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Feedrate scheduling strategies for free-form surfaces

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Abstract

Free-form machining is one of the commonly used manufacturing processes for several industries such as automobile, aerospace, die and mold industries. In 3D complicated free-form surfaces, it is critical, but often difficult, to select applicable cutting conditions to achieve high productivity while maintaining high quality of parts. It is essential to optimize the feedrate in order to improve the machining efficiency of the ball-end milling. Conservative constant feedrate values have been mostly used up to now since there was a lock of physical models and optimization tools for the machining processes.

The common approach used in feedrate scheduling is material removal rate (MRR) model. In the MRR based approach, feedrate is inversely proportional to either average or instantaneous volumetric removal rate. Commonly used CAM programs and NC code generators based on only the geometric and volumetric analysis, but they do not concern the physics of the free-form machining process yet. The new approach that is also introduced in this paper is based on the mechanics of the process. In other words, the force-based models in which feedrate is set to values which keep either average or instantaneous machining forces to prescribed values. In this study, both feedrate scheduling strategies are compared theoretically and experimentally for 3D ball-end milling of free-form surfaces. It is shown that MRR based feedrate strategy outputs higher feedrate values compared to force based feedrate strategy. High feedrate values of the MRR strategy increase the cutting forces extensively which can be damaging to the part quality and to the CNC Machine.

When the new force based feedrate-scheduling strategy introduced in this paper is used, it is shown that the machining time can be decreased significantly along the tool path. The force-based feedrate scheduling strategy is tested under various cutting conditions and some of the results are presented in the paper.

Keywords: Sculptured surfaces; Feedrate scheduling; Material removal rate (MRR)

1. Introduction

Free-form machining is one of the most commonly used manufacturing processes used in various industries such as automotive, aerospace and die/mold industries. In 3D free-form machining, since the workpiece and tool engagement region, and therefore, axial and radial depth of cuts are often changing, in planning machine operations, the NC code generator has to be conservative most of the time in selecting machining conditions with respect to metal removal rate in order to avoid undesirable results such as chipping, cutter breakage or over-cut due to excessive cutter deflection.

The production time and cost are the key factors in today's competitive market. However, conservative constant feedrate values have been mostly used up to now since there was a lack of physical models and optimization tools for the machining processes. Currently and commonly used CAM programs and NC code generators are based on only the geometric and volumetric analysis, but not on the physics of the free-form machining process, yet. These programs usually contain general and conservative values based on trial–error tests and conservative values.

It is often difficult to select applicable cutting conditions to achieve high productivity while maintaining part quality due to the complicated surface geometry. Cutting forces acting carry significant machining process information. Since production engineers in industry have no scientific tools based on the mechanics of the free-form surface machining in most of the cases, they cannot predict the cutting forces, therefore, they have no choice other than being conservative in the selection of the feedrate values. The selection of

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the feedrate must be performed carefully; since selection of excessive feedrate increase cutting forces, tool deflections, tool wears and chipping, etc. Setting the feedrate to a constant value brings deviations in the cutting forces; however, these deviations give an opportunity to set the resulting cutting force to a reference value. Machining a free-form surface at a single feedrate reduces the efficiency of free-form machining. Therefore, knowledge of cutting force levels and reliable force model provides to run the same job at varying feedrates. This strategy can decrease the cycle times significantly.

When the previous studies about feedrate scheduling and optimization are considered, there are not many researches performed in the literature. Most researchers have developed and used feedrate-scheduling system based on volumetric analysis by using material removal rate (MRR) approach. Ip et al. [1] proposed a fuzzy based MRR optimization approach in order to increase the machining efficiency by finding it from spindle power and specific energy. Li et al. [2] performed an offline feedrate optimization integrated with CAD/CAM by relating the average power with MRR. Wang [3] also developed an algorithm for adjusting feedrate, using MRR.

Present CAM technology does not consider important physical properties, such as cutting forces and the machined surface. Besides, some commercial software packages such as Vericut's feedrate optimization module Optipath [4] and Mastercam's Hifeed [5] work on a volumetric analysis premise. They are based on the amount of material removal rate (MRR) in each segment of the cut.

When the previous studies about feedrate scheduling are considered, feedrate scheduling for free-form surfaces has became popular recently. White and Houshyar [6] employed industrial engineering methodology dealing with optimization of a single item in single and multi-stage metal cutting systems. Besides the MRR models, some researchers have performed off-line feedrate scheduling based on the mechanistic cutting force models. Yazar et al. [7] performed feedrate optimization based on cutting force calculations in three-axis milling of dies and molds. Lim and Hsiang [8] proposed a cutting path adaptive feedrate strategy, which improves the productivity of free form surface machining when subjected to both force and dimensional constraints. An example was also shown to the application of machining of turbine blade [9]. Baek et al. [10] focused to find optimal feedrate for face milling operations in order to maximize MRR with a surface roughness constraint. Taunsi and Elbestawi [11] integrated the feed drive dynamics, described by the acceleration/deceleration profile, with the minimum-time trajectory planning in order to achieve the desired feedrate at the appropriate position. Kim et al. [12] changed the cutting speed according to the effective tool diameter. Feng and Su [13] optimized the feedrate with the tool path based on the calculation of cutting forces and the machining errors in 3D plane surface machining. Ko et al. [14] presented an off-line feedrate-scheduling model based on the mechanistic cutting force model for flat end milling by adjusting the acceleration and deceleration time of the controller. Yun et al. [15] built an off-line feedrate-scheduling model using the cutting force model in flat end milling. Guzel and Lazoglu [16] presented an off-line feedrate-scheduling system for sculptured surface machining based on the cutting force model. This force model was built upon the previous studies of Lazoglu [17]. Cheni et al. [18] studied the feedrate optimization of high-speed ball-end milling process. The feed-interval scallop height is an important source to limit the feedrate for high efficiency machining using CBN tools. Ko and Cho [19] proposed a scheme for off-line feedrate scheduling for 3D ball-end milling based on the cutting force model considering transverse rupture strength of the tool.

