actual machined parts in virtual environments can be analyzed by using virtual machining system. Actual machined parts are simulated in the virtual environments by considering errors of part production in order to be analyzed by virtual machining system. Internet-Based and web-Based virtual CNC machining systems are presented in order to analyze actual machining processes by using a network. The virtual machining can be used in error monitoring systems in order to be analyzed and decreased in virtual environments. Virtual machining systems in 5-Axis CNC machine tools are presented to analyze and modify machining operations of sophisticated parts in virtual environments.
Feed rate scheduling systems based on virtual machining are presented in order to increase accuracy and efficiency of part manufacturing. Cutting tool paths are optimized in order to increase accuracy and efficiency of part manufacturing using virtual machining system. Errors of machining operations can be decreased by applying optimization methods to the simulated machining processes in virtual environments. Machine tool elements can be simulated in the virtual environments to provide an effective device in analyzing and modifying machine tool elements. Thus, designing procedures of machine tool elements can be modified by analyzing and optimizing simulated machine tool elements in the virtual environments.
The virtual machining system can be used in analyzing effects of manufacturing process errors by the Finite Element Method (FEM) to analyze stress and strain of actual produced parts as well as machine tool elements in virtual environments. Therefore, accuracy as well as reliability of part manufacturing can be improved by analyzing residual stress in produced parts. To increase accuracy as well as efficiency of part manufacturing, simulated machining processes in virtual environments can be analyzed in order to obtain optimized machining parameters.
The virtual machining system can be used in process planning of part production by considering the most suitable steps of machining operations with regard to the time and cost of part manufacturing. So, efficiency of machining operations can be improved by applying process planning methodologies to simulated machining processes in virtual environments. Machining operations of workpieces with thin-walled structures and flexible materials can be analyzed in virtual environments in order to increase accuracy of part manufacturing. The actual machining operation can be simulated in virtual

environments in order to be used as a virtual machining training system. So, the operators can be trained by the system without the need of physical machining operations.
The simulated machining process can be used in terms of collision detection process in order to be detected and prevented. As a result, more safety in machining processes can be achieve by analyzing machining paths in terms of collision detection process using virtual machining systems. Possibility of chatter along cutting tool paths in machining operations can be predicted by developed virtual machining system in order to be analyzed and decreased. Virtual inspection system can be used to evaluate accuracy of simulated actual machined parts in virtual environments. As a result, accuracy of produced parts as well as efficiency of part manufacturing can be increased by analyzing simulated actual machined parts in virtual environments. Material removal rate in machining operations of complex surfaces can be simulated in virtual environments in order to be analyzed and optimized. Energy of machine tool can be analyzed and optimized in order to increase efficiency of part manufacturing by virtual machining systems.
The presented research works prove that virtual machining systems are effective and powerful devices for increasing accuracy as well as efficiency of part manufacturing. Flexibility, adaptability and analysis power are some advantage of these systems by applying virtual environments to manufacturing processes. Optimization methods as well as finite element analysis can develop the applications of virtual machining systems in machining operations to increase efficiency of part production. As a result, more added value can be achieved using the developed virtual machining systems in machining operations. From the view point of the authors, machining operations will be developed in future by expanding influences of virtual machining systems in part manufacturing processes.

7. FUTURE RESEARCH WORKS

Applications of virtual machining systems in part manufacturing process are expanding to predict and analyze real working conditions in virtual environments. To increase accuracy as well as efficiency of part manufacturing, the research issue is developing by using mathematical concepts and programming languages to find the best solution for many problems and challenges of machining operations. Although a significant amount of works are presented in the field, but there are a lot of remaining issues of research works for accuracy analysis as well as optimization procedures in manufacturing processes using virtual machining systems.
Free form surfaces of workpieces can be simulated and analyzed in virtual environments. Machining strategies of the surfaces can be analyzed and optimized to improve the accuracy of part manufacturing. The machining strategies can be analyzed and modified in virtual environments in terms of collision detection processes. As a result, machining errors can be decreased by using modified version of machining strategies in machining operations of free form surfaces using 5-axis CNC machine tools. Vibrations of machine tools as well as possibility of chatter along cutting tool paths in machining operations can be analyzed by using simulated machining operations in virtual environments.
Virtual inspection systems can also be applied to the simulated parts in virtual environments in order to increase accuracy of part production. Experiences and knowledge of machining scientists can be analyzed and modified by using mathematical concepts to find the best machining strategies in manufacturing process of sophisticated parts to present an advanced Computer Aided Process Planning (CAPP).

