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Effect of Toolpath and Feed Rate on the Machining of Coons Surfaces

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ABSTRACT

In this study, complex shapes are defined as the sculptured surfaces created by the blending of curves, to form surface patches. Past investigations show that non-uniform rational B-Splines (NURBS) curves are the most appropriate for the modeling of sculptured surfaces. The main objective of this research is to examine the effects of toolpath and feed rate variations on the machining of the Coons surface, which is modeled through NURBS. Based on simulation results, it is clear that toolpath and feed rate selection plays a significant role in sculptured surface machining. In particular, the toolpath selection seemed to have a greater effect on the surface finish and machining time than the feed rate. The results also show that the feed rate option has a much greater effect on roughing than finishing operations. It can also be seen in this research that the toolpath option played a more significant role than feed rate selection in determining the file size.

Keywords: *Sculptured Surface Modeling, NURBS, Blending Function, Feed Rate, Toolpath, Computer Aided Design and Manufacturing*

Introduction

Current trends in consumer product design see the increasing use of freeform shapes. Most modern computer-aided design (CAD) packages support the creation of free-form surfaces [1]. Algebraic and parametric rules generally govern the creation of these surfaces [2]. Sculptured surfaces were formerly considered to be impractical to produce with numerical control (NC) machines [3]. These surfaces are used in a wide range of applications including those for aircraft, automobiles, construction and agricultural equipment, machine tools, digital appliances, and instrument cases. To accurately manufacture molds for these sculptured objects and achieve the tight tolerances, several methods of toolpath generation were used [4] in the past.

However, the existing toolpath generation techniques seek to maximize the volume of material removed. But here, it is also important to recognize that the current toolpath generation techniques only take the tool and toolpath geometry into consideration, and neglect the important aspect of load on the tool. Thus the principle of optimized feed rates to achieve constant load on the tool has become necessary. Optimized feed rates have been shown to improve surface finish and decreased machining time [5] and thus the same principle has extended in this paper to determine the feasible conditions for machining of sculptured surfaces.

Research has also been carried out in determining the best cutter geometry for the machining of sculptured surfaces. Current research shows the use of ball end-mills as the tool of choice for finishing operations, while flat and bull-nosed/ torus end-mills are used for roughing and semi-finishing operations [6]. To determine a desirable configuration for machining of a sculptured surface, an attempt is being made in this paper to investigate the effects of toolpath and feed rate on the surface finish and machining time. The rest of the paper is organized as follows: Section 2 reviews the literature on toolpath and federate issues. Research methodology is dealt with in Section 3. Experimental results are presented in section 4. Discussion of results is provided in Section 5. Finally, the conclusions and future research directions are presented in Section 6.

Literature Review

In sculptured surface technology, complex contours are represented as a network of patches each expressed in terms of known points, vectors, and curves [3]. The contour of each patch conforms to that of the small surface section it is intended to represent. Together, the patches describe surface contours that would otherwise be difficult to define mathematically. In this research paper, complex shapes will be defined as the sculptured surfaces created by the blending of curves, to form surface patches.

Out of the currently available toolpath generation methods, *iso-cusped* and *steepest directed tree* toolpath generation strategies seem to be the most efficient for sculptured surface machining [7]. The *iso-cusped* [2] method evenly distributes toolpaths across the surface to ensure that cusps are of equal height, thus eliminating redundant machining. The steepest directed tree method defines tool paths by connecting the nodes of generated surface mesh to climb the geometry features in a steepest way. The disadvantage of these methods is that the tool does not remove the maximum volume of material in each tool motion step if the speed and feed rate are kept at a constant pace. The following two sections will elaborate on toolpath and feed rate issues in the manufacture of sculptured surfaces.

Toolpath Issues

Toolpath generation for sculptured surfaces is a difficult task, which has been investigated rigorously by various researchers since twenty five years [8]. Many researchers have investigated to various degrees of the geometric simulation of machining process. In particular, Bertok [9] proposed a torque prediction system based on the geometric simulation of flat-end milling operation which was able to compute the removed volume of material per tooth. Based on constructive solid geometry (CSG) part representation, Wang [10] investigated a similar method to predict average cutting forces. Takata [11] described a milling simulation system to predict instantaneous cutting forces where a geometric simulation model was a combination of the z-buffer and the swept volume generation techniques. Spence [12] discussed a simulated in-process model for flat-end milling operation in which the instantaneous chip geometry was computed by sweeping a semicircle along the toolpath. Feng and Menq [13] laid the foundation to determine the boundary of engaged surface between tool and workpiece. However, the calculations are not based on a geometric model of in-process part. El-Mounayri et al.[14] studied a ball-end milling simulation model to compute the volume of material removed, where the cutting edge was modeled with a cubic Bezier curve.

Research has also been conducted on toolpath planning of sculptured surfaces formed by swept or revolved profiles [15]. These studies highlight the importance of non-uniform rational B-Splines (NURBS) or other curve type interpolators for the conversion of the knot and control points of the profile to the NC equivalent. Thus, it is possible to simplify very long and complicated programs to shorter ones. Some of the more recent investigations in toolpath planning are in some ways similar to the methods of Chen *et al.* [16]. The study of Giri *et al.* [17] described the use of master cutter path based on maximum and minimum convex curvature principles. This method has shown to reduce machining times for maximum convex curvature and reduce cutter location (CL) data file size for minimum convex curvature.