Force based off-line feedrate-scheduling model presented in this paper is based on mechanistic cutting force model. It is shown that a relationship between the feedrate and force can be established for the selection of optimum feedrate values for machining of free-form surfaces. The feedrate is simultaneously optimized with the simple tool path based on the calculation of cutting forces. Both geometry based volumetric (MRR) and physics based feedrate scheduling strategies are compared theoretically and experimentally for 3D ball-end milling of free-form surfaces. It is shown that volumetric based feedrate strategy outputs higher feedrate values. In MRR model predictions, it is shown and emphasized that the scheduled feedrate values cause greater forces, which can damage the cutting tool and CNC machine tool.

Force based off-line feedrate scheduling is suggested as the advanced technology to regulate cutting forces through change of feed per tooth, which directly affects variation of uncut chip thickness. This force-based strategy overcomes the limits of present CAM technology.

The off-line method predicts cutting load by using cutting force model and adjusts cutting parameters before actual machining. It can adjust feedrate based on the specific cutting conditions for each segment of the tool path. Cycle time can be decreased significantly along the tool path and resulting cutting forces can be kept constant when the new force model based feedrate strategy is used. This model is tested under various cutting conditions and some of the results are presented in this paper.

2. Mechanistic cutting force model

Ball-end milling is widely used in machining sculptured surfaces of dies and molds. Usually, a cutter deflects during sidewall machining and results in significant geometric error. Currently, in order to avoid excessive cutter deflection and assure high quality of the machined parts, conservative machining conditions are selected which result in longer machining time and higher cost. Therefore, it is necessary to develop a model that can characterize the cutting process and predict cutting forces accurately in ball-end milling.

The calculated cutting force can be used as fundamental data for determining cutter deflection and form accuracy, tool breakage detection, and process planning.

An effective and precise cutting force model is the key for the off-line force based feedrate-scheduling method. Therefore, the calibration coefficients for the cutting force model become important for the robustness of the force model. Calibration tests have been performed in advance to obtain the cutting constants and edge coefficients to be used in the mathematical model. Cutting model presented here consists of various modules such as tool geometry, engagement region, kinematics/chip load and cutting force modules. This force model builds upon the previous studies of Guzel and Lazoglu [16,17]. However, chip load approach has been changed with a new introduced uncut chip thickness. The calibration method has been improved in such a way that the maximum values of each tooth are averaged in order to decrease the runout effect, and the cutting element position angle (ψ) is changed for the depth of cut interval. The calibration was performed at 48, 96, 144 and 192 mm/min feedrate values. The model developed here has the flexibility of working for any general tool/cutting edge, workpiece geometry and non-horizontal cutter feed motion. Thus, the uncut chip thickness model should be calculated to improve the accuracy of cutting force regulation in feedrate scheduling. Only, analytical engagement region determination, the chip load and cutting force modules will be explained in details, however more details about tool geometry and calibration coefficients modules can be found in reference [16,17].

2.1. Cutter/workpiece intersection modules

In the process of cutter/workpiece intersection along the tool path, the output (CL file) of commercial CAM packages is post processed by an advanced Analytical Contact Region Simulation algorithm (namely, ACRsim). This fast analytical algorithm determines the engagement domain between the workpiece and ball-end mill at every CL point for monotonic free-form surfaces. Details of the analytical model and algorithm can be found in [21]. However, briefly it can be said that complete engagement domain can be stated as start and exit angles and a sample from the analytical algorithm is given for locally and positively inclined slot cutting process in Eq. (1). Fig. 1 shows the boundaries of contact region.

$$\bar{\phi}_{\mathrm{st}} = \frac{\sum_{i=1}^{F} \tan^{-1}\left(\frac{y}{x}\right)}{F}, \quad \bar{\phi}_{\mathrm{ex}} = \frac{\sum_{i=1}^{F} \tan^{-1}\left(-\frac{y}{x}\right)}{F},$$
$$x_i = \frac{r_i^2 - R_2^2}{1-(R_2/R)^2}, \quad y_i = \sqrt{r_i^2 - x^2}, \qquad (1)$$
$$r_i = \sqrt{R^2 - (R - z_i)^2}, \quad z_i = \frac{R}{F} i$$

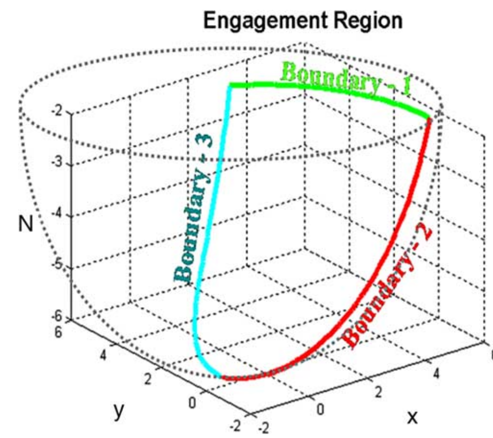


Fig. 1. Boundaries of contact region.

where F is total disc number and $i = 1 \ldots F$ and $R_2 = R\sin(\alpha)$ where α is the inclination angle. Since engagement domain is simply the combination of start and exit angles of each discrete disc located on the cutter, the final step is to assign the start and exit angles to each respective disc by using Eq. (1). In the machining of free-form surfaces, axial depth of cut is not constant throughout the tool path. Therefore, engagement region changes at each CL point. There are three boundaries, which are enough to define the engagement region. Since all boundaries are analytically known, there is no need for Z-mapping or for a solid modeler based technique. ACRsim generates the engagement domain for the cases in this paper in seconds; on the other hand other algorithms generate the engagement domain in the order of hours.

2.2. Chip load thickness module

The model developed here has the flexibility of working for any general tool/cutting edge, workpiece geometry and non-horizontal cutter feed motion. Since, the force-based feedrate scheduling method relies on variation of cutting forces, which is directly related to instantaneous undeformed chip thickness. Thus, the uncut chip thickness model should be calculated to improve the accuracy of cutting force regulation in feedrate scheduling.

