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Original scientific paper

MINIMIZATION OF DEFLECTION ERROR IN FIVE AXIS MILLING OF IMPELLER BLADES

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Abstract. *The 5-axis CNC machine tools are used for manufacturing free form surfaces of sophisticated parts such as turbine blades, airfoils, impellers, and aircraft components. The virtual machining systems can be used in order to analyze and modify the 5-axis CNC machine tools operations. Cutting forces and cutting temperatures induce deflection errors in thin-walled structures such as impeller blades through machining operations. Thin-walled impeller blades' flexibility can result in machining errors such as overcutting or undercutting. So, decreasing the deflection error during machining operations of impeller blades can achieve the desired accuracy in produced parts. Optimized machining parameters can be obtained to minimize the deflection of machined impeller blades. In terms of precision and efficiency enhancement in component production processes, a virtual machining system is developed to predict and minimize deflection errors of 5-axis milling operations of impeller blades. The deflection error in machined impeller blades is calculated by using finite element analysis. The optimization methodology based on the genetic algorithm is applied to minimize the deflection error of impeller blades in machining operations. To validate the integrated virtual machining system in the study, the impeller is milled by using a 5-axis CNC machine tool. The CMM machine is used in order to measure and analyze deflection error in the machined impeller blades. As a result, by using the developed virtual machining system in the study, accuracy and efficiency in 5-axis milling operations of impellers can be increased.*

Key Words: *Deflection Error, Impeller, 5-Axis CNC Machine Tools, Virtual Machining*

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1. INTRODUCTION

In order to increase machining performance, virtual machining systems are recently introduced to the process of part manufacturing using CNC machine tools. The systems will reach into the development process of machining operations. Virtual machining systems can be built into machining process optimizations to increase efficiency in milling processes. To minimize deflection error in machining operations of thin-walled element, optimization techniques can be implemented to obtain optimized machining parameters. So, virtual machining systems can be applied to develop the part manufacturing by using CNC machine tools in order to increase added value in the processes of part production.

The integral impeller and bladed disk are extensively used in various aircraft jet engines. Jet engine components are produced with a high degree of precision and reliability by considering the aviation safety issues to present a good performance in working environments. Machining operations of sophisticated parts with free form surfaces, such as impeller blades are implemented by using 5-axis CNC machine tools. The high precision required in 5-axis machining operations of complex parts like jet engine impeller blades is filled with complexities and complications. So, to increase accuracy and efficiency in 5-axis milling operations of free form surfaces, the process of part production is investigated by indifferent research works. Cutting forces and cutting temperature induce deflection error during machining of thin-walled structures like impeller blades. Thin-walled impeller blades' flexibility can result in machining errors such as overcutting or undercutting. As a result, deflection error in machined parts can cause inaccuracy, which should be analyzed and minimized. Thus, a virtual machining system which can analyze and minimize deflection error in 5-axis machining operations of thin-walled impeller blades can provide an effective device to increase the accuracy and efficiency in the process of part production.

Zhao et al. present a method for assessing milling accuracy of thin-walled narrow-vane turbine impellers made of NiAl-based superalloys in order to increase the precision and reliability of machined turbine impellers [1]. Huang et al. developed an optimization algorithm for the cutting tool direction in order to reduce friction and deformation in ball-end milling of thin-walled impeller blades [2]. Chaves-Jacob et al. present an efficient strategy for finishing operations in the final phase of the machining program to enhance precision in 5-axis machining operations of impeller blades [3]. Huang et al. examine and reduce machining operations errors in 5-Axis adaptive flank milling of thin walled impeller blades to integrate the method of machining operations of flexible components [4]. Liu et al. analyze an improved technique to predict the deflection error in milling thin-walled impeller blades in order to evaluate and reduce the deflection error [5].

The application of Homotopy Analysis Method is presented by Zargar et al. to determine the thermal response of convective-radiative porous fins with temperature-dependent properties [6]. Dynamical behavior of the vehicle structure is optimized by Zargar et al. to obtain vehicle dynamic characteristics such as natural frequencies and mode-shapes [7].

Khandagale et al. evaluate the quantitative methods of the thin-walled workpiece to minimize the deflection error in milling operations of flexible parts due to cutting forces [8]. In order to enhance machined component precision, Kang and Wang present an effective way of deflection error prediction in peripheral milling of thin-walled workpieces [9]. Del Sol et al. analyzed milling operations of light alloys with thin walled structures to eliminate deflection errors caused by instability and deformation in machined components [10].

Bolar and Joshi investigate the impact of cutting tool variables such as tool helix angle on the precision and efficiency of machined parts in terms of precision enhancement of machined parts using milling operations [11]. To minimize deflection errors in machined components, De Oliveira et al. explored the impact of machining parameters on surface roughness and shape errors in 4-axis milling of thin-walled free-form parts [12].