Feed Rate Issues

In current commercial CAD/CAM packages, the NC program for milling of a given surface is normally generated with a constant spindle speed and feed. Therefore, the NC programmer is forced to use conservative spindle speeds and feeds based on the worst cutting conditions [18]. This approach has shown that there is a greater scope for improvements to be made in this area [5].

Optimization results of Feng and Su [19] have indicated that the shortest total toolpath length, favored by most existing optimization approaches, does not result in maximum efficiency because the corresponding feed rate is often constrained by the specified tolerance. The optimum cutter feed direction is in general not unique but falls within an optimum range in the finishing machining of 3D plane surfaces.

Current practices determine toolpath and feed rate individually. Optimization of these two parameters is accomplished sequentially and independently. This sequential approach limits further optimization of the process and leads to higher product cost. Toolpaths and feed rates in 3D surface machining are in fact closely related with each other. Variable feed rate that maintains safe cutting could provide substantial time savings to manufacturers [20]. An integrated planning approach is necessary to optimize the machining process by determining tool path and feed rate simultaneously.

Of the simpler methods available for determining the optimum feed rate, the most prominent method of recent works is based on analyzing the tool as a cantilever beam. The feed rate is adjusted to keep the force on the tool equal to the maximum safe load, which it can withstand. Jerard *et al.* [5] managed to achieve constant cutting forces in the machining of a mold cavity by using this method.

The computer aided part programming methods that are currently in use identified the cutter geometry, toolpath, and feed rate as some of the critical factors for improving the surface finish and machining time. Ample investigations have been carried in this area. However, from the literature it is clear (refer to Table 1 and Figure 1) that most of the research work in this area has focused on the modeling of cutter geometry. This is understandable since cutter geometry models would be necessary at the product design stage. This research seeks to further examine the effects of toolpath and feed rate variations on the machining of sculptured surfaces with goals of obtaining better surface finish and shorter machining times.

Methodology

To achieve the objective of the study, two steps which are taken into consideration are: selection of the construction curve to form the sculptured surface and determination of a desirable toolpath and feed rate configuration for machining of a Coons sculptured surface, which are explained below.

Step I: Selection of the Construction Curve

Five curve creation methods for design and development of the Coons surface are reviewed with an objective of decreasing the machining time and improvement in surface finish of blended surfaces. The curves examined are: i) Parametric Polynomial, ii) Hermite, iii) Bezier, iv) B-Splines and v) NURBS.

Table 1. A Review of the Issues in Machining of Sculptured Surfaces

Cutter Geometry		Toolpath Optimization		Feed rate Optimization		Toolpath/Feed rate Integration	
Author(s)	Ref.	Author(s)	Ref.	Author(s)	Ref.	Author(s)	Ref.
Jerard, Fussell, Hemmett, and Ercan (2000)	[5]	Imani, Sadeghi, and Elbestawi (1998)	[18]	Imani, Sadeghi, and Elbestawi (1998)	[18]	Feng and Su (2000)	[19]
Engin and Altintas (2001)	[6]	Sheu (1999)	[31]	Feng and Su (2000)	[19]		
Jung, Kim, and Hwang (2001)	[23]	Chen and Ye (2002)	[8]	Jerard, Fussell, Hemmett, and Ercan (2000)	[5]		
Wang and Zheng (2002)	[24]	Mansour (2002)	[25]	Fussell, Jerard, and Hemmett (2001)	[20]		
Chen and Ye (2002)	[8]	Omirou (2003)	[15]	Hemmett, Fussell, and Jerard (2001)	[22]		
Mansour (2002)	[25]	Chen, Vickers, and Dong (2003)	[16]	Milfelner, Kopac, Cus, and Zuperl (2005)	[32]		
Chen, Vickers, and Dong (2003)	[16]	Chen, Vickers, and Dong (2004)	[7]				
Lazoglu (2003)	[26]	Giri, Bezbaruah, Bubna, and Choudhury (2005)	[17]				
Bouzakis, Aichouh, and Efstathiou (2003)	[21]						
Kim, Kim, and Chu (2003)	[27]						
Xu, Qu, Zhang, and Huang (2003)	[28]						
Lamikiz, De Lacalle, Sanchez, and Salgado (2004)	[29]						
Kim and Chu (2004)	[30]						

