Issues in the Manufacture of Sculptured Surfaces through an Existing Force Prediction Approach

Anton Gittens
Department of Mechanical and Manufacturing Engineering
The University of the West Indies
St. Augustine, Trinidad and Tobago
agittens@eng.uwi.tt

B. V. Chowdary
Department of Mechanical and Manufacturing Engineering
The University of the West Indies
St. Augustine, Trinidad and Tobago
chowdary@eng.uwi.tt

Abstract

In sculptured surface modeling, complex contours are represented as a network of patches, each expressed in terms of known points, vectors, and curves. In this study, complex shapes are defined as the sculptured surfaces created by the blending of curves, to form surface patches. Based on our preliminary investigations on general types of curves, it was concluded that NURBS curves are the most appropriate for the modeling of sculptured surfaces.

In this paper, the issues involved in the machining of sculptured surfaces are investigated, with an aim to improve machining time and surface finish. For this purpose multi-variable regression equations were derived between depth of cut and feed rate with cutting force, surface finish and machining time. Using these equations, variable feed rates are calculated and then the machine code is regenerated to attain a predetermined cutting time and surface finish values while maintaining cutting force as constant. The study results indicate that it is possible to target high surface finish and low machining time while maintaining low cutting forces.

Background

Sculptured surfaces are formerly considered to be impractical to produce with numerical control machining [1]. Most modern computer-aided design (CAD) packages support the creation of free-form surfaces [2], in which, algebraic and parametric rules generally govern the creation of the sculptured surfaces [3]. These surfaces are found in a wide range of components including those for aircraft, automobiles, construction and agricultural equipment, machine tools, home and office appliances, cameras, and instrument cases. Based on our preliminary investigations [4] on general types of curves, it was concluded that NURBS curves are the most appropriate for the modeling of sculptured surfaces.

Inferior surface finish and machining times are obtained when inaccurate force prediction models are used during the machining of sculptured surfaces [5]. Variable feed rate yields constant cutting force which gives a better surface finish. The feed rates may be varied to match the required force based on a force prediction model. This occurs since there is less tool deflection and vibration, allowing for fewer surface form errors [6].

It can be clearly seen 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 design stage for any further work in this field. The past studies (Table 1 and Figure 1) also show this trend of the bulk of research being done in the modeling of cutter geometry, with more scope in manufacturing area which includes toolpath and feed rate optimization, and the integration of these methods. The cause of this trend may be owing to the novelty of machining of sculptured surfaces.

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

Cutter Geometry	
Author(s)	**Year**
Jerard, Fussell, Hemmett, and Ercan[6]	2000
Engin and Altintas[7]	2001
Jung, Kim, and Hwang [8]	2001
Wang and Zhen[9]	2002
Chen and Ye[10]	2002
Mansour[11]	2002
Chen, Vickers, and Dong[12]	2003
Lazoglu[13]	2003
Bouzakis, Aichouh, and Efstathiou[14]	2003
Kim, Kim, and Chu[15]	2003
Xu, Qu, Zhang, and Huang[16]	2003
Lamikiz, De Lacalle, Sanchez, and Salgado[17]	2004
Kim and Chu[18]	2004

Toolpath Optimization	
Author(s)	**Year**
Imani, Sadeghi, and Elbestawi[19]	1998
Sheu[20]	1999
Chen and Ye[10]	2002
Mansour[11]	2002
Omirou[21]	2003
Chen, Vickers, and Dong[12]	2003
Chen, Vickers, and Dong[22]	2004
Giri, Bezbaruah, Bubna, and Choudhury[23]	2005

Feed rate Optimization	
Author(s)	**Year**
Imani, Sadeghi, and Elbestawi[19]	1998
Feng and Su[24]	2000
Hemmett, Fussell, and Jerard[25]	2000
Jerard, Fussell, Hemmett, and Ercan[6]	2000
Fussell, Jerard, and Hemmett[26]	2001
Milfelner, Kopac, Cus, and Zuperl[27]	2005