Bolar and Joshi present an efficient statistical modeling system to model and analyze cutting tool and workpiece deflection error in machining operations of low rigidity thin walled components [13]. To compensate and reduce deflection error in thin walled component during flank milling operations, Li and Zhu constructed an advanced cutting tool path optimization approach [14]. To improve the surface precision and reliability of machined impellers using 5-axis CNC machine tools, Wang et al. present an integrated machining parameters optimization system [15]. To increase surface properties of machined thin walled parts by reducing workpiece deformation errors, Ratchev et al. investigate an integrated machining parameter optimization method [16].

Soori et al. expressed virtual machining systems and applications to evaluate and modify machining operations in virtual environments [17-22]. Altintas and Merdol also introduce a virtual machining method and application in order to obtain excellent milling conditions [23].

An innovative virtual machining system is proposed in the study to predict and minimize deflection errors in 5-axis milling operations of thin-walled impeller blades. By measuring the cutting forces and cutting temperatures at each position of the cutting tool along machining paths, a virtual machining is developed to predict and minimize the deflection error of machined thin-walled impeller blades. The deflection errors in the machined impeller blades are calculated by using Finite Element Analysis (FEM). To attain the optimized machining parameters, an optimization technique based on the genetic algorithm is performed in order to minimize the deflection error. To validate the effectiveness of the established virtual machining system in the research work, machining operations of the sample impeller blades are milled by using a 5-axis CNC milling machine tool. The machined impellers are then measured by using CMM machine in order to obtain and analyze the deflection error. Thus, by using the developed methodology in the study, accuracy and efficiency in 5-axis machining operations of impellers can be enhanced.

Sections 2 and 3 discuss the equations for obtaining the cutting forces in milling operations of thin-walled parts, and cutting temperature calculation. Section 4 describes the deflection error of thin-wall workpieces during machining operations. In Section 5, the developed virtual machining system to predict and minimize the deflection error is discussed. Eventually, Section 6 is presented to validate the integrated virtual machining system in order to minimize the deflection error of machined impeller blades.

2. Cutting Force Model in Milling Operations of Thin-Walled Parts

The cutting force theory proposed by Li et al. is used to determine cutting forces in 5-axis machining operations of thin walled components. [24].

A moving feed coordinate will be used to identify the cutting tool position of the (CL) as,

$$x_f = \frac{y_f \times A(u)}{\|y_f \times A(u)\|},\ y_f = \frac{A(u) \times \acute{p}(u)}{\|A(u) \times \acute{p}(u)\|}, z_f = A(u), \tag{1}$$

where $\acute{p}(u)$ is the feed vector at the cutting tool tip which is due to guiding curve $P(u)$. Moreover, x_f is described in the plane defined by the feed direction and axis vectors of cutting tool along machining paths and y_f is normal to this obtained plane. Also, $A(u)$ presents the unit vector along the cutting tool axis [24],

$$A(u) = \frac{Q(u)-P(u)}{\|Q(u)-P(u)\|} \tag{2}$$

The cutting entering angle can be presented as [24],

$$\theta'_{en,ij} = \theta_{ex,ij} - \text{acos}\,(\frac{\delta_{t,ij}+\delta_{w,ij}+R_{ij}.Cos(\theta_{ex,ij}-\theta_{en,ij})}{R_{ij}}) \tag{3}$$

where $\theta_{en,ij}$ is the entry angle of the cutting tool along machining paths, $\delta_{t,ij}$ and $\delta_{w,ij}$ are the deflection errors of the cutting tool and workpiece for the normal direction of the i_{th} cutter element surface on the j_{th} flute of the cutting tool, respectively. Moreover, R_{ij} is the rotation radius of the i_{th} cutter element on the j_{th} flute of the cutting tool. In five-Axis milling operations of thin-walled components, the cutting tool is within the cutting entry angle for the i_{th} cutting portion of the cutting tool as shown in Fig. 1 [24].

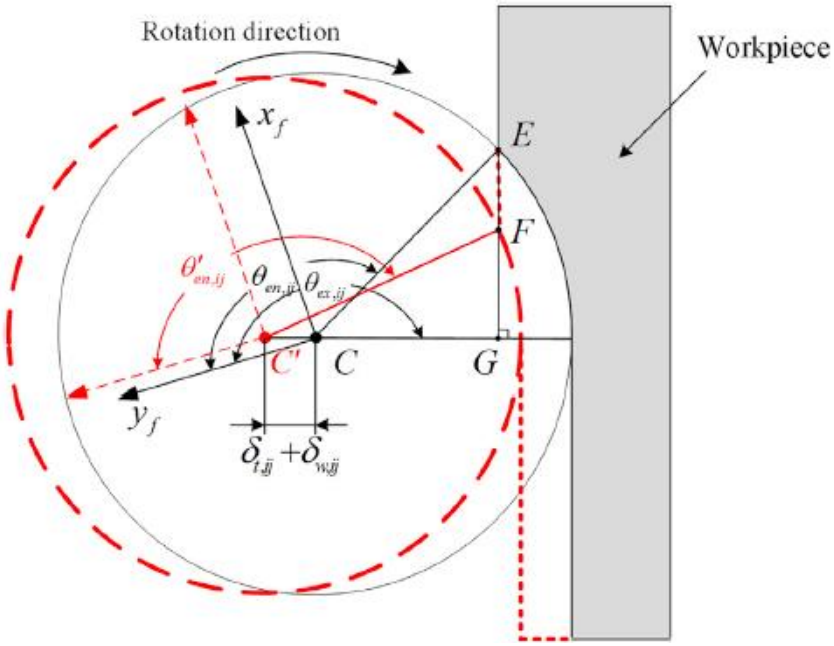

Fig. 1 The entry angle for the i_{th} cutting element of cutting tool during the five axis milling of thin walled workpiece [24]