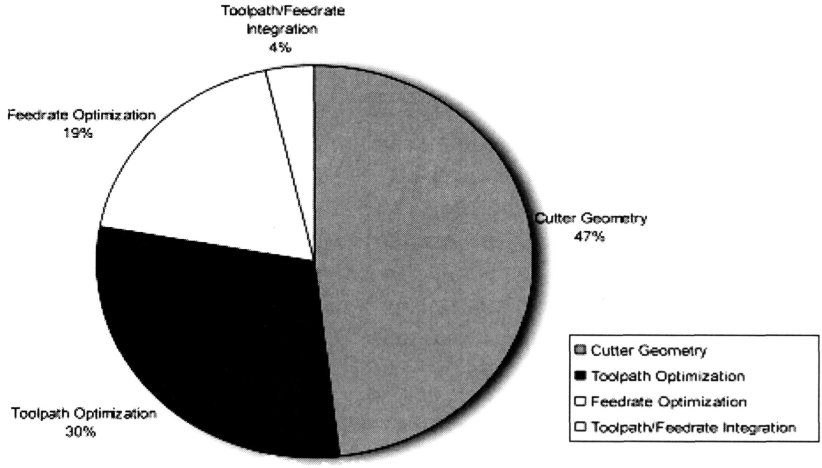

Figure 1: The Distribution of Critical Research Papers in Sculptured Machining Area

Each curve type is used for the creation of a Coons surface, and it is finally concluded that NURBS would be a suitable curve creation method to model sculptured surfaces. Based on this, in this study, the Coons surface shown in Figure 2 is considered for demonstration, which is modeled by blending of four drive profiles.

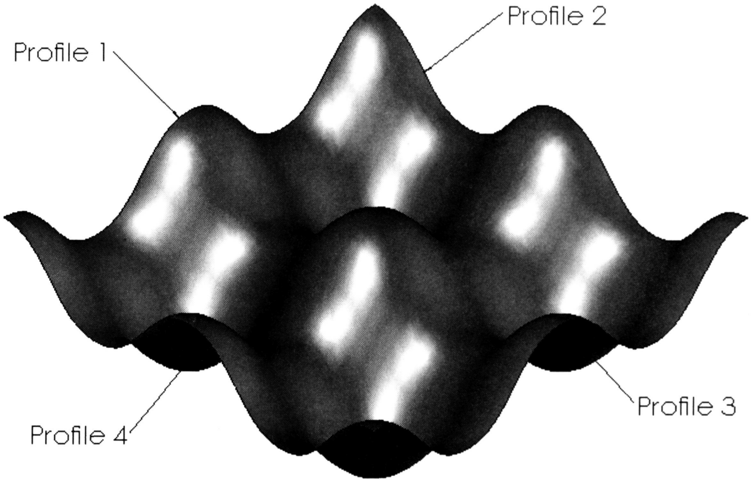

Figure 2: Selected Coons Surface for the Study

Step II: Determination of a Desirable Machining Configuration

The machining of the sculptured surface shown in Figure 2 was simulated using Mastercam® package. The size of the stock used was 120 x 120 x 50 mm with a 9.525 mm flat end mill for roughing, and a 6.25 mm ball end mill for the finishing operation. Aluminium was selected as the stock material.

The experiments done in this study were based on Taguchi design of experiments. A 36 ($2^2 \times 3^2$) orthogonal array of experiments was designed with the aid of Minitab® statistical software. The factors chosen were the toolpath and feed rate for roughing and finishing operations, with the levels being parallel, contour and flowline for the toolpath factor, and standard and highfeed for the feed rate factor. The hierarchical structure for the design of experiments is presented in Figure 3, and the configuration for the 12 experiments actually performed can be seen in Table 2.

Experimental Results

The surface finish, machining time and file size were recorded for each experiment. The machining time and file size were recorded directly from Mastercam® simulation, whereas the surface finish was measured using 3D Reshaper® software. Figures 4, 5 and 6 show some of the types of surface attained in the machining of the Coons surface. Main effects plots for the machining time, surface finish and file size are plotted and shown in Figures 7 to 10.

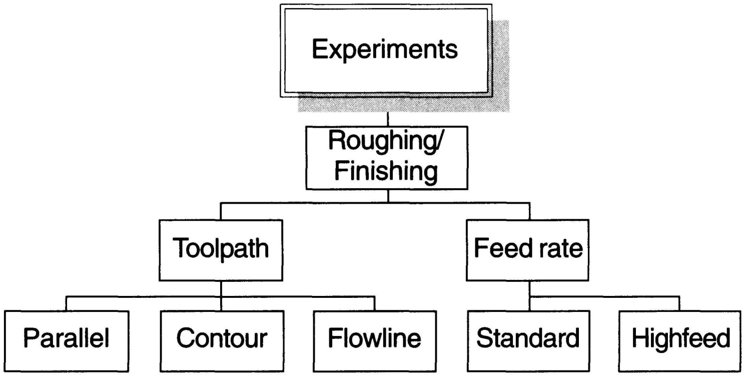

Figure 3: Hierarchical Structure for Design of Experiments

Table 2: Layout of Performed Experiments

Experiment Number	Feedrate		Toolpath	
	Roughing	Finishing	Roughing	Finishing
1	Standard	Standard	Parallel	Parallel
2	Standard	Standard	Flowline	Flowline
3	Standard	Standard	Contour	Contour
4	Standard	Highfeed	Parallel	Parallel
5	Standard	Highfeed	Flowline	Flowline
6	Standard	Highfeed	Contour	Contour
7	Standard	Highfeed	Parallel	Flowline
8	Standard	Highfeed	Flowline	Contour
9	Standard	Highfeed	Contour	Parallel
10	Highfeed	Standard	Parallel	Contour
11	Highfeed	Standard	Flowline	Parallel
12	Highfeed	Standard	Contour	Flowline