To increase the experiences of novice operators in machining operations of complex surfaces using 5-axis CNC machine tools, more advanced versions of virtual environments should be developed for the training programs. So the cost and time of accurate production can be decreased by using the developed virtual machining systems. To increase the added value of part production processes, energy consumption of machine tool elements such as electric motors, pumps and moving axis can be simulated and analyzed in virtual environments. Process planning of part production can be optimized by analyzing and modifying in virtual environments. As a result, efficiency of the process planning of sophisticated workpices such as 5-axis CNC machining operations can be increased by using the developed virtual machining systems.

Geometry of cutting tools can be analyzed and modified as a result of simulated cutting forces in virtual environments. To decrease cutting forces at each edge of cutting tool, 3D simulation of actual machining processes in virtual environments can be used. Direction of chip flow in cutting tool can be simulated in virtual environments to be analyzed and managed. Machining times as well as surface roughness can be minimized and tool life can be maximized as a result of decreasing cutting forces by using the modified geometries of cutting tools. The modified versions of cutting tool geometries with regards to minimizing cutting forces can decrease the cost of cutting tools by presenting a wider range of acceptable materials for cutting tools in machining operations. So, the most suitable cutting tool for each condition of machining operations can be properly designed. New material of cutting tools can be simulated and analyzed in virtual environments. Thus, tool deflection error of new cutting tools along machining paths can be studied without the need of actual machining operations. The generated heat in the cutting tools and workpieces can be simulated in virtual environments in order to be analyzed and decreased and hence the tool life can be maximized.

The amount of coolant can be properly managed with regards to the cutting forces as well as generated heat. Failure of cutting tools and tool life can also be predicted by using the virtual machining system in order to increase efficiency of part manufacturing. Also, cutting tool wear can be analyzed in order to be modified with regards to actual working conditions. So, the virtual machining systems can be used for developing cutting tools in advanced machining operations. Deformation and deflections of large workpieces can be simulated and analyzed in virtual environments.

Machining operations of expensive materials such as gold as well as super alloys can be simulated in virtual environments to predict real machining conditions without the need of shop floor testing. Experiences as well as capabilities of different virtual machining systems can be shared in the web to increase efficiency of part production. 3D vision of machining operations with errors of actual machined parts and tool deflection error in virtual environments can help designers as well as machining strategists to analyze and modify the process of part production.

Virtual machining systems can be used in terms of programming strategies for automated machining operations such as machining codes, robotic arms for loading and unloading workpices on machine tool bed, automated cutting tool changing and controlling systems of machine tools with regards to the desired accuracy of part production. To increase the efficiency of part production, feed rates as well as depth of cut can be dynamically and effectively managed with regards to the power of machine tool, workpiece material and cutting tool, time and cost of machining operations.

More elements and structures of machine tools can be simulated in the virtual environments in order to be analyzed and modified. As a result, optimized versions of machine tool elements can boost levels of technology in part manufacturing. The system can be used in prediction of deflection error in machining operations of flexible parts such as turbine blades in order to increase accuracy of part production.

Finite element analysis of produced parts can be applied to the virtual machining systems in order to modify performances of produced parts in actual working conditions. Machining operations of new alloys can be simulated in virtual environments in order to be studied. Thus, deformation, surface properties of produced parts with new alloys can be analyzed and modified. Residual stress due to machining operations of sophisticated parts such as gas turbine blades can also be analyzed in virtual environments in order to be minimized. Decision making for the most suitable cutting tool and machine tool selection regarding the machining conditions is another future research work in the field of virtual machining systems. Surface roughness quality of produced parts can be predicted and analyzed in order to be modified with regards to desired designing conditions.

Modified fixtures and clamps can also be designed in virtual environments in order to increase accuracy of part production. Developed virtual machining systems can be connected together via internet in order to increase efficiency of part manufacturing by sharing machining knowledge. So, more added values can be achieved by using machining knowledge of different scientists in order to boost level of manufacturing technology in future of production engineering. The authors suggest that the section will be discussed by the other researchers in the future to be developed as well as possible.

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