The chip load of ball-end milling can be best understood by examining the early detailed kinematic analysis by Martelotti [20]. His analysis showed that, the true path of the cutter tooth is an arc of a trochoid, rather than a circle, which complicates the mathematics in the analysis. In most practical cutting conditions where the cutter radius is much larger than the feed per tooth, the circular tool path assumption is valid and the error introduced is insignificant. The geometry and chip formation of a straight-end milling operation is displayed as;

$$t_c = t_x \cdot \sin(\theta) \qquad (2)$$

where t_c is the instantaneous chip load, t_x is the feed per tooth and θ is the immersion angle of cutting point. The formulation for straight-end mill should be modified, since the chip thickness varies along the cutting edge as the depth of cut is changed. The above chip thickness combines only the rotational and linear straight motion of the cutter, however rotational motion, and non-horizontal cutter feed motion and spherical part of the ball-end mill should be combined for an accurate chip thickness.

The non-horizontal cutter feed motion for ball-end milling process with a horizontal feed component f_h and a vertical feed component f_v results are shown for different cases in Fig. 2. When the cutter moves upwards or downwards with feed inclination angle, as in upward and downward ramping, the feed direction vector is not perpendicular to the cutter rotation vector, and the cutting edge element produces different undeformed chip geometry, as shown in Fig. 2. When downward ramping occurs, the following term is added to calculate the uncut chip thickness; however this term is subtracted for upward ramping case. There is also a drilling action act on the ball-end mill for the downward ramping case. This affect is added to chip thickness term:

$$\Delta t = t_x \cdot \cos(\psi) \cdot \sin(\alpha). \quad (3)$$

The instantaneous undeformed chip thickness for ball-end mill cutter is found as follows:

$$(t_c)_{kn,new} = t_x \cdot \sin(\theta) \cdot \sin(\psi) \cdot \cos(\alpha) \pm t_x \cdot \cos(\psi) \cdot \sin(\alpha) \quad (4)$$

where $(t_c)_{kn,new}$ is the new ball-end mill chip load, t_x is the feed per tooth, θ is the immersion angle of cutting point, ψ is the cutting element position angle (Fig. 3) and α is the feed inclination angle ($0<\alpha<90°$).

2.3. Cutting force model

For a differential chip load (dA_c) in engagement domain, the differential radial (dF_r), zenith (dF_ψ) and tangential (dF_t) cutting forces can be written as follows [16],

$$dF_r = K_{rc} \cdot dA_c + K_{re} \cdot dz, \quad dF_\psi = K_{\psi c} \cdot dA_c + K_{\psi e} \cdot dz, \quad dF_t = K_{tc} \cdot dA_c + K_{te} \cdot dz \quad (5)$$

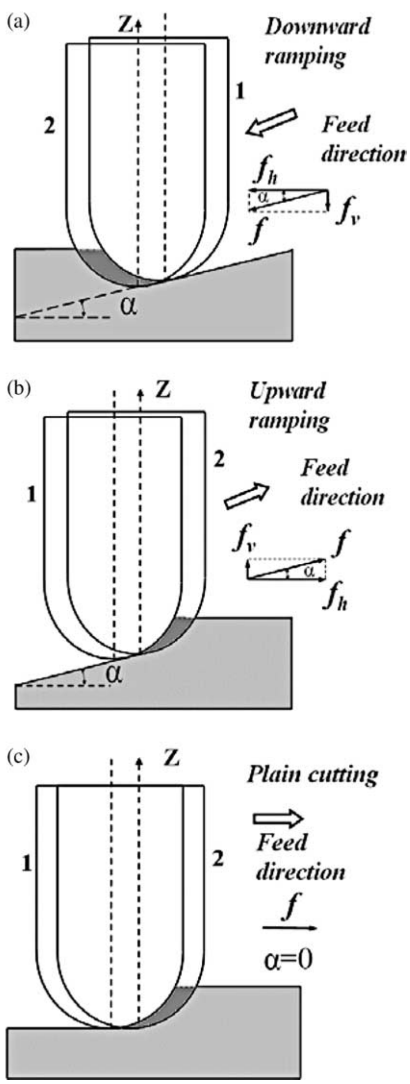


Fig. 2. Feed motions: (a) downward ramping; (b) upward ramping; (c) plain cutting.

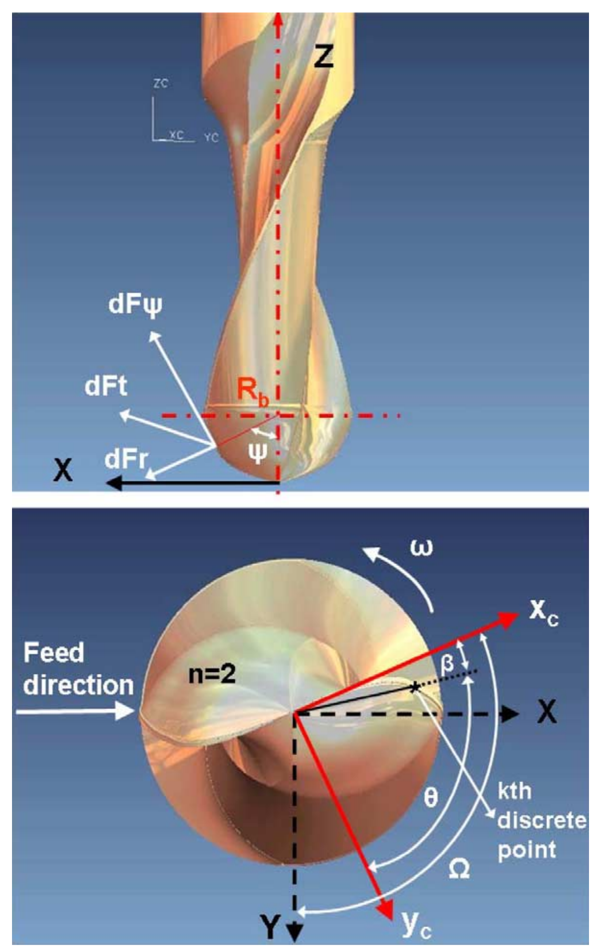


Fig. 3. Illustration of cutting force components and angular relationships.