Cutting tool orientation changes constantly during five axis milling process of thin-walled parts due to cutting tool paths on free form surfaces and new angles and locations of flexible parts through cutting forces of machining operations. As a consequence, the cutter runout should be taken into account when calculating cutting forces. [24].

As a result, the uncut chip thickness for the i_{th}cutter element of the j_{th}flute by considering the k_{th} previous flute at angular position $\theta_{ij}$and cutter location u can be obtained as,

$$h_{ij,k}(\theta_{ij}, u) \approx \frac{k.f_t}{\|\acute{p}(u)\|}\left(\acute{p}(u) + z_i \acute{z}_f(u)\right) n + R_{ij} - R_{i(j-K)} \quad (4)$$

where $$n = \sin\theta_{ij} x_f(u) + \cos\theta_{ij} y_f(u) \quad (5)$$

and where R_{ij} is the radius of rotation for the i_{th}cutting tool element on the j_{th} flute and f_t is the feed per tooth for the cutting tool during machining operations.

The instant uncut chip thickness is calculated by taking cutter runout into account during five axis milling operations of thin walled components is shown in Fig. 2 [24].

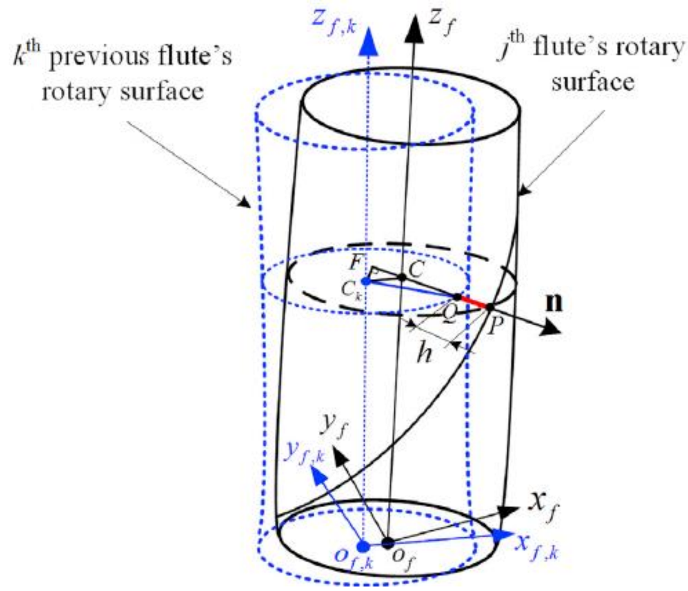

Fig. 2 The instant uncut chip thickness is calculated by taking cutter runout into account during five axis milling operations of thin-walled components[24]

So, the applied cutting forces in the directions of radial, tangential and axial for the i_{th} axial disk element of the j_{th} flute of cutting tool can be obtained as [24],

$$F_{q,ij}(\theta_{ij}, u) = g(\theta_{ij})\left[K_{qc} h_{ij}(\theta_{ij}, u) b_i + K_{qe} \cdot S_i\right],\ q = r, t, a \quad (6)$$

where the shear and edge force coefficients are presented as $K_{qc}(q = r, t, a)$ and $K_{qe}(q = r, t, a)$, respectively. The differential chip width and flute length of the i_{th}cutter element is presented by $b_i$and S_i, respectively. Also, in order to obtain the i_{th} cutter element of the j_{th} flute which is engaged in the cutting process, the $g(\theta_{ij})$ window function is determined as [24],

$$g(\theta_{ij}) = \begin{cases} 1, & \theta_{en,ij} \leq \theta_{ij} \leq \theta_{ex,ij} \\ 0, & Otherwise \end{cases} \quad (7)$$

Thus, the computed cutting forces for each cutting item in the radial, tangential, and axial directions can be converted into the feed or workpiece coordinate system as [24],

$$F_{ij}(\theta_{ij},u) = \begin{bmatrix} F_{x,ij}(\theta_{ij},u) \\ F_{y,ij}(\theta_{ij},u) \\ F_{z,ij}(\theta_{ij},u) \end{bmatrix} = WH_{ij} \begin{bmatrix} F_{r,ij}(\theta_{ij},u) \\ F_{t,ij}(\theta_{ij},u) \\ F_{a,ij}(\theta_{ij},u) \end{bmatrix}, \quad (8)$$

where

$$H_{ij} = \begin{bmatrix} -\sin(\theta_{ij}) & -\cos(\theta_{ij}) & 0 \\ -\cos(\theta_{ij}) & \sin(\theta_{ij}) & 0 \\ 0 & 0 & -1 \end{bmatrix} \quad (9)$$

and

$$W = \left\{ \begin{array}{ll} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, & for\ the\ feed\ coordinate\ frame \\ \begin{bmatrix} x_f & y_f & z_f \end{bmatrix}, & for\ the\ workpiece\ coordinateframe \end{array} \right\} \quad (10)$$