Toolpath/Feed rate Integration	
Author(s)	**Year**
Feng and Su[23]	2000

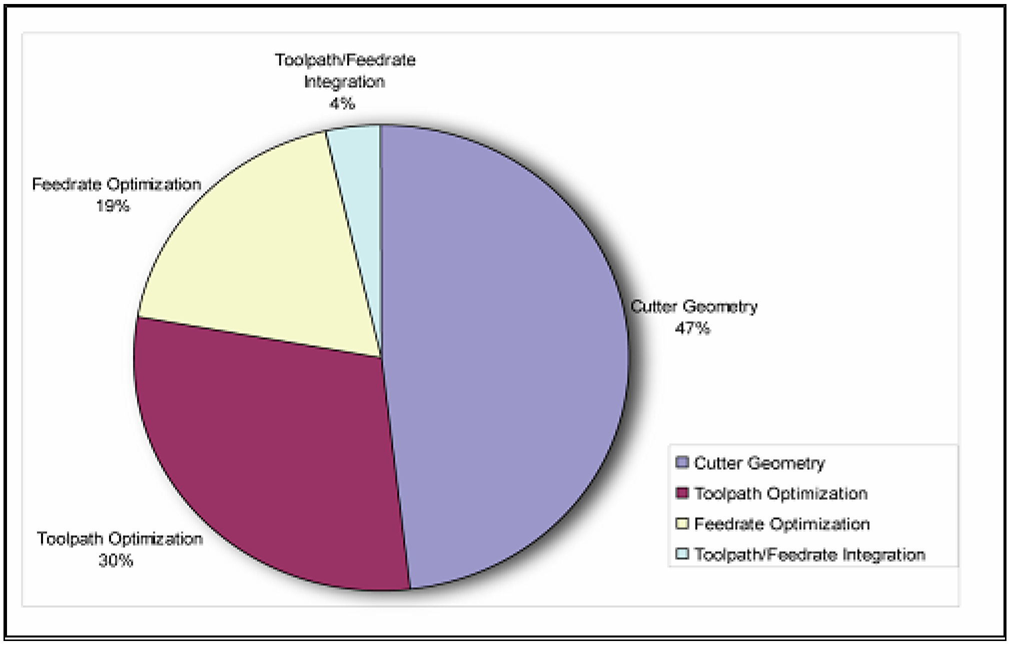


Figure 1: Issue-wise Distribution of Critical Research Papers in Sculptured Machining Area

The objective of this paper is to develop multi-variable regression equations between depth of cut and feed rate with cutting force, surface finish and machining time based on Jerard *et al.'s* [6] force prediction model. Using these equations, variable feed rates are calculated and then the NC code is regenerated to attain a predetermined cutting time and surface finish values while maintaining cutting force as constant. The main differences among the issues dealt in the past and proposed to estimate feed rates are summarized in Figure 2.

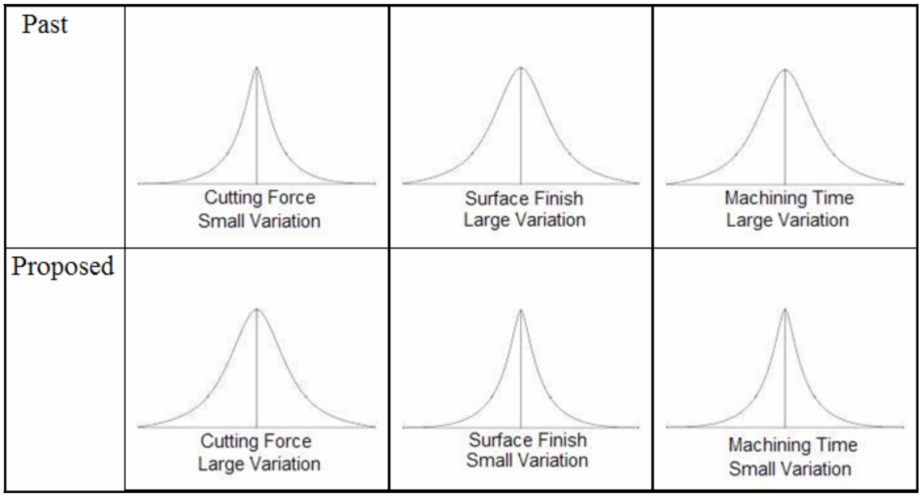


Figure 2: Past and Proposed Approaches for Feed Rate Estimation

Past approach: Minimize cutting force variation with hope of achieving good surface finish and short machining time, through feed rate variation.