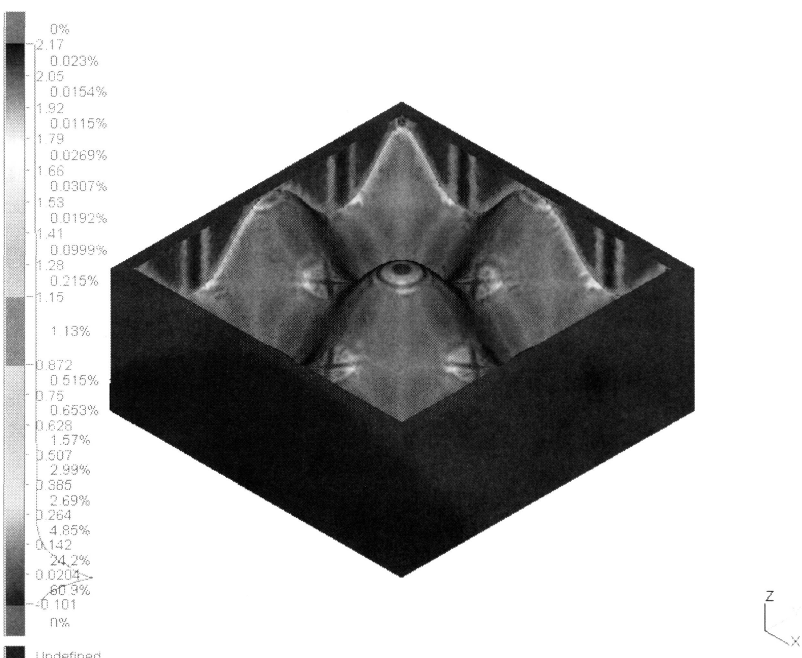

Figure 4: Simulated Surface Finish with 60.9% Accuracy to Theoretical Surface

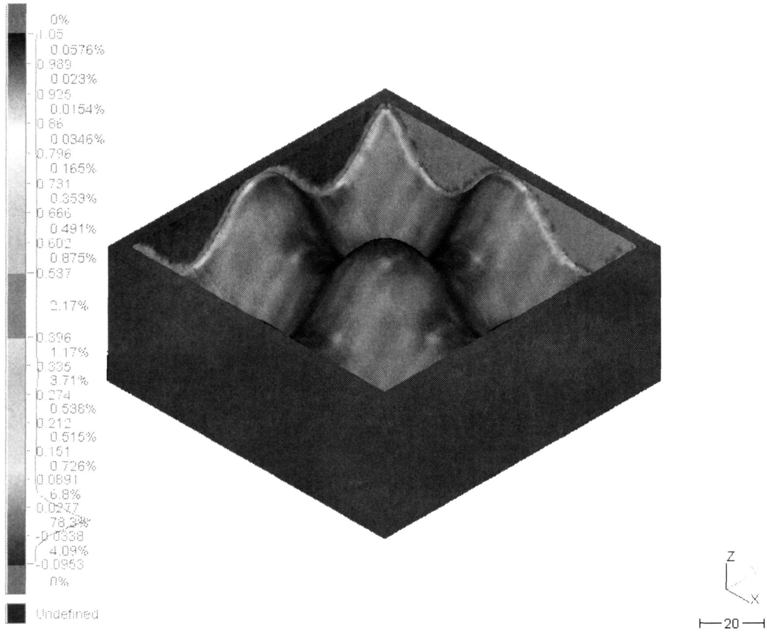

Figure 5: Simulated Surface Finish with 78.3% Accuracy to Theoretical Surface

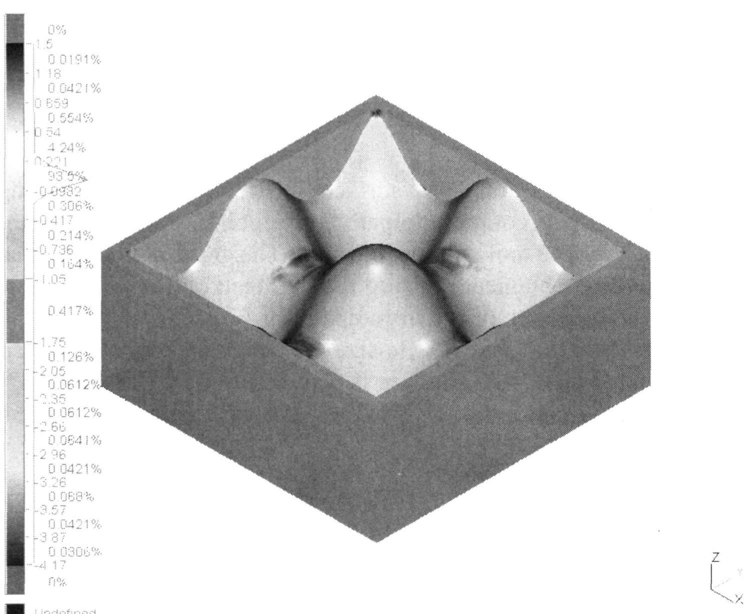

Figure 6: Simulated Surface Finish with 93.5% Accuracy to Theoretical Surface

Figure 7 shows that to decrease the roughing time, it is best to use the highfeed option and parallel toolpath. The worst combination would be a standard feed rate with a flowline toolpath. To decrease the finishing time, it is again best to use a highfeed feed rate and a parallel toolpath. However, the bad combination would be a standard feed rate with a contour toolpath.