where K_{rc}, $K_{\psi c}$ and K_{tc} are the radial, zenith and tangential cutting constants, and K_{re}, $K_{\psi e}$ and K_{te} are the related edge coefficients, respectively. These specific cutting energy coefficients vary mainly based on the cutter/workpiece material combination. In order to evaluate these parameters, calibration tests were performed with ball-end mill cutter and an Al7039 workpiece material has been used in all tests. The 6 mm radius cutter has been divided into seven separate disks along the cutter axis in the ball section and cutting constants were evaluated for each region individually by performing incremental slot cutting runs with different feeds (Table 1). Once differential radial, zenith and tangential components, dF_r, dF_ψ and dF_t were obtained, respectively, through use of Eq. (5), these cutting force components can be easily transformed into the X–Y–Z global coordinate system as the following,

$$\begin{bmatrix} dF_X \\ dF_Y \\ dF_Z \end{bmatrix}\Bigg|_{k,n} = A\cdot\begin{bmatrix} dF_r \\ dF_\psi \\ dFt \end{bmatrix}\Bigg|_{k,n}, \quad A = \begin{bmatrix} -\sin(\psi)\cdot\sin(\theta) & -\cos(\psi)\cdot\sin(\theta) & -\cos(\theta) \\ \sin(\psi)\cdot\cos(\theta) & \cos(\psi)\cdot\cos(\theta) & -\sin(\theta) \\ \cos(\psi) & -\sin(\psi) & 0 \end{bmatrix}\Bigg|_{k,n} \tag{6}$$

Additional force is included to dF_Z, which results from a constant force per length value over the workpiece as long as the cutter moved down into the workpiece in the z direction. Its amplitude equals to constant force per length (F_c) times the contact edge length of the cutter. Some tests were performed in order to detect the force per length (F_c) [N/mm] as a function of vertical component of feedrate (f_v) [mm/min].

$$F_c = (0.3)\cdot f_v + 4.5 \tag{7}$$

3. Experimental validations with free-form surfaces

In order to test the new chip thickness equation, various experimental validations were performed for non-horizontal feed directions. Before performing these tests, firstly the validations of cutting forces were performed for slot cutting tests known as the simplest type of cut in ball-end milling. Feed inclination angle (α) is zero for slot cutting tests. Predicted and measured force magnitudes showed very good agreement in the performed slot cutting tests at 48 mm/min, 600 rpm and different axial depth of cut values (Fig. 4a). The results of predictions for upward and downward ramping cases have been investigated next. The predictions are performed for 5, 10, 20 and 30° feed angles (α). Normally, different chip thickness however the same coding of the model algorithm is used for these cases compared to slot cutting case. However, the simulation model proposed in this study is a generic one in the sense that it predicts the cutting forces for different cases without making any changes. Only, the results of 20° upward and downward ramping will be presented for comparison purpose in Fig. 5. Again the predicted results show very good agreement with reality for all cases. The cutting conditions are feedrate of 48 mm/min and spindle speed of 600 rpm. After the upward and downward ramping case validations, the validations including the correction force per length in z direction are also performed for complex free-form surface (airfoil geometry) as shown in Fig. 6a and b. The pick feed of 3 mm/track was used to create on 50 mm × 30 mm blank workpiece. In this cutting test, spindle speed and feedrate were again 600 rpm and 48 mm/min, respectively. A two fluted ball-end mill with the diameter of 12 mm, the nominal helix angle of 30°, and the projection length of 37 mm was used in all experiments. Only the simulated and experimentally measured resultant forces for the airfoil machining are shown in Fig. 6. Cutting has been realized only by the ball part of the cutter in all cases.

4. Feedrate scheduling strategies

4.1. Material removal rate (MRR) based feedrate-scheduling strategy

Implementing feedrate optimization in free-form surface machining has become widespread and it is also used in some commercial software packages. The common approach used in feedrate scheduling is material removal

Table 1
Cutting and edge calibration coefficients for AL7039

Coefficients	Interval from tip						
	0–0.5 (mm)	0.5–1 (mm)	1–1.5 (mm)	1.5–2 (mm)	2–3 (mm)	3–4 (mm)	4–6 [mm]
K_{rc} (N/mm^2)	2991	695	22	196	105	483	353
K_{re} (N/mm)	31	10	9	2	7	15	12
$K_{\psi c}$ (N/mm^2)	1113	785	753	179	101	31	6
$K_{\psi e}$ (N/mm)	12	13	4	19	14	9	0
K_{tc} (N/mm^2)	5354	2549	1182	1429	971	848	932
K_{te} (N/mm)	37	17	30	3	16	17	11