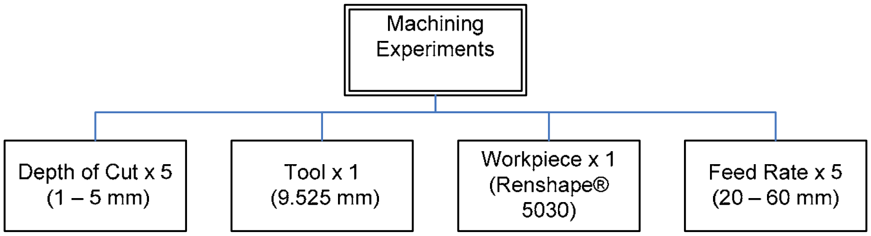
Proposed approach: Target good surface finish and low machining time with hope of minimizing cutting force variation, through variable feed rates.

Methodology

To establish the multi-variable regression equations between cutting force, surface finish, machining time, and feed rate and axial depth of cut we used the following 4-step procedure:

Step 1: Design of Experiments

Experiments were performed based on Taguchi's approach (Refer Figure 3). Roland MDX650 CNC machine and 9.525 mm carbide flat end-mill were used to machine Renshape® 5030 prototyping material. The experiments were performed in a method similar to [26].



Legend: Total number of experiments = $5 \times 1 \times 1 \times 5 = 25$

Figure 3: Design of Experiments

Step 2: Measure various parameters for each experiment

The cutting parameters set during the machining process are:

- rpm: 15000 min -1,
- feed rate from 20 to 60 mm/s
- tool diameter: 9.525mm.

For each experiment, c*utting force* was measured with Kistler® multi-component force dynamometer and the s*urface finish* was measured with Mitytoyo® profilometer. The *machining time* was also measured using Gerard et al.'s [6] method.

Step 3: Make a 3D plot

Step 2 results are used to plot the graphs between cutting force, surface finish, and machining time with depth of cut and feed rate.

Step 4: Determine the multi-variable regression equations

The multi-variable regression equations for cutting force, surface finish and machining time are fitted as a function of feed rate and axial depth of cut.

Results

Experiments were conducted to establish multi-variable regression equations between cutting force, surface finish and machining time, and feed rate and axial depth of cut in the manufacture of sculptured surface with 9.525 mm carbide flat end-mill and Renshape® 5030 material. Out of the 25 experiments conducted, 12 were considered suitable for this study as the cutting forces recorded were within the acceptable range as suggested by Jerard *et al.* [6]. The cutting force, surface finish and machining time were monitored at different cutting conditions (axial depth of cut = 1 – 5 mm, radial depth of cut = 9.525 mm, rpm = 15000 min^{-1} and feed rate = 20 – 60 mm/s). On the basis of experimental data, multi-variable regression equations were developed using Labfit® software [28]. The resulted multi-variable 3D graphs are shown in Figures 4, 5 and 6.