3. Cutting Temperature Model

In machining operations, chip forming produces heat in the cutting region, raising the temperature of the cutting tool and workpiece. Shaw [25] presents the cutting temperature equation in terms of the cutting parameters as,

$$\theta = C_\theta V^{b1} f_z^{b2} a_e^{b3} a_p^{b4} \quad (11)$$

where θ is the temperature of cutting process (degree Celsius), C_θ is temperature coefficient obtained by material of workpiece, machine tool, and cutting tool geometry parameter. The $b1$, $b2$, $b3$, and $b4$ are exponents influencing the machining parameters V, f_z, a_e and a_p, as cutting speed (m/minutes), feed rate (mm/z), radial feed and axial feed (mm), respectively.

Santos et al. [26] present formulas for cutting tool and workpiece temperatures in AL alloy machining operations consisting of multiple nonlinear regression analysis.

$$\theta_t = 116.503\, V^{0.211} f_z^{0.181} a_e^{0.0464} a_p^{0.00391} \quad (12)$$

$$\theta_w = 43.319\, V^{0.365} f_z^{0.244} a_e^{0.0423} a_p^{0.019} \quad (13)$$

4. Deflection Error Analysis of Thin-Wall Workpiece in Machining Operations

The volume of difference between the real machined surface and the nominal surface of the workpiece CAD model is called dimensional error of machined surfaces. Cutting forces and cutting temperature contribute to create the deflection error during machining operations of thin-walled components.

Cutting forces and temperatures cause the workpiece to deflect to a new location, resulting in dimensional error and inaccuracy during machining operations.

Eq. (14) can be used to represent the corresponding surface dimensional error [27],

$$e_p = \delta_{t,p} + \delta_{f,p} + R_N - R_A \quad (14)$$

where, $\delta_{t,p}$ and $\delta_{f,p}$ are the normal projections of the cutting force and cutting temperature induced deflection error for point P, respectively. Also, R_N and R_A are the nominal and specified radial depth of cut, respectively.

5. Virtual Machining System to Predict and Minimize the Deflection Error

The Visual Basic programming language is utilized in the research work in order to develop applications of virtual machining systems to predict and minimize deflection error during milling operations of thin-walled components. The device receives the nominal machining path, the geometry and material parameters of the cutting tool, as well as the CAD model of the workpiece. Then, the cutting forces for each position of the cutting tool along machining paths regarding the cutting tool information and machining process parameters are calculated by using the developed virtual machining system in the study. Fig. 3 shows the dialog box for the cutting force calculator.

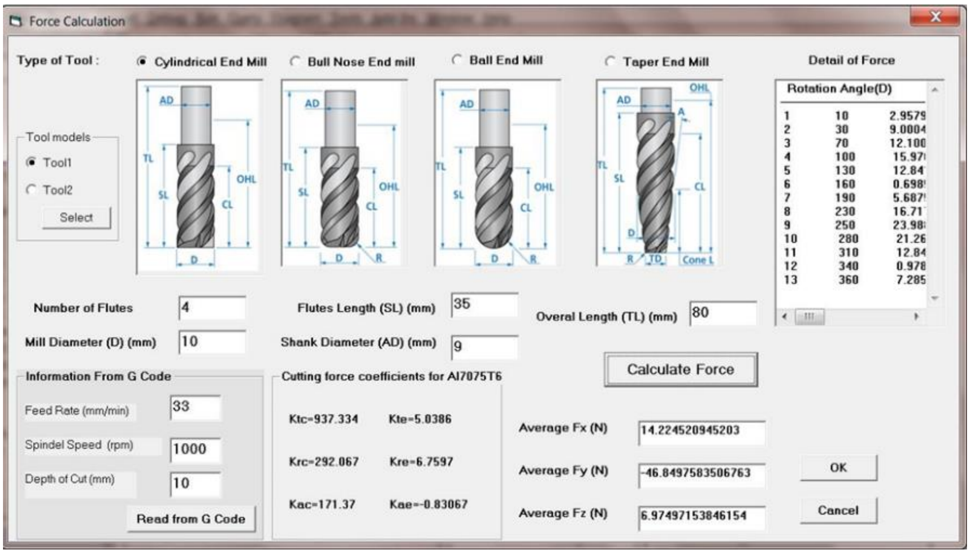

Fig. 3 Dialogue box of cutting force calculator

Furthermore, the cutting temperatures at each position of the cutting tool along machining paths are calculated by the developed software in the study. Then, the obtained cutting force and temperature data are transferred to the Abaqus R2016X FEM analysis program, in order to measure the deflection error of machined impeller blades [28]. To calculate deflection error due to cutting force and temperature during milling operations of impellers, mesh is applied to a CAD model of sample impeller blades. Then, the calculated cutting forces and cutting temperature at each position of the cutting tool along machining paths are applied to each node of the meshed model of sample impeller in order to determine node displacement. As a consequence, the deflection error due to cutting forces and cutting temperatures at each position of the cutting tool along machining paths of sample impeller can be assessed and displayed.