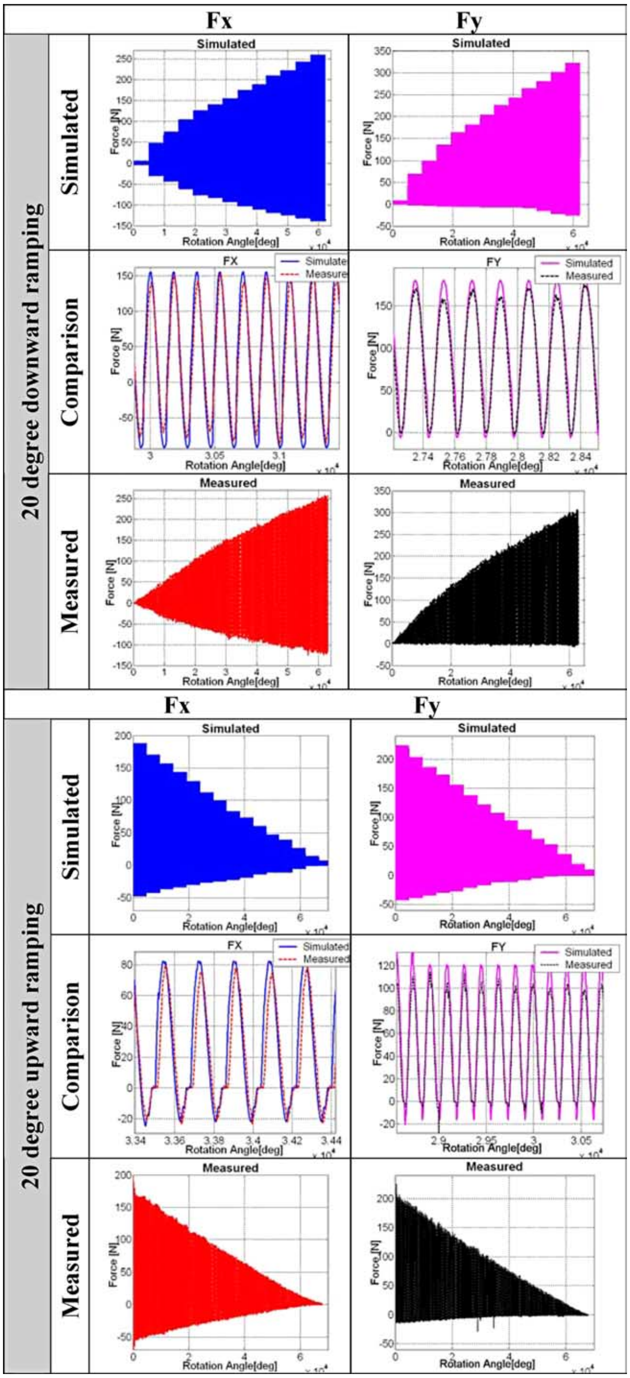


Fig. 4. X and Y Force components for 20° upward and downward ramping cases with constant feedrate case.

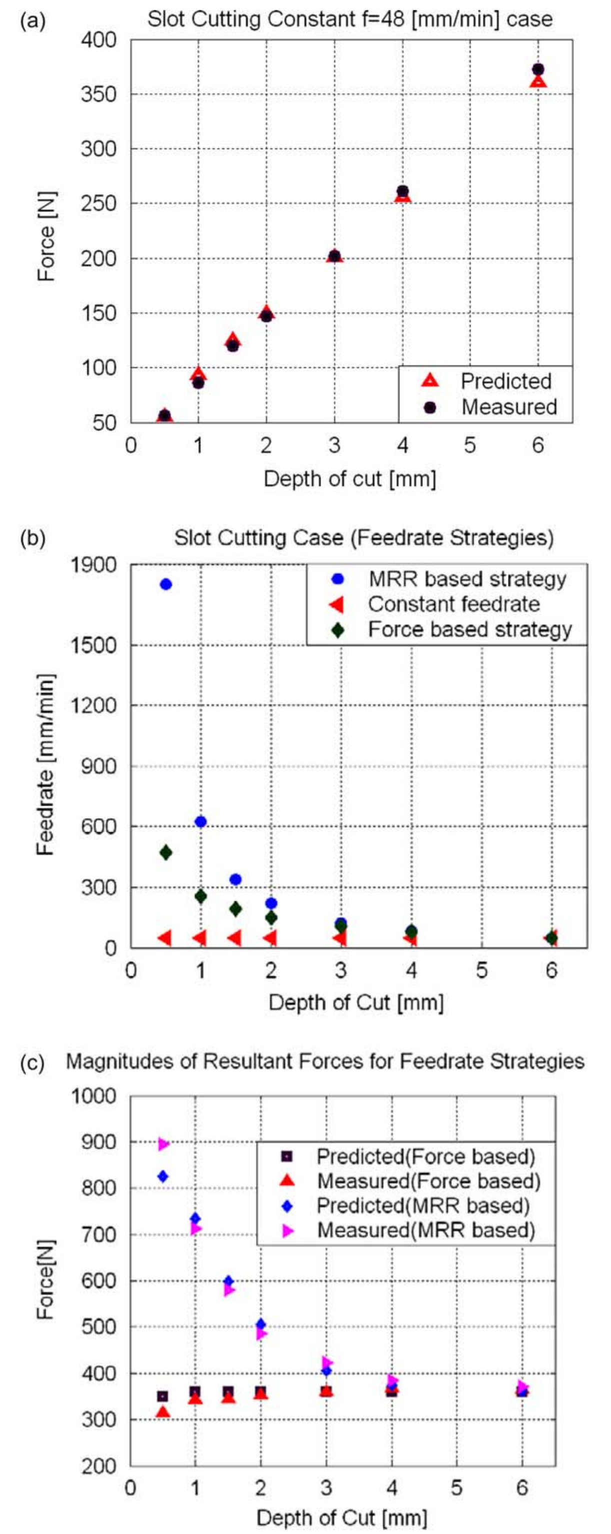


Fig. 5. Slot cutting feedrate strategies: (a) magnitudes of resultant forces in constant feedrate case, (b) scheduled feedrate values for feedrate strategies, (c) measured and simulated forces in scheduled cases.

rate (MRR) model. In this approach, feedrate is expected to be proportional to either average or instantaneous volumetric removal rate. Feedrate-scheduling method based on volumetric analysis which uses material removal rate (MRR) is commonly used by researchers. Currently and commonly used CAM programs and NC code generators based on only the geometric and volumetric analysis, but they do not concern the physics of the free-form machining process yet. On the other hand, force based feedrate scheduling regulates the resultant force at a reference force value; however MRR model regulates at a reference MRR value.

In this part, the volumetric based feedrate strategy will be compared for the simplest type of cut known as slot cutting