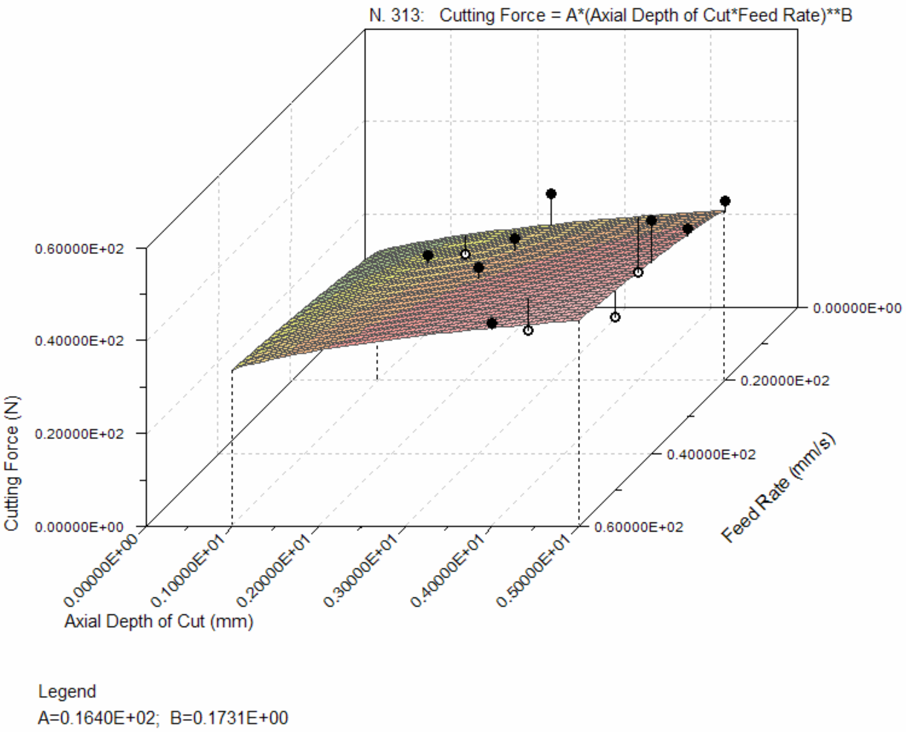


Figure 4: Relationship between Depth of Cut and Feed Rate with Cutting Force

From Figure 4, the range of cutting forces can be found between 23.25 – 50.19 N. The cutting force was lowest (23.25 N) when machining with a small axial depth of cut and low feed rate (20 mm/s), while a large axial depth of cut and high feed rate (60 mm/s) yielded the largest cutting force (50.19 N). This trend can be given by the following equation:

$$Cutting\ Force = 0.1640E+02\left(Axial\ Depth\ of\ \ Cut \times Feed\ \ Rate\right)^{0.1731E+00}.$$