The genetic technique is used in order to calculate the optimized machining parameters in terms of deflection error minimization. In the optimization process, the natural process of evolution and the collection of chromosomes are integrated. The binary encoding process is used to construct the initial population for the optimal solution.

The fitness function is determined as shown in Eq. (15) to provide measurement parameters in the optimal solution and to rank the chromosomes in the population [29].

$$F(x) = \frac{1}{1+f(x)} \tag{15}$$

$F(x)$ and $f(x)$ denote the fitness and objective functions, respectively. The algorithms' key operators are regeneration, crossover, and mutation. The operator's reproduction, crossover, and mutation are added to the original population of the optimization problem in order to create a quicker migration to the optimal machining parameters. Fig. 4 displays the flowchart of virtual machining system in order to calculate cutting force and temperature and obtain the deflection error of machined parts.

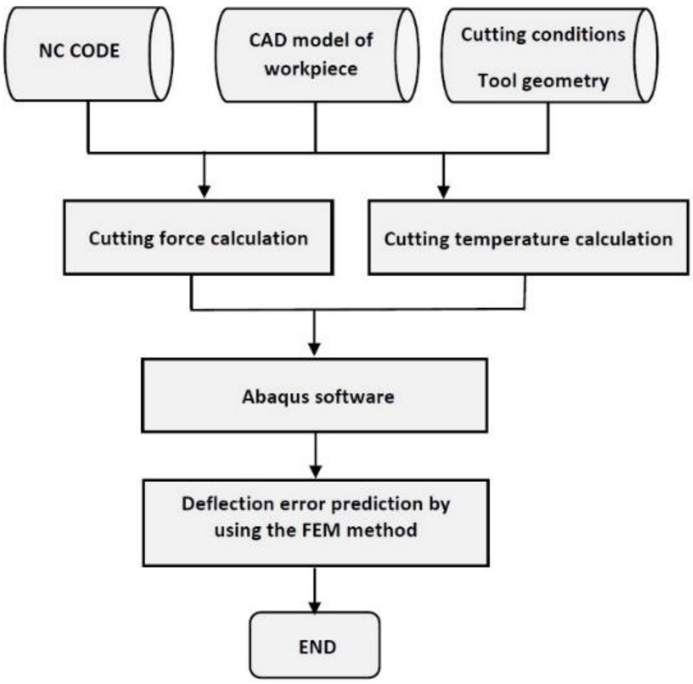

Fig. 4 The flowchart of virtual machining system to calculate cutting forces, cutting temperature and deflection error

Eq. (16) is presented to calculate the surface roughness of machined parts using mathematical theorems [30].

$$R_a = 318\frac{f^2}{4d} \tag{16}$$

where *f* is the feed rate and *d* is the cutting tool diameter. Furthermore, in order to reduce the cost of machined parts, the machining process time should be reduced. Eq. (17) shows the mathematical equation for machining time. [30].

$$t_m = \frac{k}{f} \tag{17}$$

where k is the cutting tool's distance from the operating region, and *f* is the feed rate. In order to reduce the cost of machining, cutting tool life should also be maximized during the optimization phase. Eq. (18) can be used to represent the cutting tool life. [30].

$$T_L = \left(\frac{60}{Q}\right)\left[\frac{C\left(\frac{G}{5}\right)}{V(A)^w}\right]^{\frac{1}{m}} \tag{18}$$

where Q is the cutting edge's contact ratio with the workpiece per rotation, C is 33.98 for HSS tools and 100.05 for carbide tools, $g=0.14$, V is cutting speed (mm/minutes), $w=0.28$, m is 0.15 for HSS tools and 0.30 for carbide tools, G and A are the slenderness ratio and chip cross-section, which can be seen as Eqs. (19) and (20), respectively [30].

$$G = \frac{a}{f} \tag{19}$$

$$A = a \cdot f \tag{20}$$

where a is depth of cut and f is feed rate in machining operations.

The cutting temperature can be decreased by lowering the feed rate and spindle speed, according to Eqs. (12) and (13). Also, according to Eq. (16), by reducing the feed rate, the surface roughness can be decreased. However, according to Eq. (17), reducing the feed rate can increase the machining time. Furthermore, according to Eqs. (8) and (18), increasing the spindle speed can decrease cutting forces as well as cutting tool life during machining operations. It is clear that the mathematical models of cutting forces, cutting temperature, machining time, surface roughness, feed rate, and cutting tool life presented here are interconnected and should be treated as an optimization problem. As a result, to determine the optimized feed rate and spindle speed in terms of deflection error minimization during machining operations, an optimization technique of machining parameters should be implemented. In order to minimize the deflection error, the Matlab programming language is used to obtain the optimized machining parameters. Thus, optimized feed rate and spindle speed are obtained in milling operations of thin-walled impeller blades in order to minimize deflection errors.