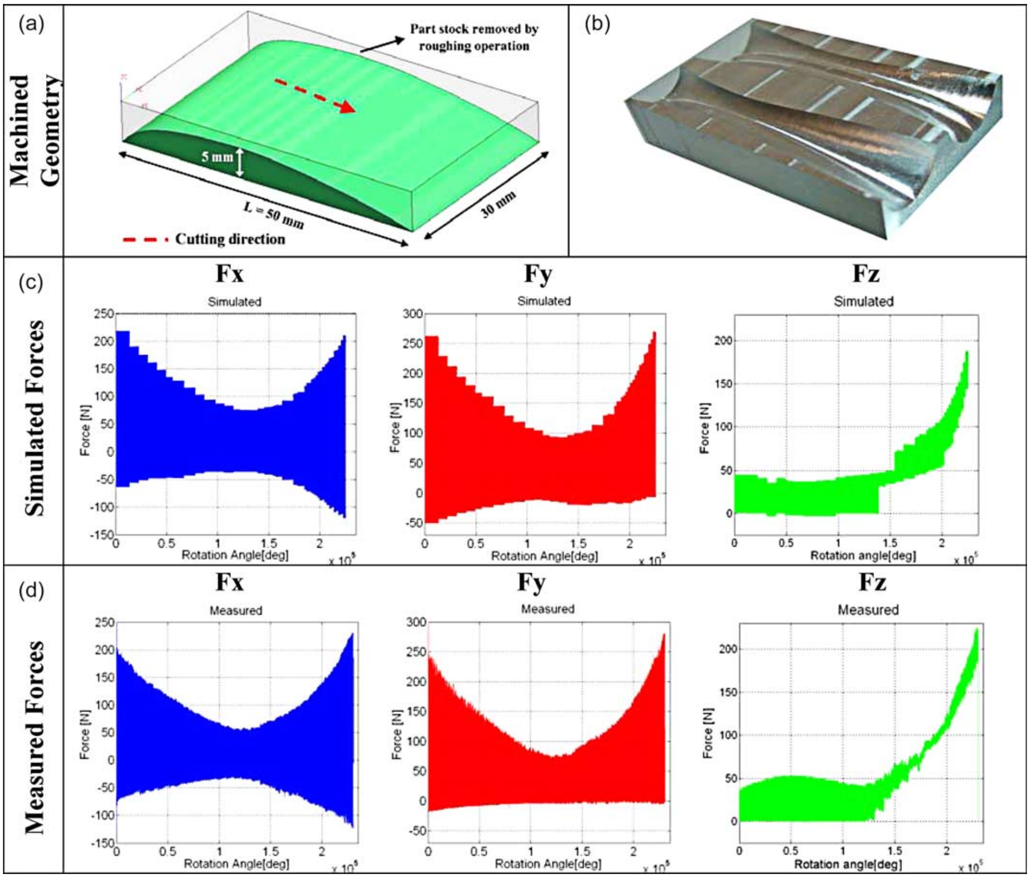
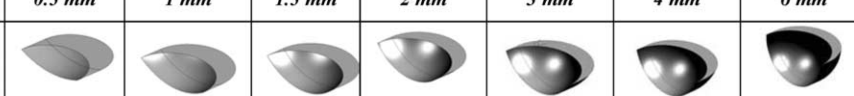


Fig. 6. Airfoil shape: (a) part geometry, (b) photo of real geometry, (c) simulated forces, (d) measured forces.

and then it will be applied to more complex free-form surface (airfoil geometry). The feedrate of the cutter has been chosen to be 48 mm/min, the magnitudes of resultant forces of *X* and *Y* is compared for this chosen feedrate value. The maximum material removal rate at the maximum depth of cut, which is 6 mm, will be selected for reference value for slot cutting case. The swept volumes and the corresponding contact regions are given for different depth of cuts for slot cutting case in Table 2. The material removal rates for each depth of cut value are determined from the swept volume and time between two CL points for slot cutting case. These volumes are calculated for 2 mm distance and 48 mm/min feedrate value between two CL points by using analysis section of Unigraphics NX2. The material removal rates for consecutive two CL points are found by using swept volume, distance and time.

Material removal rate (MRR) regulates the material removal rate in the feed direction at a reference material removal rate. The initial constant feedrate value is taken as 48 mm/min. When the MRR value of worst case is used as limiting reference value, the scheduled feedrate values and the corresponding resultant forces are shown in Fig. 4b and c. As it is seen from scheduled resultant forces, they are not constant and not below a certain constant value. Greater

Table 2
Swept volumes and contact regions for slot cutting case

Depth of Cut	0.5 mm	1 mm	1.5 mm	2 mm	3 mm	4 mm	6 mm
Swept volume							
Contact region							
Volume	3.225 mm^3	9.003 mm^3	16.319 mm^3	24.779 mm^3	44.22 mm^3	66.01 mm^3	113.1 mm^3

forces and feedrate values occur in MRR based feedrate scheduling case when compared with the force-based feedrate scheduling strategy. The discrepancy at 0.5 and 1 mm depth of cuts occurs, since shearing and ploughing occurs at small depth of cuts (very close to tip of the cutter).

As it is also seen from Fig. 4, the cutting force is not related to the material removal rate for the corresponding depth of cut. The volumetric approach mainly deals with the swept volumes between two CL points, and then it schedules the feedrate values according to the material removal rates.

4.1.1. MRR based feedrate scheduling in free-form surface

The feedrate scheduling based on MRR approach was also performed for complex free-form surface (airfoil geometry) in which the feed is in non-horizontal direction. As it is also seen from Fig. 7a, the cutting force is not related to the material removal rate for the corresponding CL points. The feedrate values were again regulated according to a reference material removal rate value in the feed direction. The maximum MRR value is obtained at the maximum depth of cut for airfoil geometry. The constant feedrate value is taken as 48 mm/min. When the MRR value

