Tool Path Generation for Milling of Free Form Surfaces With Feedrate Scheduling

Goran M. Mladenovic
Teaching Assistant
University of Belgrade
Faculty of Mechanical Engineering

Ljubodrag M. Tanovic
Full Professor
University of Belgrade
Faculty of Mechanical Engineering

Kornel F. Ehmann
Full time Professor
Northwestern University
Department of Mechanical Engineering
Evanston, Illinois,
USA

The use of freeform (sculptured) surfaces in the product design process is accelerating at an exponential rate driven by functional as well as esthetics demands. CAD/CAM software is a must in their design and manufacture. While the geometric aspects of the design are relatively well-covered, issues still remain when it comes to the actual manufacture of freeform surfaces. The major issues are related to the generation of the proper toolpaths that would assure the required surface quality, the minimization of the total maching time, the control of the magnitude of the cutting forces, etc. This paper presents an algotithmic procedure for tool path generation based on the criterion of maintaing the cutting forces at a constant pre-defined level for 3-axis ball end milling processes. To this end, a model for cutting force prediction is formulated and incorporated into the tolpath generation algorithm and software that is compatible with all CAD/CAM systems. It has been experimentally confirmed that the proposed algorithm offers a number advantages over the machining strategies used in commercial CAD/CAM software.

Keywords: *Free form surface, tool path, ball-end milling.*

1. INTRODUCTION

Today, many products are designed by using freeform (sculptured) surfaces, not only in the automobile, aerospace and shipbuilding industries but also in the die/mold industries for various machined parts. Freeform surfaces are predominantly used to improve design and/or to enhance functional requirements. The most commonly used machining procedures are 3 or 5-axis ball-end milling operations. This fact entails the issue of tool path generation that implies the use of CAD/CAM systems to analytically represent the surface and, based on it, to generate an appropriate tool path.

The determination of the optimal tool path for machining of freeform surfaces requires the simultaneous fulfillment of a number of requirements, such as the amount of data that have to be stored in the machine tool control unit (MTCU), quality and accuracy of the machined surfaces, milling forces, total machining time, and the like.

Cutting forces are the main factors governing machining accuracy, surface quality, machine tool vibrations, power requirements and tool life. The ability to predict the cutting forces is useful for the design of machine tool structures and cutting tools, as well as for the control and optimization of the machining processes to achieve high accuracy and productivity [1].

The steps required to perform freeform surface machining are usually classified into roughing, semi-finishing and finishing machining operations. In rough cutting, most of the material is removed from the surface to generate an approximate shape of the surface. Shoulders left from the roughing stage by large machine tools are removed in semi-finishing to yield a continuous offset surface for finishing. In the finishing stage, the rough surface is transformed into the exact shape [2, 3]. In rough cutting, as much material as possible needs to be removed in the shortest possible time, so extensive research work is devoted to this area. One of the applied methods is feedrate scheduling to maintain the cutting force at a constant value, which results in a significant reduction of the total machining time compared to the method of maintaining a constant depth of cut and feedrate [4]. The use of such an optimization method is justifiable only in rough cutting, because the depths of cut are very small in surface finishing and consequently the cutting force is small.

In addition to the above-mentioned methods multicriteria optimization methods for freeform surface machining where also developed. They include mathematical solutions that consist of the physical relationship between the mean resultant forces, cycle time and scallop heights [5].

The use of multicriteria optimization can be justified only in the case when roughing is, at the same time, the finishing operation. In cases when it is necessary to remove as much material as possible in the shortest possible time and preferably in a single-pass it is necessary to develop a machining strategy in which the roughness and tolerances are maintained within the prescribed limits, and tool breakage, and the overstepping of the cutting force limits and/or the overloading of the drive motor of the servo axis of the machine is avoided.

This paper presents a three-axis ball-end milling process simulation algorithm for obtaining a tool path

---

Received: October 2014, Accepted: December 2014
Correspondence to: Goran Mladenović
Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade 35, Serbia
E-mail: gmladenovic@mas.bg.ac.rs
doi:10.5937/fmet1501009M

that maintains the cutting force at a constant pre-specified level.

Henceforth, the paper is organized as follows: An overview of the developed methods for machining of free form surfaces is presented in Section 2, followed by a description of the procedure for developing a cutting force model in Section 3. The use of the developed cutting force model in the proposed algorithm for the generation of tool paths that maintain a constant cutting force is described in Sections 4. The implementation and feasibility of the proposed algorithm and machining strategies are demostrated through experiments and implementation in commercial CAD/CAM software in Section 5. The paper concludes with a summary in Section 6.