The objective function of the optimization process is the minimization of deflection error by obtaining the optimized machining parameters as spindle speed and feed rate along machining paths of impeller blade. So, accuracy as well as efficiency in machining operations of impeller blades can be increased.

The method of machining parameter optimization is shown in Fig. 5, while the flowchart of the study is shown in Fig. 6.

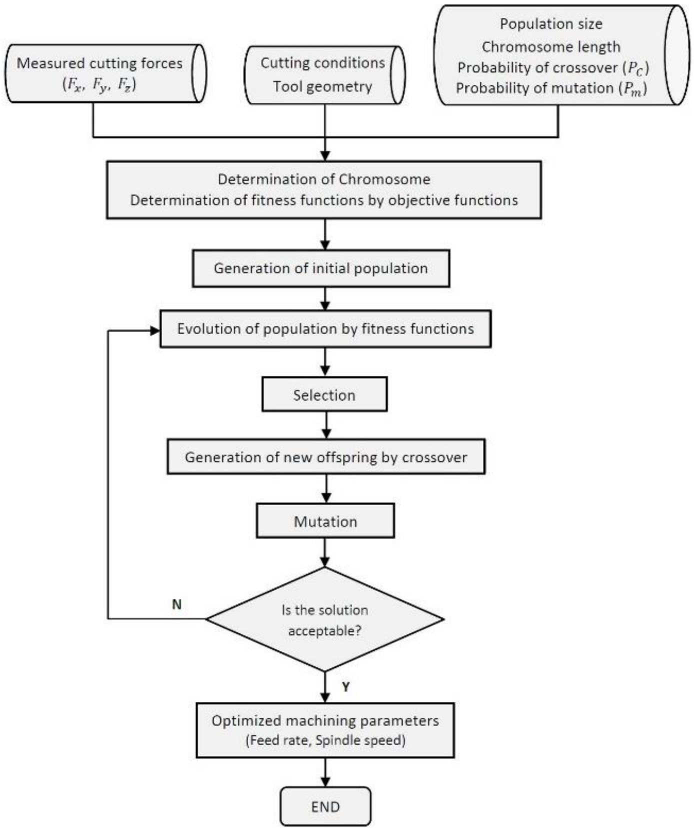

Fig. 5 The method of machining parameter optimization

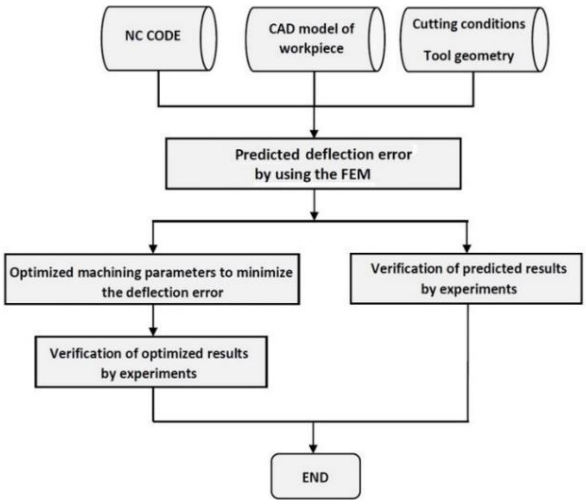

Fig. 6 The flowchart of the study

6. VALIDATION

In order to validate the proposed virtual machining system in the study, the sample impeller is machined by using a 5-axis CNC milling machine tool Kondia HM 1060. The material of sample impeller is AL 7075. The dimensions of the sample impeller in millimeter unit are shown in the Fig. 7.

Fig. 8 shows the cutting tool path and machining procedures of sample impeller.

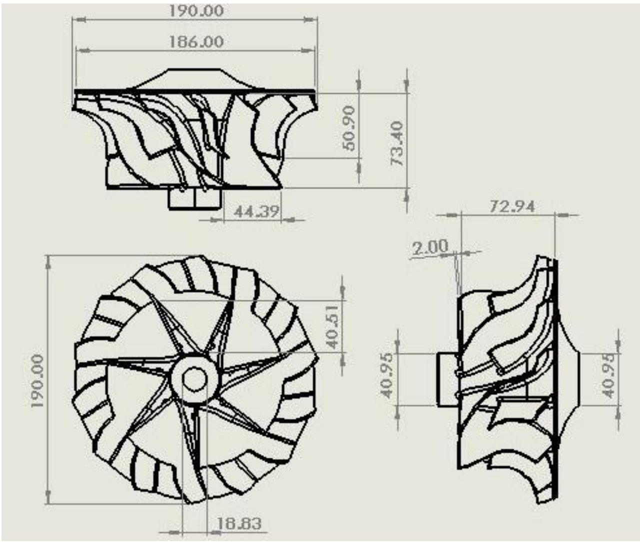

Fig. 7 Dimensions of sample impeller in millimeter unit

The Mastercam software [31] is used to generate cutting tool paths and strategies in machining operations of sample impeller by using a 5-Axis CNC milling machine tool.