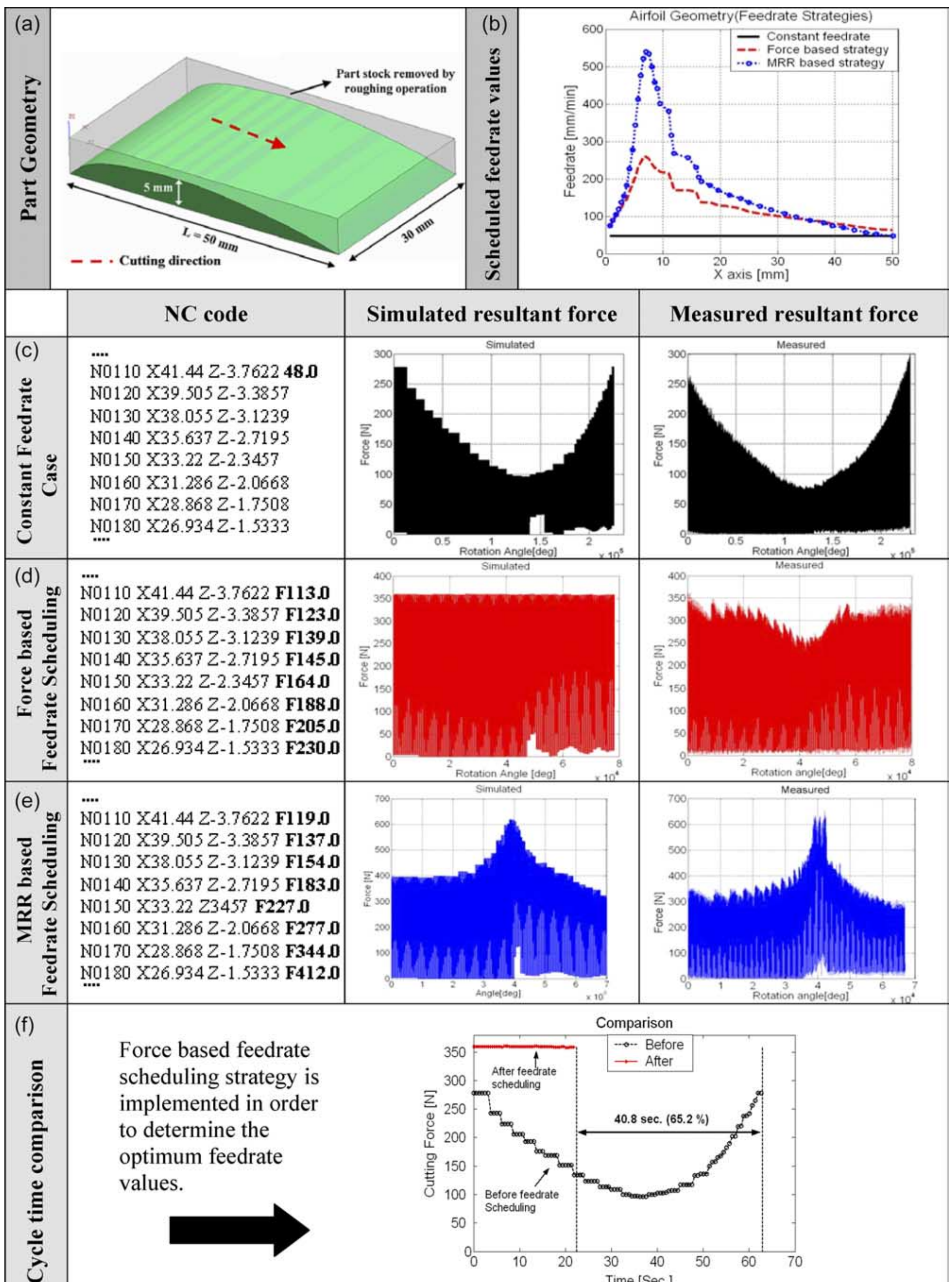


Fig. 7. Machining of airfoil geometry: (a) part geometry, (b) scheduled feedrate values for feedrate strategies, (c) forces in constant $f = 48$ mm/min feedrate case, (d) forces in force based feedrate case, (e) forces in MRR based feedrate case, (f) envelopes of resultant forces and comparison of cycle times.

of worst case is used as limiting reference value, the scheduled feedrate values and the corresponding resultant forces are shown in Fig. 7b and e. It should be noted that the scheduled resultant force values are not under the prescribed limit value of 360 N.

4.2. Force based feedrate-scheduling strategy

The off-line feedrate scheduling regulates the constant feedrate according to the reference cutting force, which is determined before. In order to increase the resultant force to the desired reference value, a simple linear relation is found between the feedrate and the reference limiting cutting force. Slot cuts at various depths of cut have been performed in order to test this linear relation. From the slot cutting tests, it is observed that the resultant cutting forces increase linearly with increasing feedrate values, therefore, this simple relation is found for the feedrate-scheduling formula and it is also verified for non-slot cuts. When the feedrate is zero, it seems to be zero that there is no force acting on the cutting tool, since the tool is not moving. However there is a force, which occurs due to edge coefficients and rubbing effect between tool and workpiece. The relation can be expressed from the cutting force and chip load module. When the cutting forces are analyzed for CL points, the equation of line is changed for each depth of cut value, so that the feedrate scheduling formula should change for each depth of cut. The instantaneous infinitesimal chip load for ball-end mill cutter is obtained as follows:

$$\mathrm{d}A_\mathrm{c} = (t_\mathrm{c})_\mathrm{kn} \cdot (\mathrm{d}z)_\mathrm{kn} \quad (8)$$

For a differential chip load ($\mathrm{d}A_\mathrm{c}$) in engagement domain, the differential cutting forces in r,ψ and t directions is written as follows:

$$\mathrm{d}F_i = \mathrm{d}F_\mathrm{cutting} + \mathrm{d}F_\mathrm{edge} = K_\mathrm{ci} \cdot \mathrm{d}A_c + K_\mathrm{ei.}\mathrm{d}z \text{ where } i = r, \psi, t \quad (9)$$

It is also seen from the differential cutting force equation, the differential cutting force consists of cutting and edge parts like calibration constants. This provides to derive a linear relation depending on feedrate

$$\mathrm{d}F_i = A \cdot f + B. \quad (10)$$

The model is processed to keep the resultant force at the desired level for the CL points; the model uses the contact region defined for each CL point. The feedrate formula for the ith CL point is given as follows:

$$f_{\mathrm{lim},i} = (F_{\mathrm{lim},i} - F_{1,i}) \cdot \frac{f_2 - f_1}{F_{2,i} - F_{1,i}} + f_1 \quad (11)$$

where $i = 1,2\ldots C$, and C is the total CL point number in the tool path, f_1 (mm/min) is the constant feedrate for the tool path; f_2 (mm/min) is two times of f_1 in order to obtain the linear relation for the ith CL point at f_1 feedrate. Simulating the force model at f_2 feedrate does not increase computational time. F_1 is the maximum resultant force for the ith CL point at f_1 feedrate, F_2 is the maximum resultant force for ith CL point at f_2 feedrate, and $f_{\mathrm{lim},i}$ is obtained as scheduled new feedrate for the ith CL point.