2. TOOL PATH GENERATION

The determination of the tool path is a very significant step in the process of designing the technology for complex surface machining. When the optimal tool path, aimed at achieving a satisfactory quality of the machined surface and an optimal machining time, is to be obtained, various specific constraints must be observed. For the case of rough cutting the machining time needs to be minimized, but the quality of the machined surface is not that much important. In surface finishing, in turn, care should be taken that the scallop height does not exceed the allowable deviation as prescribed by the technical documentation, but machining time does not play a significant role in the design of the machining technology. An ideal tool path should generate uniformly distributed scallops across the whole surface [6]. Smaller scallop heights than prescribed do not necessarily mean a better tool path, because the required increase in the number of tool passes increases machining time and, thereby, the cost of the part. On the other hand, a minimal machining time will be achieved when the scallop height is set to the maximal allowable measure [7].

Sculptured surfaces are most frequently represented as a bicubic Bézier, B spline or NURBS surface, which are defined and based on control points specified in Cartesian coordinates. Each point on the surface is calculated using the corresponding formulas as a function of two parameters, u and v. Specifying one parametric value enables the construction of a curve as a function of the other parameter, whereby a surface grid is generated. Three methods for complex surface machining have been developed so far, i.e., iso-parametric, iso-planar and iso-scallop.

2.1 Iso-parametric method

Iso-parametric paths have first been addressed by Loney and Ozroy [8]. The method of iso-parametric machining of complex surfaces takes advantage of the straightforward utilization of data on surface points to generate the tool path in such a way that the cutter location (CL) point is located on the surface normal vector at a distance equal to the radius of the spherical part of the ball-end mill. The disadvantage of this method is the varying scallop-height distribution on the machined surface, because keeping constant steps in parametric space leads to non-uniform steps in Cartesian space. Elber and Cohen were the first to report the solution to this problem and their method was referred to as the adaptive iso-parametric method [9].

2.2 Iso-planar method

In most cases the tool path in complex surface machining coincides with one of the coordinate axes of the machine tool. This has led to the development of the iso-planar method of machining, which means that the tool path is determined as an intersection of a freeform surface ($S_{u,v}$) with one of the coordinate planes of the Cartesian coordinate system. As it is difficult to determine the points of intersection between the surface and the plane, the surface should be approximated by a set of planar triangular surfaces, where every triangle is defined by the coordinates of its three vertices [10]. This method is very robust and widely used in commercial CAM systems [11]. The side step (L) in this method equals the distance between the parallel planes and is determined from the conditions defined by the maximum allowable scallop height of the machined surface (h), whereas the size of the forward step (L_{CL}) is determined from the condition of the highest allowable deviation (t), Fig. 1.

In this method, the adequate choice of the intersecting planes has a straightforward impact on the tool path length and, thereby, on the total machining time.

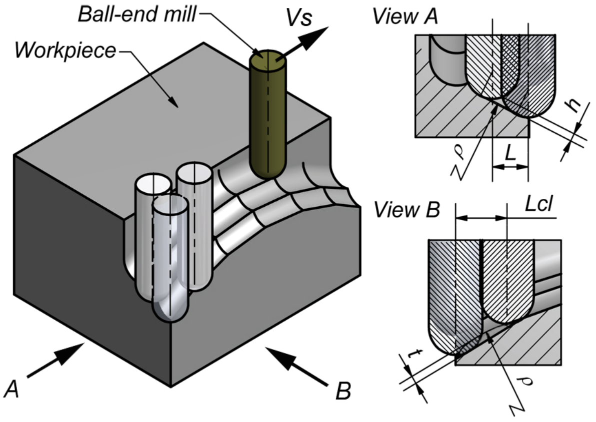

Figure 1. Side step and forward step

Both of the above-mentioned methods lead, in only a very small number of cases, to a uniform distribution of scallop heights on the machined surface. When there are parallel plane-surface intersections, and the parallel planes are eqidistant, unnecessary large scallop heights may be realized in some places on the machined surface, whereas, at other places, they may be very small.

2.3 Iso-scallop method

To obtain a uniform scallop height distribution across the machined surface, a novel machining method, called the iso-scallop method, has been introduced [12, 13]. The method of iso-scallop machining is an improved iso-parametric and iso-planar method. To define the tool path that respects the condition of uniform scallop height, subsequent tool paths must be defined based on the known preceding paths and the condition that the curve representing the scallop peaks between two tool passes is common for both passes. This principle implies that the known iso-scallop surface is an edge intersection curve of the tool envelope surface and the iso-scallop surface.