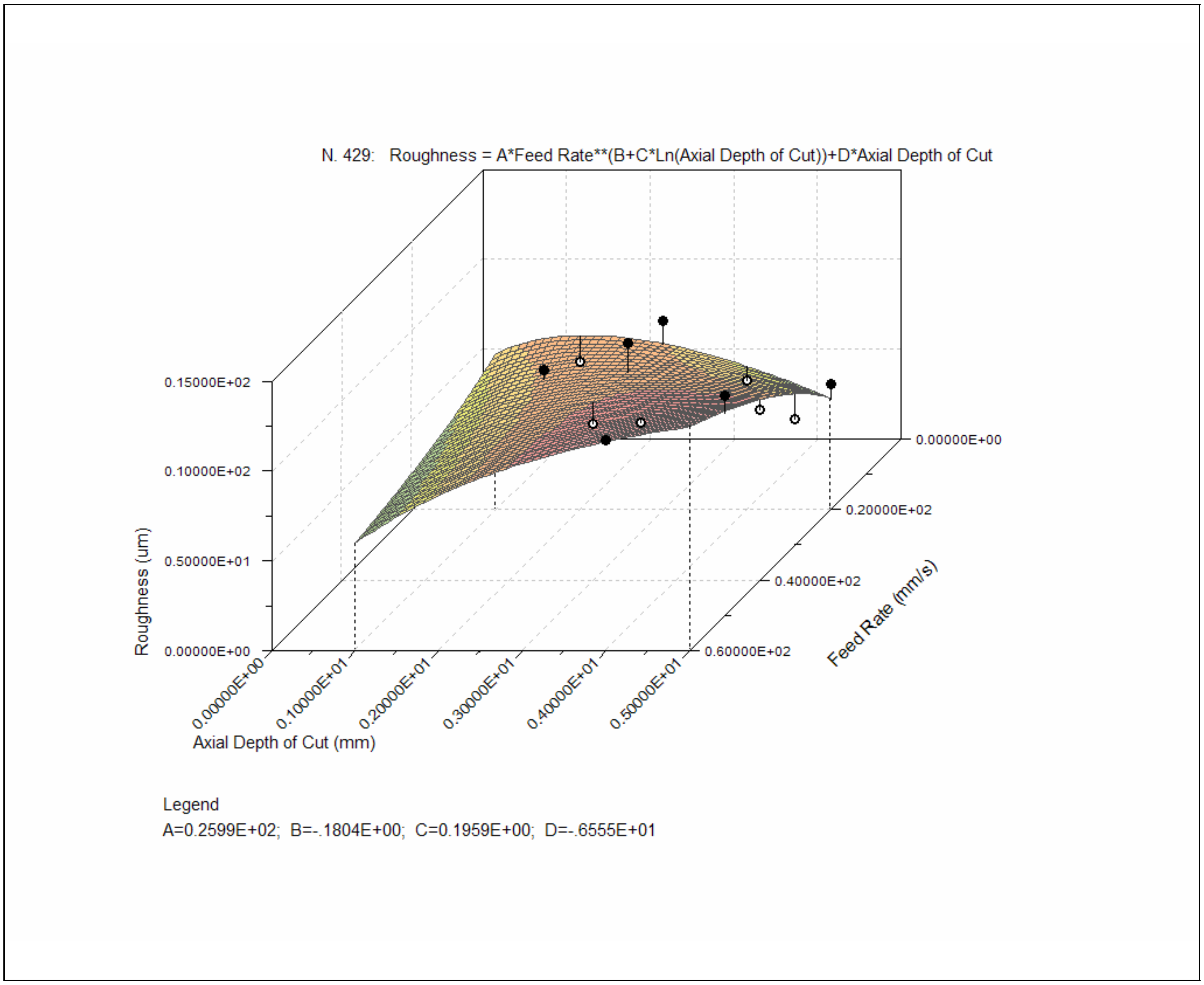


Figure 5: Relationship between Depth of Cut and Feed Rate with Surface Finish

The surface finish was best (7 µm) when machining with a small axial depth of cut (1 mm) and high feed rate (60 mm/s), while a large axial depth of cut (5 mm) and high feed rate (60 mm/s) yielded the worst surface finish. This can be seen in the Figure 5, and is given by the equation:

$$\begin{aligned} &Surface\ Finish = 0.2599E+02 \times Feed\ \ Rate^{\left(-0.1804E+00+0.1959E+00\ln\left(Axial\ Depth\ of\ \ Cut\right)\right)} \\ &+\left(-0.6555E+01 \times Axial\ Depth\ of\ \ Cut\right) \end{aligned}.$$