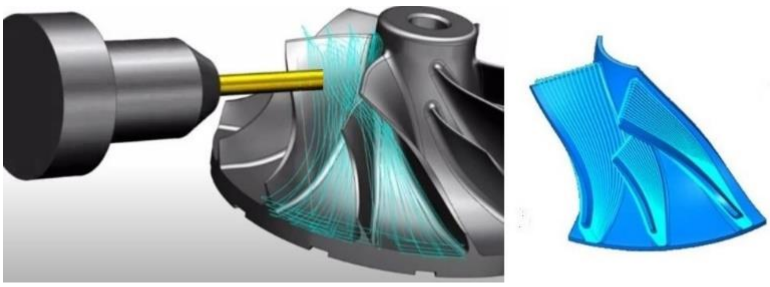

Fig. 8 The cutting tool path and machining procedures of sample impeller

The 5-axis Kondia HM 1060 CNC machine tool is then used in milling operations of test impellers. The cutting tool in the experiment is carbide end mill with 8 mm diameter, 30° helix angle, flute number 4, total length 60 mm, and flute length 35 mm. The feed rate is 200 mm/min and the spindle speed is 200 m/min. Fig. 9 shows the 5-axis milling operation of the test impeller.

Fig. 9 The 5-axis milling operation of test impeller

Fig. 10 shows a real AL impeller which has been machined.

Fig. 10 The real machined AL impeller

The CMM machine is used in order to measure the deflection error in the machined impeller blades. The Renishaw RSH 250 probe is used [32] to calculate the deflection error of a machined impeller blades with a 1 μm repeatability in touching directions. Fig. 11 shows the process of measuring the machined impeller by using the CMM machine.

Fig. 11 The measuring process of the machined impeller blades using the CMM machine

Fig. 12 shows the procedure of impeller blade measuring by using the CMM machine.

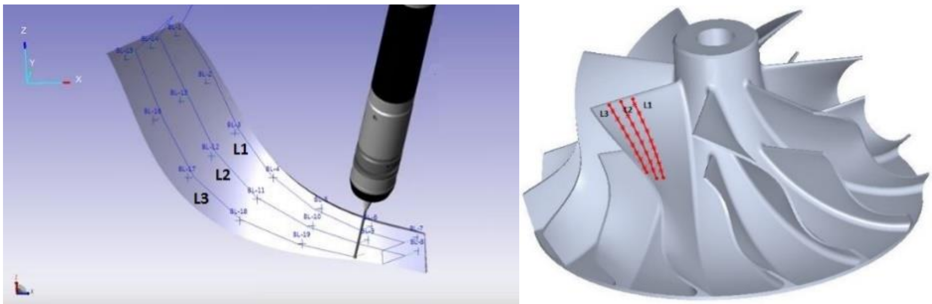

Fig. 12 Procedure of impeller blade measuring by using the CMM

This study uses the cutting force model of 5-axis CNC machine tools in machining operations of thin-walled parts presented by Li et al. [24]in order to calculate cutting forces in virtual environment. The Kistler dynamometer Type 9129AA is used to determine the coefficients of the basic cutting force for milling operations of thin-walled blades by using 5-axis CNC milling machine tool Kondia HM 1060. The feed per tooth and feed rate are 0.5 mm and 100 mm/min, respectively. The spindle rotates at 3000 rpm. As a consequence, the specific cutting force coefficients are obtained as Table 1.

Table 1 The specific cutting force coefficients

The specific cutting coefficients	Krc (N/mm^2)	Kre (N/mm)	Ktc (N/mm^2)	Kte (N/mm)	Kac ((N/mm^2)	Kae (N/mm)
	406.1	17.68	810.42	16.93	241.28	0.74

The deflection errors of the impeller blade due to cutting forces and temperature are measured by using the Abaqus software [28]. As a result, Fig. 13 shows the FEM-calculated deflection error of a machined thin-walled impeller blade.

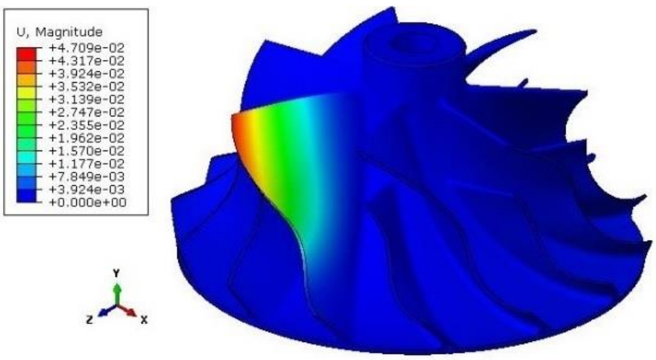

Fig. 13 The FEM-calculated deflection error of a machined thin-walled impeller blade

Thus, the measured and FEM simulated deflection errors in the machined impeller blade are obtained as shown in Fig. 14.