The off-line method predicts cutting-load by using cutting force model and adjusts cutting parameters before actual machining. It can adjust the feedrate values based on the specific cutting conditions for each part of the CL points of the tool path. Scheduling the feedrate values are based on a limiting force value, which is the maximum resultant cutting force value. According to this reference force value, the scheduled optimal feed values are less than scheduled feedrate values based on material removal rate model. Some examples are given for force-based feedrate scheduling strategy in Section 5.

5. Force-based feedrate scheduling model and validation

Off-line feedrate scheduling regulates the maximum resultant cutting force in the x–y plane during one revolution of a cutter at a reference value for a given NC code. The scheduling requires accurate predictions of the cutting force waveforms and magnitudes (i.e. the cutting force profiles). In order to test the feedrate scheduling that is based on the force system model, some experimental validation tests were performed on Mazak FJV-200 UHS Vertical Machining Center using Al7039 workpiece material. A two fluted ball-end mill with the diameter of 12 mm, the nominal helix angle of 30°, and the projection length of 37 mm was used in the experiments. Kistler three-component dynamometer (Model 9257B) has been used to measure cutting forces. The displayed validation experiments were run at a spindle speed of 600 rpm. The original and constant scheduled feedrate value is 48 mm/min for all the tests. The new scheduled feedrate values have been given. In the simulation, ball part of the cutter was discretized into disks of 0.1 mm height, and the force calculations were performed every 3° of the cutter rotation. In order to perform concave and convex machining cases, off-line feedrate scheduling was applied to airfoil shape in Fig. 7a. The reference cutting force for force-based strategy was set to 360 N which is the resultant cutting force at 48 mm/min and 6 mm depth of cut for slot cutting case.

Firstly, the validation of force based feedrate scheduling was performed for airfoil geometry. Fig. 7c shows the simulated and measured cutting forces generated when machining using the constant feedrate value and constant non-modified NC code. The feedrate scheduling logic was applied to the part, and the optimal scheduled feedrate values were obtained in Fig. 7b for force-based feedrate scheduling strategy. The original NC code is changed (Fig. 7d) and scheduled according to the limiting resultant force. In order to verify the validity of the proposed method, the workpiece was machined along the tool path using the scheduled feedrate values. Fig. 7d shows the simulated and measured cutting forces in scheduled feedrate case for this part. It can be seen that both the measured and simulated forces are under the specified force value.

After applying force based strategy, MRR based feedrate strategy is applied to airfoil geometry. This time the maximum material removal rate is used as the reference MRR value in order to schedule feedrate values. Again the original NC code is changed (Fig. 7e) and scheduled according to the reference MRR value. In order to verify the validity of the proposed method, the workpiece was machined along the tool path using the scheduled feedrate values. Fig. 7e shows the simulated and measured cutting forces in scheduled feedrate case for this part. It is clear that the cutting forces are not below a prescribed value compared to force based strategy. Both the measured and simulated resultant forces are above the reference cutting force value, which is used in force-based strategy. The increase in forces is due to increase in scheduled feedrate values. When the scheduled feedrate values were compared in Fig. 7b, the MRR based strategy outputs higher feedrate values compared to force based strategy. This higher feedrate values will cause higher forces (Fig. 7e), which can damage the CNC machine, increase the tool wear, and deteriorate the final surface.

After verifying that the force based strategy determines the ideal feedrate values and forces, the force envelopes (Fig. 7f) before and after the force base feedrate scheduling were compared. Production time in this example was reduced considerably corresponding to 65.2% decrease compared to constant feedrate case. This decrease could be further reduced by setting a larger reference value; however, this can cause excessive forces, deflection and surface errors. The only observable difference between the constant and scheduled feedrate cases was the tooth marks on the machined workpiece surface, due to the high feed values, near the maximum points of the machined surface. This can be tolerated in rough milling.

6. Computation and cycle time results

The cutter has been moved through convex and concave paths in the x–y plane for the part given in Fig. 7a. Measured forces, patterns and predictions made by simulation for these paths showed very good agreement. The feedrate scheduling based on the mechanistic cutting force model was performed for airfoil geometry. Production time also known as cycle time in this example was reduced substantially. The cycle time of the airfoil was given for one pass of the tool path in Fig. 7f. However, the overall cycle time contains many passes. The pick feed was chosen to as 3 mm in this example. The width of the workpiece was 30 mm that contain eight passes. The original cycle time before the feedrate scheduling was 500.8 s, and both the simulated and measured scheduled new cycle time was 178.5 s. This shows that the production time was reduced significantly to 65% decrease compared to original case. Another important criterion for force-based feedrate scheduling strategy is the computation time of the simulation. ACRsim (Analytical Contact Region simulation program) generates the engagement domain of such a machining process in seconds; on the other hand other algorithms such as Z-mapping generate the engagement domain in the order of hours. The engagement domain computation time was 73 s for this airfoil shape by using ACRsim. The computation time for calculating the cutting forces and obtaining the scheduled feedrate values was 95 s. The overall computation time is obtained as 168 s. The computations were performed by using Matlab 6.5 software on HP Laptop Intel Pentium M, Processor 1.5GHz and 512 MB of RAM.

7. Conclusions

In this paper, both volumetric (Material Removal Rate (MRR)) and force-based feedrate scheduling strategies are compared theoretically and experimentally for 3D ball-end milling of free-form surfaces. It is shown and verified that MRR based feedrate strategy gives higher feedrate and cutting forces. Force based feedrate strategy is more meaningful in terms of cutting forces and feedrate values compared to MRR based. Since, the volumetric based feedrate scheduling method does not rely on the physics of the process. This lack causes the cutting forces not to be maintained at a constant limiting level.

A new uncut chip thickness was introduced with a new analytical contact region, and embedded into this enhanced force model. By using this enhanced force model, the resultant cutting force is kept under a pre-set threshold value. The NC code of the machined part is modified in order to produce the part with new scheduled feedrate values. Force based feedrate strategy is tested for some conditions including both concave and convex machining cases. Comparison of the simulated forces before and after the feedrate scheduling situations showed good agreement with the measured forces. Production times in these examples were reduced considerably corresponding to 45–65% decrease compared to constant feedrate cases.

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