The iso-scallop tool paths do not lead to redundancy and multiple machining passes over the same part surface are unnecessary. This implies that a shorter path is obtained in this way, i.e., workpiece machining is performed for a shorter time as compared to NC machining with iso-parametric or iso-planar tool paths [14].

3. DEVELOPING A CUTTING FORCE MODEL

Many researchers have developed models for cutting force prediction in milling operations [15-24].

As the cutting speed is varying on the spherical part of a ball-end mill, it is difficult to maintain valid machining parameters to achieve a satisfactory quality of the machined surface. The cutting force acting on the workpiece is one of the variables that has a crucial impact on machined surface quality.

An adequate cutting force model should ensure accurate prediction of the real cutting force for determining the proper machining technology for the part. The specificity of milling compared to other methods includes intermittent cutting and the variable position of the primary cutting edges as well as the thickness of the uncut chip removed by the different sections of the cutting edges. For these reasons, cutting force prediction involves calculations of the instantaneous values of the cutting force components at a sufficiently large number of consecutive angular positions corresponding to a complete revolution of the tool for the given machining conditions [16].

For the above stated reasons the mechanistic approach first developed by DeVoret al. (1980) [15] will be used to formulate a suitable force model to be included ito the proposed toolpath generation algorithn. The procedure for the discretization of the ball-end mill's edge was implemented by slicing the ball ehnd mill into infinitesimal discs of thickness (dz), Fig. 2a.

Based on the angular position (φ) of a particular cutting edge segment, Fig. 2b, calculations are conducted to determine the current axial (aax) and radial (arad) depths of cut as shown in Fig 2c for each disk, i.e., for each infinitesimal cutting edge segments. A constant helix angle is assumed in the implemented model. Calculations are performed based on the entry (φst) and exit (φex) angles, Z-coordinate of the current Cutter Location points (Cl) and the ball-end mill radius (R). The elemental cutting force in a plane perpendicular to the tool axis in decomposed into its tangential and radial component as shown in Fig. 2b where the X-direction is the feedrate direction. The scheme displays an arbitrary position of the tool's primary cutting edge position in an arbitrary angular position relative to the reference direction defined by the angle φ.

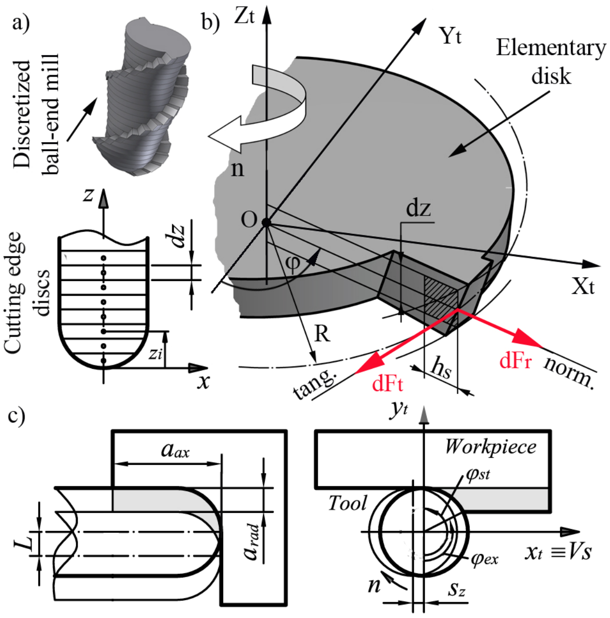

Figure 2. Discretization of the ball-end mill cutting edge (a), scheme of cutting forces on the mill's primary cutting edge (b), axial and radial depth of cut (c)

Along the primary cutting edge length, according to [15], the components of the cutting force in the tangential and radial direction are calculated using Eqs. (1) and (2), whereas relative to the tool coordinate system $X_tY_tZ_t$ using Eqs.(3) and (4):

$$dF_t = K_{tc}h_s dz + K_{te}dz \quad (1)$$

$$dF_r = K_{rc}h_s dz + K_{re}dz \quad (2)$$

$$dF_X = -dF_t \cos\varphi + dF_r \sin\varphi \quad (3)$$

$$dF_Y = -dF_t \sin\varphi - dF_r \cos\varphi \quad (4)$$

The resultant force in two perpendicular directions (X_t and Y_t) is obtained by summing up all forces of the primary cutting edge that participate in the machining process.

The cutting force coefficients (K_{tc}, K_{te}, K_{rc}, K_{re}) are experimentally determined according to the experimental scheme presented in Fig. 3 according to the customaty procedures described in [21, 24].