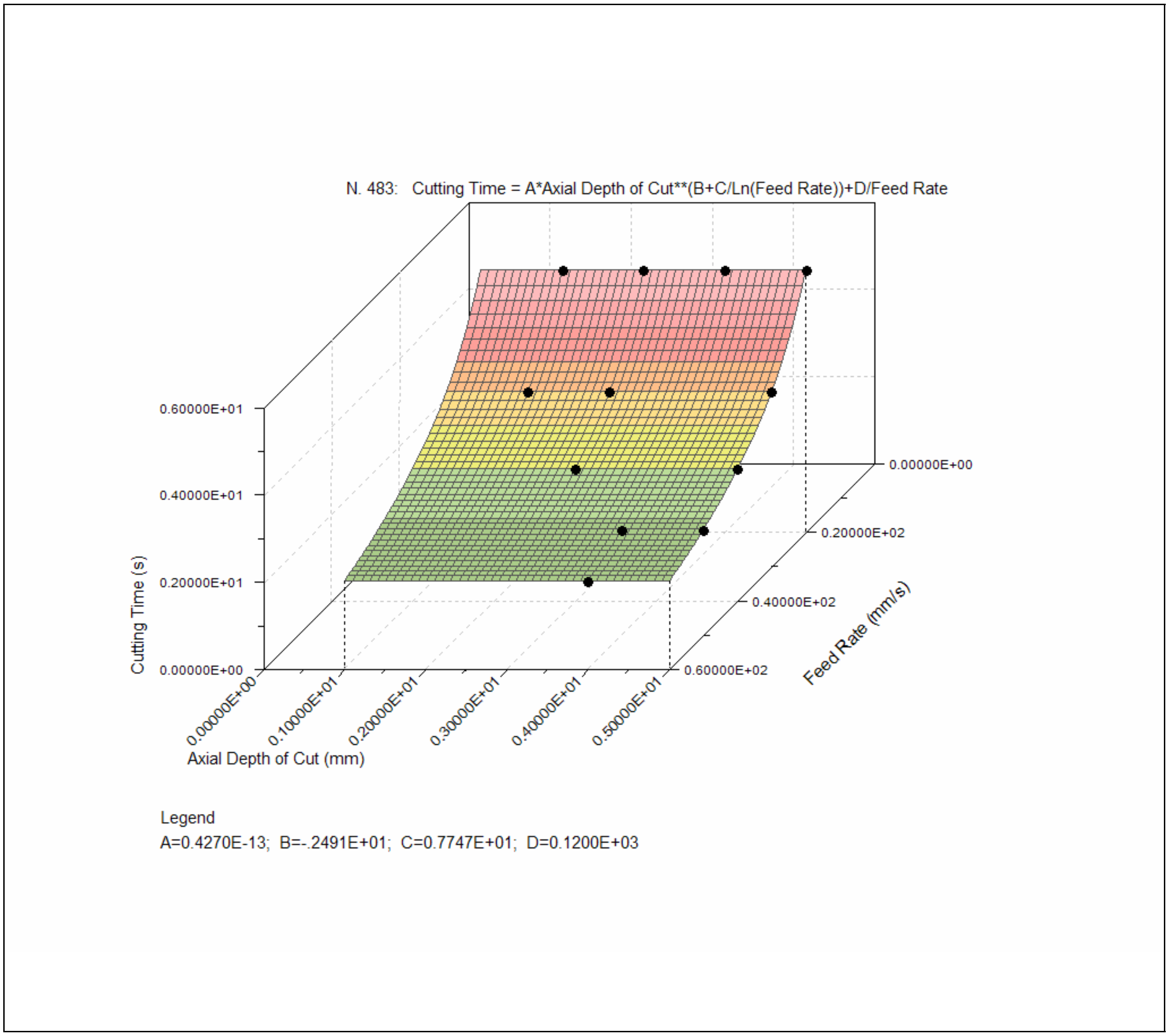


Figure 6: Relationship between Depth of Cut and Feed rate with Machining Time

The machining time was shortest when machining with a high feed rate, while a large low feed rate yielded the longest machining time. This trend can be seen in the Figure 6, and is given by the equation:

$$Machining\ Time = 0.4270E-13\left(Axial\ Depth\ of\ Cut\right)^{\left(-0.2491E+01+\frac{0.7747E+01}{\ln\left(Feed\ Rate\right)}\right)}+\frac{0.1200E+03}{Feed\ Rate}.$$