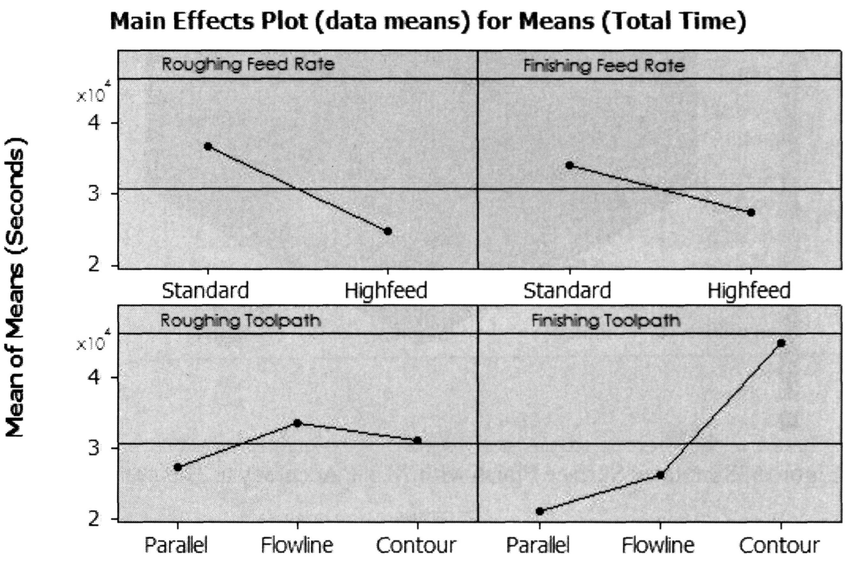

Figure 7: Machining Time Plots for Simulated Results of Toolpath and Feed Rate Variation

Figure 8 indicates that the best surface finish was obtained by using the standard feed rate and a contour toolpath for roughing, while using standard feed rate and a flowline toolpath for finishing. The graph also shows that the worst finish will be obtained by using the highfeed option with a flowline toolpath for roughing and a contour toolpath for finishing.

Figure 9 shows that the NC file size for roughing is greater when the highfeed option is used. The file size is also affected by the toolpath, with flowline paths generating the largest files, and with parallel toolpaths the smallest files.

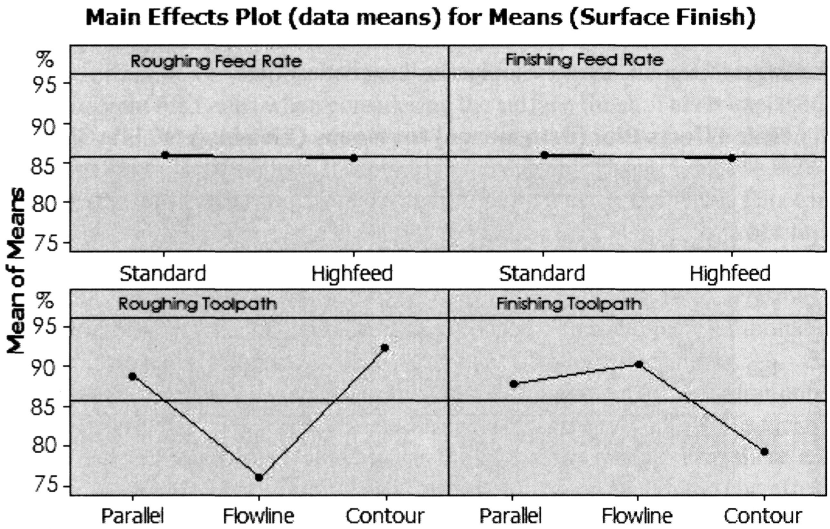

Figure 8: Surface Finish Plots for Simulated Results of Toolpath and Feed Rate Variation

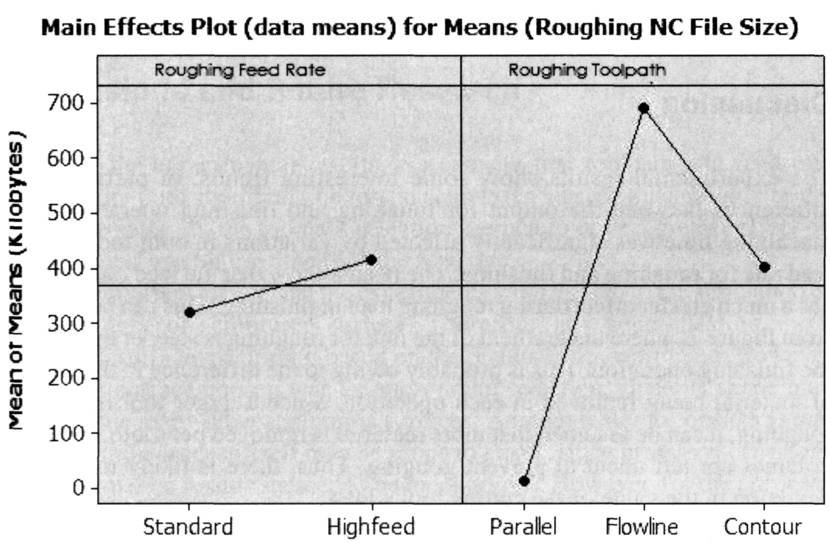

Figure 9: NC File Size Plots for the Roughing Operation

Figure 10 shows that the NC file size for finishing is greater when the highfeed option for feed rate is used. In this case it was seen that flowline paths generate the largest files, and contour toolpaths the smallest files.