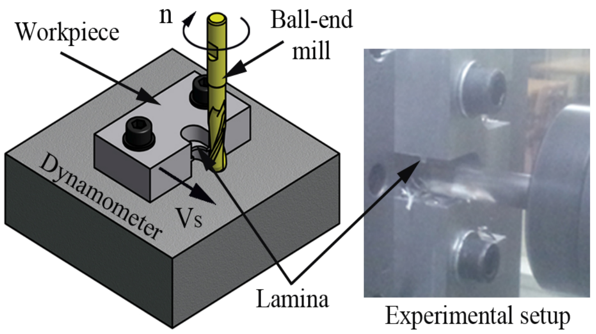

Figure 3. Experimental scheme for determining the cutting force coefficients

For the experimental determination of the cutting force coefficients a two-component dynamometer and data acquisition and processing system were used to measure the cutting forces at a cutting speed of 40 m/min and a feedrate per tooth of 0.015-0.3 mm/tooth. Aluminum (AlMg4.5Mn) laminae of 2-mm-thickness were fastened to the dynamometer. This thickness was chosen to

coincide with the disk thickness (dz) used for discretizing the tool in the model to be used for force predictions. Machining was performed with a high-speed cutting steel (NSSE 8% Co) ball-end mill with a 12 mm in diameter with 2 teeth and a helix angle of 30^0 on a horizontal machining centre ILR HMC500/40.
Measurements were performed at four positions along the tool axis, i.e., at three positions along the ball part and at one along the cylindrical part of the cutter. The experimentally determined values of the cutting force coefficients along the tool axis are presented in Table 1.

Table 1. Dependence of the cutting force coefficients on cutting edge segment location along the tool axis

Z/R	K_{tc}[N/mm^2]	K_{rc}[N/mm^2]	K_{te}[N/mm^2]	K_{re}[N/mm^2]
0.03	1230	348.4	16.6	5.6
0.33	957.8	443.5	6.8	3.8
0.67	930	442.9	6.5	3.3
1	940	557.1	6	0.9

In order to verify the applicability of the determined cutting force coefficients comparative analysis of the cutting forces obtained by simulation and experiments was carried out under the following machining conditions: axial depth of cut of 2 mm, radial depth of cut od 12 mm, feedrate per tooth 0.07 mm/tooth and cutting speed of 40 m/min performed with a ball-end mill of 12 mm in diameter with 2 teeth.

The cutting forces were simulated using MATLAB code that was developed in accordance with the algorithm described in [20]. A comparison of the experimentally determined and simulated cutting forces, based on the cutting force coefficients in Table 1, for a complete revolution of the tool, are given in Fig. 4. A slight disagreement between the simulation results (Sym-1) and the experimentally determined values of the cutting forces (Exp) is caused by the tool's radial eccentricity, amounting to 0.01 mm. Simulation results with included radial eccentricity are represented by the line Sym-2. Based on the above, it can be concluded that the applied model for cutting force prediction produces results acceptable for further use in the toolpath generation algorithm.

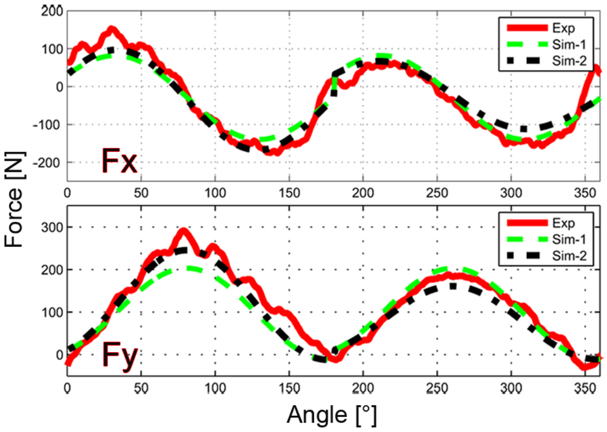

Figure 4. Comparison of cutting forces determined based on simulation and experiment

4. TOOL PATH OPTIMIZATION

4.1 Algorithm

Using the developed cutting force model for the given combination of tool and workpiece material, CAM software has been developed and employed to generate tool paths according to the iso-parametric method, using as an example bicubic Bézier surfaces. The software generates a surface grid according to the equation:

$$S(u,v)=\sum_{i=0}^{3}\sum_{j=0}^{3}b_i(u)b_j(v)P_{ij} \tag{5}$$

where the basic functions $b_i(u)$ and $b_j(v)$, i,j=0,1,2,3 are defined by relations:

$$\begin{aligned} b_0(t)&=(1-t)^3\\ b_1(t)&=3t(1-t)^2\\ b_2(t)&=3t^2(1-t)\\ b_3(t)&=t^3 \end{aligned} \tag{6}$$