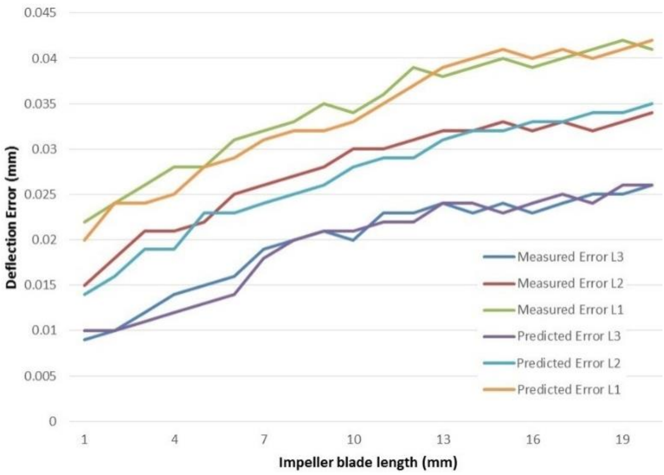

Fig. 14 The measured and predicted deflection errors in the machined impeller blade

When the experimental test results are compared to the expected deflection error of the machined thin-walled impeller, a good compatibility is obtained. The developed optimization techniques based on the genetic algorithm in the study are used to measure optimized machining parameters. The population size of 39 is chosen during the optimization process, which is iterated for 306 generations. Crossover probability of 0.68 and mutation probability of 0.001 are also chosen. As a result, the feed rate is 170 mm/min, and the spindle speed is 260 m/min.

Fig. 15 shows the measured and FEM simulated deflection errors in the machined impeller blade by using optimized machining parameters.

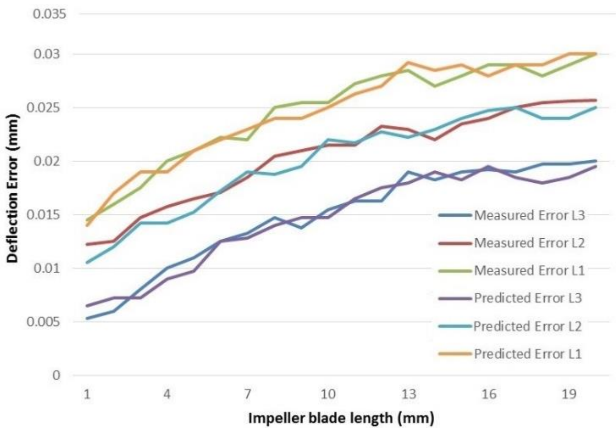

Fig. 15 The measured and predicted deflection errors of machined impeller blade by using optimized machining parameters

7. CONCLUSIONS

Application of virtual machining system is developed in the study to predict and minimize the deflection errors in 5-Axis milling operations of thin-walled impellers. As a result, by using the CAD model of the workpiece, cutting conditions and cutting tool geometries in the developed virtual machining system, cutting forces and temperatures at each location of the cutting tool along the machining path are determined. To calculate the deflection error in a thin-walled workpiece, the Finite Element Method is used. A real impeller is milled by using a 5-Axis CNC machine tool in order to validate the integrated virtual machining system in the study. The machined impeller blades are measured by using a CMM machine in order to obtain the deflection error. The obtained results from the virtual machining system and experimental tests are evaluated in order to determine the reliability rate in the established system. In comparison to the experimental and virtual machining system results, there is a 91.6 percent compatibility. Optimized machining parameters are obtained by using the genetic algorithm to minimize the deflection error in 5-axis machining operations of impeller blades. The optimized machining parameters resulted in a 24.4 percent decrease in deflection error of the machined impeller blade. As a result, the developed virtual machining system in the study can minimize the deflection error in 5-axis milling operations of thin-walled impeller blades by using the optimized machining parameters. It is also concluded that using optimization techniques in virtual machining systems will improve the accuracy as well as reliability of machined parts. Moreover, the developed methodology in the study can be used for increasing the accuracy of 5-axis CNC milling operations of turbine blades by minimizing the cutting tool and workpiece deflection errors. Also, deformation errors due to cutting forces and temperature in the cutting tool as well as workpiece can be predicted and compensated by the modified cutting tool paths in order to increase accuracy of machined components using the virtual machining systems. To minimize the vibration during machining operations, the optimized machining parameters can also be calculated by using virtual machining system. The cutting tool paths in the 5-axis CNC machining operations of free form surfaces such as impellers as well as turbine blades can be optimized by using virtual machining systems in order to decrease the errors of machined parts. Furthermore, applications of the virtual machining systems can be developed in order to improve the surfaces quality of machined parts. These are the concepts of future research works for the authors.

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