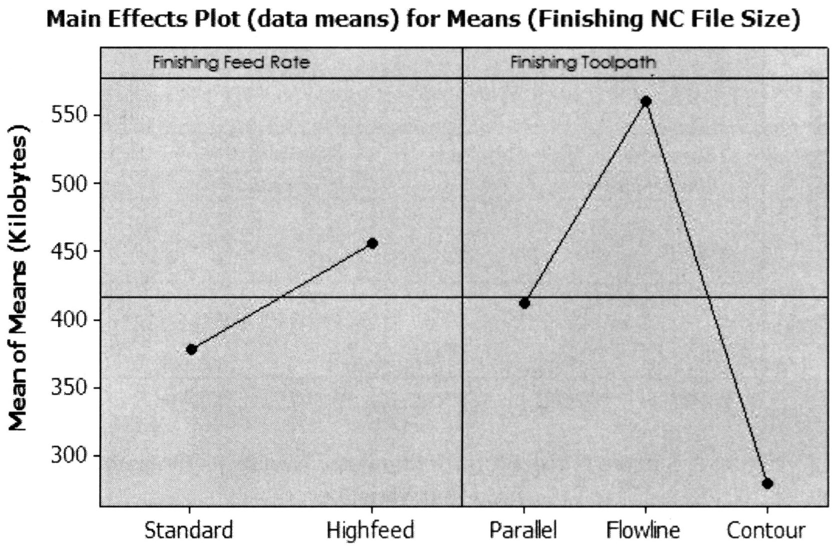

Figure 10: NC File Size Plots for the Finishing Operation

Discussion

The experimental results show some interesting trends, in particular the differences between the output for roughing and finishing operations. The machining time was significantly affected by variations in both toolpath and feed rate for roughing and finishing. The results show that the feed rate selected has a much greater effect during roughing than in finishing. This can be deduced from Figure 7, where the gradient of the line for roughing is steeper than that of the finishing operation. This is probably owing to the difference in the volume of material being removed in each operation. Since a larger tool is used for roughing, it can be assumed that more material is removed per tooth, and more volumes are left uncut to prevent gouging. Thus, there is likely to be more deviation in the value of the cutting tool's load.

It is apparent from Figure 8, that the feed rate has a very insignificant effect on the surface finish. This was expected, since the effects of tool vibration and deflection are present when there is unbalanced tool loading. Therefore it can be expected that when the highfeed option was used, the surface finish would be better. However, this is inconsistent with the trends on the graph. A possible reason for this may have been that the size of workpiece and tool used will not allow for the amplification and measurement of minor defects.

The effect of varying the toolpath seems to be much greater than that of using different feed rates when considering the surface finish. This is expected, since the volume of material removed owing to tool vibration and deflection is much less than that of each tool step during machining. The toolpaths selected had less effect on machining time during roughing than on finishing. This can be seen in Figure 7, where the spread of the points for roughing is much less than that of finishing. It must be noted though that time values given are based on simulation, and thus is more suitable for comparison than for determining actual machining times. It is interesting to observe that the parallel toolpath gave the best machining times for roughing and finishing operations.

The NC file size was recorded, to help determine which configuration is most desirable when considering the buffer capacity of the machine. As expected, larger files were generated when using the highfeed option, since there are additional codes in almost every line for the changes in feed rate. The effect was almost equal for roughing and finishing as it can be seen in Figure 9 and Figure 10.

The toolpath which was selected played a more significant role than feed rate selection in determining the file size. The spread of the points was much greater than that of feed rate selection. It is also apparent from the graphs that flowline toolpaths produce the largest file sizes.

Conclusions and Future Research

Based on the experimental results, we can say that toolpath and feed rate selection are both significant factors in sculptured surface machining. For the workpiece selected, the toolpath selection seemed to have a greater effect on the finish and machining time than the feed rate.

It is important to note that the experiments were limited to the simulation of only one type of sculptured surface. Therefore, any generalisation about sculptured surface machining based on the results is not warranted. However the Coons surface chosen was an appropriate selection, since its shape may approximate many other sculptured surfaces. Another factor to consider is that the simulation process itself may be prone to errors, since in several occasions the experimental results seemed to be incongruous. However, for the purposes of this research, they were deemed suitable.

Auxiliary to the fact that the simulation results may have been flawed, it might be useful to undertake the actual machining of the surface. This should provide more accurate results, since measurements may be taken directly. It might be useful to record the force on the cutting tool during this time to determine if the algorithm used for obtaining highfeed machining accurately calculates the correct feed rate to produce a constant load. The work in this direction is in progress.