where t is a parameter defined in the range of [0,1] and P_{ij} are control points whose coordinates are inputed into the MATLAB code. Further, in accordance to the tool radius used the software determines the Cl points which lie in the direction of the surface normal vector offset from the surface by a distance equal to the tool radius (R). The normal vector can be calculated from:

$$n=\frac{S_u\times S_v}{|S_u\times S_v|} \tag{7}$$

where S_u represents the partial derivate of surface S with respect to the parameter u, and S_v with respect to v. According to the workpiece geometry and tool radius, the developed software determines at each point of the grid the axial and radial depth of cut according to the scheme in Fig. 2c. For the recommended cutting speed and the initial value for the feedrate per tooth that is defined according to the recommendations of the tool manufacturer the maximum value of the resulting cutting force in the plane perpendicular to the tool axis is calculated according to:

$$F=F_{XY}=\sqrt{F_X^2+F_Y^2} \tag{8}$$

where F_X and F_Y are determined according to the method described in Section 3 for the given combination of the workpiece and tool material. Based on the defined maximum value of the cutting force the software performs a correction of the initial feedrate if necessary, so that the cutting force is maintained (within a tolerance limit of ±5%) at the user specified level (F_{XYmax}).

The described procedure is summarized by the flow chart of the algorithm shown in Fig. 5.

According to the procedure described above the software generates tool paths for which the cutting force is maintained at a constant value by varying the feedrate in the specified range, e.g., from 0.015-0.13 mm/tooth for a cutting speed of 40 m/min used above. In the case that the value of the feedrate reaches the minimum allowable value, and the cutting force value is higher than the maximum allowable, a notification is received that the surface cannot be machined using the specified machining parameters, and, as a consequence, machining should be done in several passes.

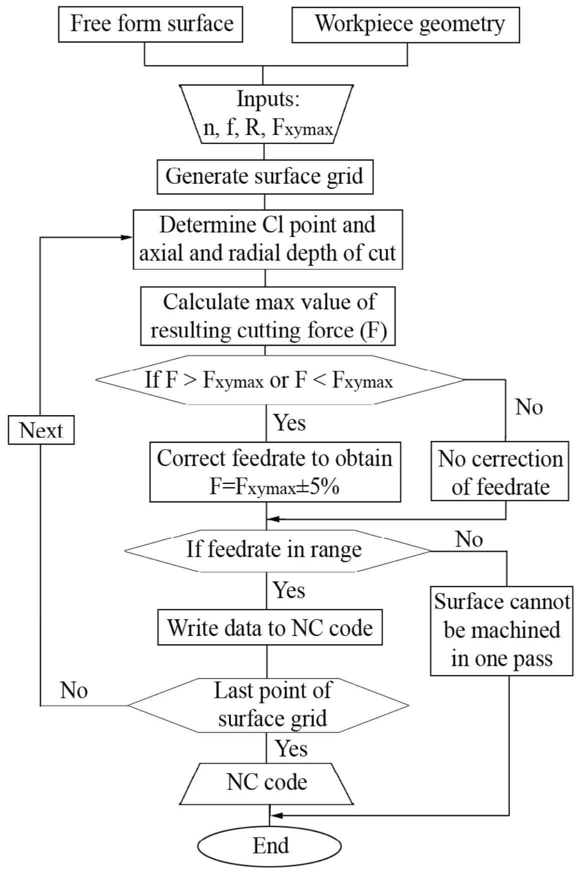

Figure 5. Algorithm for tool path generation

4.2 Experimental verification

Based on the above-described algorithm an NC program for free form machining with the following machining parameters was created: number of tool revolutions 1,060 RPM which for the defined range of the value of the feed per tooth of 0.015-0.13 mm/tooth and ball-end mill diameted of 12 mm gives a range for feedrates of 31-180 mm/min. In the experiments the same tool and workpiece materials were used as in Section 3.

Figure 6a presents the generated tool path which consists of 21 passes and the change of the axial and radial depth of cut for one pass (pass number 7).

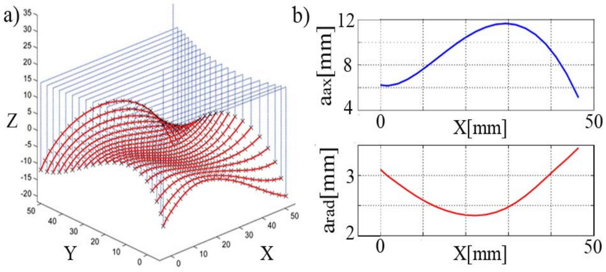

Figure 6. Generated tool path (a), the change of axial and radial depth of cut for pass number 7 (b)

The experimental setup for the determination of the cutting forces in freeform surface machining is shown in Fig. 7. The workpiece 50x50x50 mm in size was fastened through a distance plate to a two-component dynamometer mounted, through a fixture, to the working table of an ILR HMC 500/40 machine. Signals of the two perpendicular components of the cutting force enter two amplifiers KWS3082A, HBM Co., where their conditioning is performed. From the amplifiers, signals enter the system for data acquisition that consists of NI Compact DAQ USB cDAQ-9174 with a NI9215 module for analog input: ±10 V, 16-bit with 4 channels and 100 ks/s/ch. The measurement results were analysed in LabVIEW software.

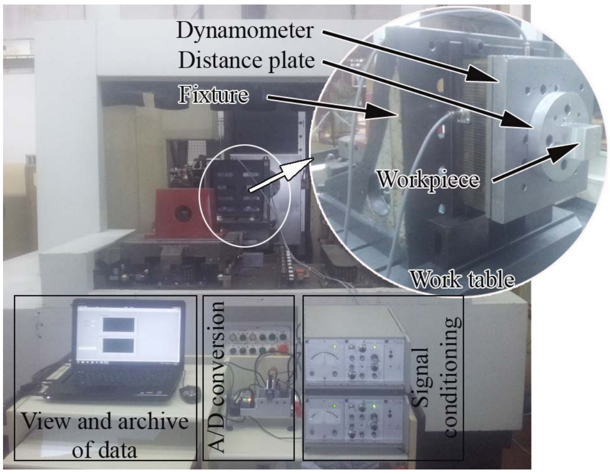

Figure 7. Experimental setup for determining the cutting forces in freeform surfaces machining

The measured values of the cutting forces as a function of time in the plane perpendicular to the tool axis for a one pass (pass number 7) is given in Fig. 8, where it is noticeable that the value of the resultant cutting force (FXY) was kept at the specified value of 600 N.

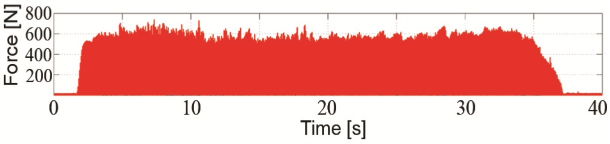

Figure 8. The resultant cutting force in the plane perpendicular to the tool axis for pass number 7

5. A COMPARATIVE ASSESSMENT OF MACHINING STRATEGIES: DEVELOPED VS. COMMERCIAL CAD/CAM SOFTWARE

During the above-specified surface machining process (Section 4.2) according to the scheme in Fig. 7 the axial depth of cut would vary from 3.8 to 27.7 mm (Fig. 9a), hence the use of the constant feedrate method would lead to tool failure if the feedrate was too high, or to a considerable extension of the machining time if the value of the feedrate was defined based on the maximal depth of cut. This situation would occur because at places with a small depth of cut the corresponding cutting force would be much smaller than the maximum allowable. Also, in the case of applying a machining strategy based on a constant feedrate, machining would have to be most often performed in several passes, with a limited maximal depth of cut.

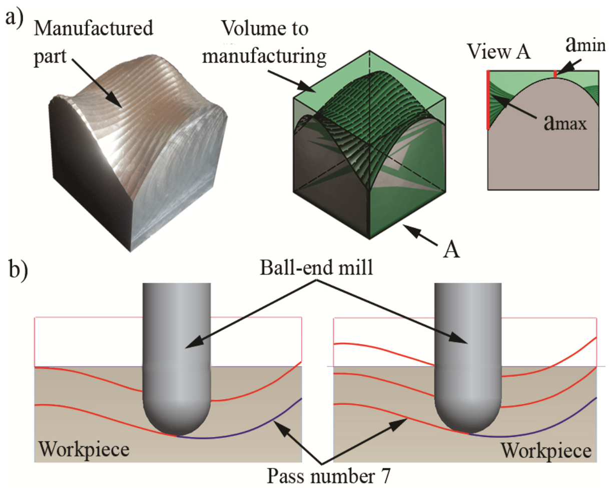

Figure 9. Representation of a machined part with marked places of maximum and minimum axial depth of cut (a), machining strategy along the trajectory chosen by the CAD/CAM software Pro/Engineer Wildfire 4.0 (b)

Table 2 shows a comparative analysis of several machining strategies for one pass (pass number 7). The machining strategy described in Section 4 of this paper is compared with the machining strategy along the trajectory chosen by the CAD/CAM software Pro/Engineer Wildfire 4.0 (Fig 9b), where the feedrate for the chosen maximum axial depth of cut is such that in none of the cases the total cutting force in the plane perpendicular to the tool axis exceeds the value of 600N. Also, the total machining time and number of sentences of the NC code is given for each of the strategies that can be used as a criterion for the choice of the strategy.