References

[1] Han, Z. and Yang, D.C.H. (1999). Iso-phote based tool-path generation for machining free-form surfaces, Journal of Manufacturing Science and Engineering, Transactions of the ASME, 121(1), 656-664.

[2] Suresh, K. and Yang, D.C.H. (1994). Constant scallop-height machining of free-form surfaces, Journal of Engineering for Industry, Transactions of the ASME, 116(2), 253-259.

[3] Krouse, J.K. (1981). Sculptured surfaces for CAD/CAM, Machine Design, 53(5), 115-120.

[4] Baptista, R. and Antune Simoes, J.F. (2000). Three and five axes milling of sculptured surfaces, Journal of Materials Processing Technology, 103(3), 398-403.

[5] Jerard, R.B., Fussell, B.K., Hemmett, J.G. and Ercan, M.T. (2000). Toolpath feed rate optimization: A case study. Proc. NSF Design and Manufacturing Research Conference, Vancouver, British Columbia, Canada.

[6] Engin, S. and Altintas, Y. (2001). "Mechanics and dynamics of general milling cutters part I: helical end mills," International Journal of Machine Tools and Manufacture, 41(15), 2195 –2207.

[7] Chen, Z.C., Vickers, G.W. and Dong, Z. (2004). A new principle of CNC tool path planning for three-axis sculptured part machining - a steepest-ascending tool path, Journal of Manufacturing Science and Engineering, Transactions of the ASME, 126(3), 515-523.

[8] Chen, T. and Ye, P. A. (2002). "Tool path generation strategy for sculptured surfaces machining," Journal of Materials Processing Technology, 127 (3), 369 –373.

[9] Bertok, P. (1983). "A system for monitoring the machining operation by referring to a predicted torque pattern," CIRP Annals, 32(1), 439-442.

[10] Wang, W. P. (1988). "Application of solid modeling to automate machining parameters for complex parts," Manufacturing Systems, 17(1), 57-63.

[11] Takata, S. (1989). "A cutting simulation system for machinability evaluation using a workpiece model," CIRP Annals, 38 (1), 417-420.

[12] Spence, A. D. (1992). "Solid modeller based milling process simulation," Ph.D. Thesis, The University of British Columbia, Canada.

[13] Feng, H. and Menq, C. (1994). "The prediction of cutting force in ball-end milling process-part I: model formulation and model building procedure," International Journal of Machine Tool Design and Manufacture, 34(5), 697-710.

[14] El-Mounayri, H., Spence, A. D. and Elbestawi, M. A. (1996). "Enhanced CAD/CAM for simulation and optimization of 3-5 axis milling of dies and molds," Proc. CSME 13th Symposium on Engineering Applications of Mechanics: Manufacturing Science and Engineering, McMaster University, Canada, 394- 401.

[15] Omirou, S.(2003). "NC Machining for revolved and swept surfaces with free-form profiles," Journal of Materials Processing Technology, 132(1-3), 332–339.

[16] Chen, Z. C., Vickers, G. W. and Dong, Z. (2003). "Most efficient tool feed direction in 3-axis cnc machining. Integrated Manufacturing Systems," 14 (7), 554–566.

[17] Giri, V., Bezbaruah, D., Bubna, P. and Choudhury, A. R. (2005). "Selection of master cutter paths in sculptured surface machining by employing curvature principle," International Journal of Machine Tools and Manufacture, 45(1), 1202 – 1209.

[18] Imani, B. M., Sadeghi, M. H. and Elbestawi, M. A. (1998). "Improved process simulation system for ball-end milling of sculptured surfaces," International Journal of Machine Tools and Manufacture, 38(9), 1089 – 1107.

[19] Feng, H. –Y. and Su, N. (2000). "Integrated tool path and feed rate optimization for the finishing machining of 3D plane surfaces," International Journal of Machine Tools and Manufacture, 40 (11), 1557 -1572.

[20] Fussell, B. K., Jerard, R. B. and Hemmett, J. G. (2001). "Robust feedrate selection for 3-axis NC machining using discrete models - a steepest-ascending tool path," Journal of Manufacturing Science and Engineering, Transactions of the ASME, 123(1),214- 224.

[21] Bouzakis, K. D., Aichouh, P. and Efstathiou, K. (2003). "Determination of the chip geometry, cutting force and roughness in free form surfaces finishing milling with ball end tools," International Journal of Machine Tools and Manufacture, 43(5), 499 – 512.

[22] Hemmett, J. G., Fussell, B. K. and Jerard, R. B.(2001). "Robust feedrate selection for 3-axis NC machining using discrete models," Journal of Manufacturing Science and Engineering, Transactions of the ASME, 123(1), 214-224.

[23] Jung, Y. H., Kim, J. S. and Hwang, S. M. (2001). "Chip load prediction in ball-end milling', Journal of Materials Processing Technology, Vol.111, No.1-3, 250 – 264.

[24] Wang, J. J. J. and Zheng, C. M. (2002). "Identification of shearing and ploughing cutting constants from average forces in ball-end milling," International Journal of Machine Tools and Manufacture, 42(6), 695 – 711.