Table 2. Comparative analysis of several machining strategies

Machining strategy	Axial depth of cut [mm]	Feedrade [mm/min]	Number of passes	Number of sentences of NC code	Total machining time [min]
Feedrate scheduling (experiment)	5.2-11.7	63-144	1	32	0.61
Constant feedrate (commercial CAM software)	6	145	2	57	1.62
	5	178	3	81	2.05

The analysis of data in Table. 2 leads to the conclusion that the described tool path generation procedure of the NC code with feedrate scheduling, aimed at keeping a cutting force constant, has advantages over the currently available machining strategies used in commercial CAM software packages.

The advantages of the feedrate scheduling method refer largely to two items:

- Shorter machining time is obtained and, thereby a lower cost of a piece.
- Significantly smaller number of sentences is obtained in the NC code, which reduces the machine operator's work.

The disadvantage of the developed CAM software is that a significantly longer time is required for tool path generation as compared to commercial CAM software packages, because, in this case, to determine the value of the maximal cutting force and, based on it, to correct the value of feedrate, it is necessary to perform the simulation of a complete tool revolution at each CL point.

6. CONCLUSION

The paper presents a procedure for generating optimized toolpaths for milling freeform surfaces according to the criterion of keeping the cutting force constant by using the cutting force model created for simulating the process of machining by a ball-end mill. Simulation results were experimentally verified at the Institute for Machine Tools, Faculty of Mechanical Engineering, Belgrade. The analysis of the experimental and simulation results lead to the conclusion that the developed algorithm for tool path generation is useable and applicable in CAM software packages primarily for the reason of minimizing the total machining time for the case of rough cutting. The given algorithm is particularly suitable for tool path generation in machining of parts with thin walls, where workpiece deformation would occur when the maximal allowable cutting force is exceeded.

REFERENCES

[1] Ikua, B. W., Tanaka, H., Obata, F. and Sakamoto, S.: Prediction of cutting forces and machining error in ball end milling of curved surfaces - I theoretical analysis, Precision Engineering, Vol. 25, Issue 4, pp. 266-273, 2001.

[2] Lee, Y.S., Choi, B.K., and Chang, T.C.: Cut distribution and cutter selection for sculptured surface cavity machining, International Journal of Production Research, Vol.30 No.6, pp. 1447–1470, 1992.

[3] Ren, Y., Yau, H.T., and Lee, Y.S.: Clean-up tool path generation by contraction tool method for machining complex polyhedral models, Computers in Industry, Vol.54 No.1, pp. 17–33, 2004.

[4] S. Ehsan Layegh K., Erdimb, H. and Lazoglu, I.: Offline Force Control and Feedrate Scheduling for Complex Free Form Surfaces in 5-Axis Milling, in: Procedia CIRP, Volume 1, 5th CIRP Conference on High Performance Cutting, pp. 96–101, 2012.

[5] Manav, C., Bank, H.S., and Lazoglu, L.: Intelligent toolpath selection via multi-criteria optimization in complex sculptured milling, Journal of Intelligent Manufacturing, Vol. 24, Issue 2, pp. 349–355, 2011.

[6] Warkentin, A., Hoskins, P., Ismail, F. and Bedi, S.: Computer aided 5-axis machining, Computer aided design, engineering and manufacturing: system techniques and applications, CRC Press [chapter 3], 2001.

[7] Lasemi, A., Xue, D., and Gu, P.: Recent development in CNC machining of freeform surfaces: A state-of-the-art review, Computer Aided Design, Vol. 42, pp. 641–654, 2010.

[8] Loney, G.C. and Ozsoy, T.M.: NC machining of free form surfaces, Computer-Aided Design, Vol. 19 No.2, pp. 85–90, 1987.

[9] Elber, G., and Cohen, E.: Toolpath generation for freeform surface models, Computer-Aided Design, Vol.26 No.6, pp. 490–496, 1994.

[10] Bojanić, P.: A Tool Path Generation For Three-Axis Ball-End milling Of Sculptured Surfaces, in: Proceedings of the 33rd Conference On Production Engineering Of Serbia, 2009, pp. 115-118, (in Serbian)

[11] Han, Z.L. and Yang, D.C.H.: Iso-phote based tool-path generation for machining free-form surfaces, Journal of Manufacturing Science and Engineering, ASME Transactions, Vol. 121 No.4, pp. 656–664, 1999.

[12] Suresh, K. and Yang, D.C.H.: Constant scallop height machining of free form surfaces, Journal of Engineering for Industry, ASME Transactions, Vol.116, pp. 253–259, 1994.

[13] Lin, R.S. and Koren, Y.: Efficient tool-path planning for machining free-form surfaces, Journal of Engineering for Industry, ASME Transactions, Vol.118 No.1, pp. 20–28, 1996.

[14] Bojanić, P., and Mladenović, G.: A Iso-Cusped Tool Path Generation For 3-Axis Sculptured Surface Machining, in: Proceedings of the 36th Jupiter Conference, 2010, pp. 2.22-2.28, (in Serbian)

[15] DeVor, R.E., Kline, W.A., and Zdeblick, W.J.: A Mechanic Model For The Force System In End Milling With Application To Machining Airframe Structures, Manufacturing Engineering Transactions, pp 297-303, 1980.

[16] Kline, W.A., DeVor, R.E., and Lindberg, J.R.: The prediction of cutting forces in end milling with application to cornering cuts, International Journal of Machine Tool Design and Research, Volume 22, Issue 1, pp 7-22, 1982.

[17] Fu, H.J., DeVor, R.E., and Kapoor, S.G.: A Mechanistic Model for the Prediction of the Force System in Face Milling Operations, ASME Journal of Manufacturing Science and Engineering, Volume 106, Issue 1, pp 81-88, 1984.

[18] Sutherland, J.W., and DeVor, R.E.: An Improved Method for Cutting Force and Surface Error Prediction in Flexible End Milling Systems, ASME Journal of Manufacturing Science and Engineering, Volume 108, Issue 4, pp 269-279, 1986.

[19] Jayaram, S., Kapoor, S.G. and DeVor, R.E.: Estimation of the specific cutting pressures for mechanistic cutting force models, International Journal of Machine Tools and Manufacture, Volume 41, Issue 2, pp 265-281, 2001.

[20] Altintas, Y.: *Manufacturing Automation – Metal Cutting Mechanics, Machine Tool Vibrations and CNC Design,* Cambridge University Press, 2000.

[21] Azeem, A., Feng, H-Y. and Wang, L.: Simplified and efficient calibration of a mechanistic cutting force model for ball-end milling, International Journal of Machine Tools and Manufacture, Vol.44, pp. 291-298, 2004.

[22] Puzović, R. and Kokotović, B.: Prediction of thrust force and torque in tapping operations using computer simulation, FME Transactions, Volume 34, Issue 1, pp 1-5, 2006.

[23] Tuysuz, O., Altintas, Y., and Feng, H.Y.: Prediction of cutting forces in three and five-axis ball-end milling with tool indentation effect, International Journal of Machine Tools and Manufacture, Volume 66, pp 66-81, 2013.

[24] Kokotović, B.: *Milling In Virtual Manufacturing System*, PhD thesis, University of Belgrade Faculty of Mechanical Engineering, Belgrade, 2013.(in Serbian)

ГЕНЕРИСАЊЕ ПУТАЊЕ АЛАТА ЗА ОБРАДУ СЛОБОДНИХ ПОВРШИНА ГЛОДАЊЕМ ВАРИРАЊЕМ БРЗИНЕ ПОМОЋНОГ КРЕТАЊА

Горан М. Младеновић, Љубодраг М. Тановић, Kornel F. Ehmann

Употреба слободних (скулпторских) површина у процесу пројектовања производа расте по експоненцијалном нивоу како из функционалних тако и из естетских разлога. У процесу пројектовања и израде слободних површина неизоставна је употреба CAD/CAM софтвера. Док су геометријски аспекти пројектовања релативно добро покривени, проблеми и даље остају када је у питању стварна производња слободних површина. Главни проблеми су повезани са одређивањем одговарајуће путање алата која би обезбедила захтеван квалитет обрађене површине, минимизацију укупног времена обраде, контролу интензитета силе резања итд. У раду је приказан алгоритам за генерисање путање алата заснован на критеријуму одржања силе резања на константну унапред дефинисану вредност за процесе 3-осне обраде лоптастим глодалом. У ту сврху је развијен модел за предикцију силе резања који је укључен у алгоритам за генерисање путање алата и софтвер који је компатибилан са свим CAD/CAM системима. Експериментално је потвђено да предложени алгоритам има бројне предности у односу на стратегије обраде комерцијалних CAD/CAM софтвера.