[25] Mansour, S. (2002). "Automatic generation of part programs for milling sculptured surfaces', Journal of Materials Processing Technology, 127(1), 31 – 44.

[26] Lazoglu (2003). "Sculpture surface machining: a generalized model of ball-end milling force system," International Journal of Machine Tools and Manufacture, 43(5), 453 – 265.

[27] Kim, G. M., Kim, B. H. and Chu, C. N. (2003). "Estimation of cutter deflection and form error in ball-end milling process," International Journal of Machine Tools & Manufacture, 43, 917–924.

[28] Xu, A. P., Qu, Y. X., Zhang, D. W. and Huang, T. (2003). Simulation and experimental investigation of the end milling process considering the cutter flexibility. International Journal of Machine Tools and Manufacture, 43(3), 283 – 295.

[29] Lamikiz, A., De Lacalle, L. N. L., Sanchez, J. A. and Salgado, M. A. (2004). "Cutting force estimation in sculptured surface milling," International Journal of Machine Tools and Manufacture, 44(14), 1511 – 1522.

[30] Kim, G. M. and Chu, C. N. (2004). "Mean cutting force prediction in ball-end milling using force map method," Journal of Materials Processing Technology, 146(3), 303 – 315.

[31] Sheu, J. J. (1999). "A three-dimensional CAD/CAM/CAE integration system of sculpture surface die for hollow cold extrusion," International Journal of Machine Tools and Manufacture, 39, 33–53.

[32] Milfelner, M., Kopac, J., Cus, F. and Zuperl, U. (2005). "Genetic equation for the cutting force in ball-end milling," Journal of Materials Processing Technology, 164–165, 1554–1560.

JOURNAL OF MECHANICAL ENGINEERING (JMechE)

Aims & Scope

Journal of Mechanical Engineering (formerly known as Journal of Faculty of Mechanical Engineering), is an international journal which provides a forum for researchers and academicians worldwide to publish the research findings and the educational methods they are engaged in. This Journal acts as a vital link for the mechanical engineering community for rapid dissemination of their academic pursuits as well as a showcase of the research activity of FKM for the outside world.

Contributions are invited from various disciplines that are allied to mechanical engineering. The contributions should be based on original research works. An attempt will be made to review the submitted contributions with competent internal and external reviewers as to the suitability of the paper for satisfying the objectives of the journal.

All papers submitted to JMechE are subjected to a rigorous reviewing process through a worldwide network of specialized and competent referees. To be considered for publication, each paper should have at least two positive referee's assessments.

General Instructions

Manuscripts intended for publication in the Journal FKM should be written in camera ready form with production-quality figures and done electronically in Microsoft Word 2000 (or above) and submitted along with one hard copy. Manuscripts should be typed using Times New Roman font (point 10) on one side of the paper (A4 size), single-spaced, with wide margins (1 in left and right, and 1 in on top and bottom). The manuscript should include the title of the paper; the author's name and affiliation; a short abstract of between 200 and 300 words which clearly summarises the paper; and a list of keywords. Limit your submission to a maximum of 20 typed pages.

Keywords

Keywords supplied by the author should appear on a line following the abstract. The keywords selected should be comprehensive and subject specific. Maximum of five keywords should be sufficient to cover the major subjects of a given paper. General terms should not appear as keywords, as they have little use as information retrieval tools. Please choose keywords to be as specific as possible and list the most specific first, proceeding to the most general last.

Units

All scientific and technical data presented should be stated in SI units.

Footnotes

Footnotes should be kept to an absolute minimum and used only when essential.

Formulae

Formulae should be typewritten using MS Word compatible Equation Editor.

Tables

Tables, should be included within the text where appropriate and must be numbered consecutively with Arabic numerals and have titles that precede the table. They should be prepared in such a manner that no break is necessary.

Figures

Authors should appreciate the importance of good-quality illustrations. All graphs and diagrams should be referred to, for example, Figure 1 in the text. All figures must be numbered consecutively with Arabic numerals. A detailed caption should be provided below each figure according to the following format:

Figure 1: (a) A simple 2-D cantilever and (b) microcantilever with a diamond probe.

Figures should be embedded within the text where appropriate. Glossy photographs when required should be scanned to a resolution suitable with the reproduction requirements (1200 dpi generally will be sufficient).

References

Use squared brackets to indicate reference citation such as [1], [3]-[5] in the main text. Include references at the end of the paper according to the citations order that appears in the paper using the following format.

[1] M. K. Ghosh and A. Nagraj, "Turbulence flow in bearings," Proceedings of the Institution of Mechanical Engineers 218 (1), 61 - 64 (2004).

[2] H. Coelho and L. M. Pereira, "Automated reasoning in geometry theorem proving with Prolog," J. Automated Reasoning 2 (3), 329-390 (1986).

[3] P. N. Rao, Manufacturing Technology Foundry, Forming and Welding, 2nd ed. (McGraw Hill, Singapore, 2000), pp. 53 – 68.

[4] Hutchinson, F. David and M. Ahmed, U.S. Patent No. 6,912,127 (28 June 2005).