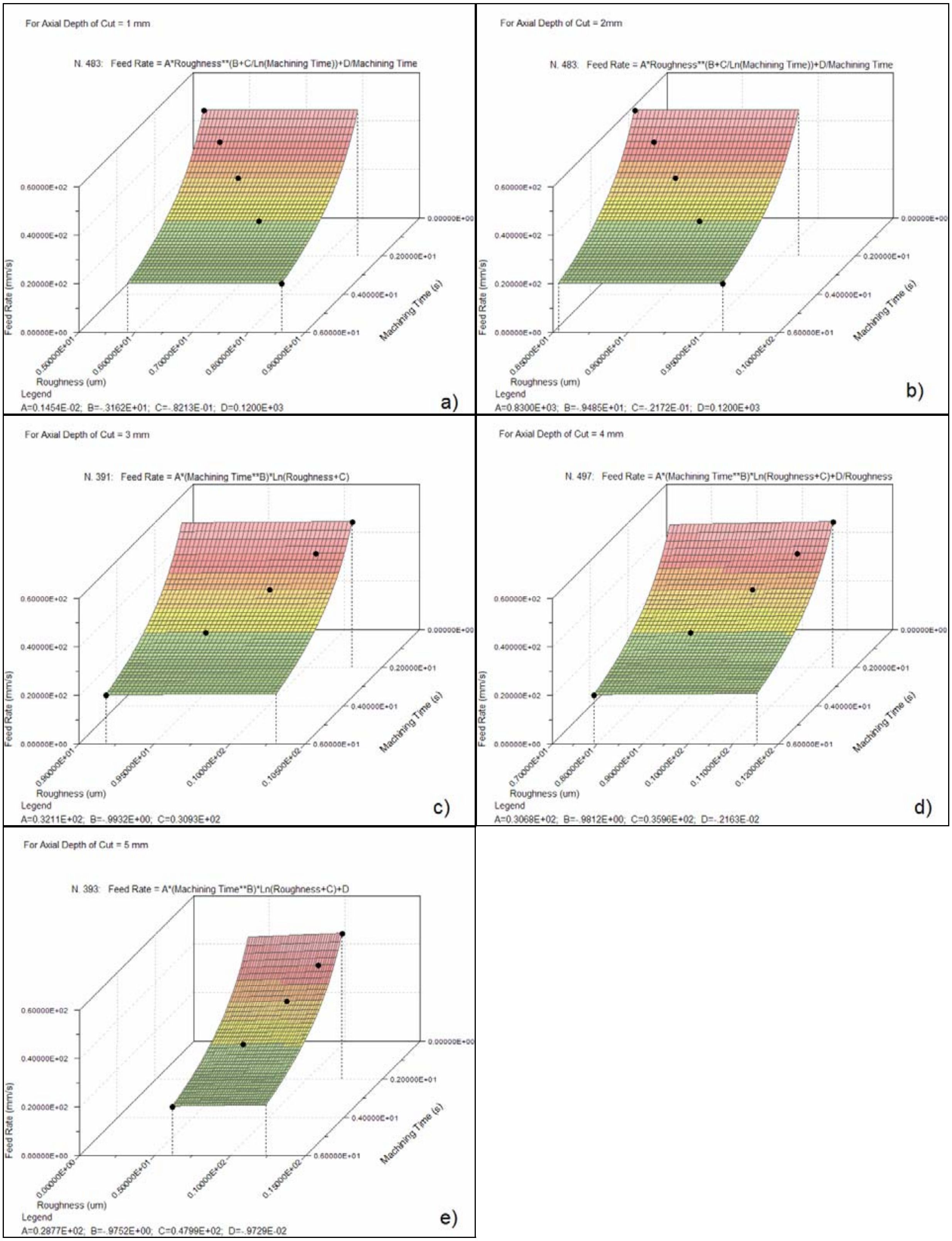


Figure 7 (a-e): Relationship between Surface Finish and Machining Time with Feed Rate

Based on the experimental results, a 3D graph showing the relationship of surface finish and machining time with feed rate was plotted for each value of axial depth of cut. The graphs showing these relationships for axial depth of cut between 1 and 5 mm are shown in Figure 7. The equation corresponding to each graph is used to determine the required feed rate, based on a predetermined surface finish = $7\mu m$ and machining time = 3 seconds.

Discussion

In this study, feed rate and depth of cut issues in manufacture of sculptured surfaces are investigated. Multi-variable relationships were developed based on Taguchi's design of experiments. Multi-variable regression equations were derived from the Labfit® [28] graphs for each of the group of relationships. The regression constants of the multi-variable equations reflect the effect of various factors such as vibration and tool wear.

Figure 4 shows the relationship of cutting force with depth of cut and feed rate. For the machining parameters used in these experiments, depth of cut and feed rate have similar effect on the cutting force, since they are both affected by the same regression constant *B (0.1731E +00)* in the derived equation:

$$Cutting\ Force = 0.1640E+02\left(Axial\ Depth\ of\ Cut \times Feed\ Rate\right)^{0.1731E+00}.$$

Similarly, Figure 5 shows the relationship of surface finish with depth of cut and feed rate. For the machining parameters used in these experiments, an increase in depth of cut and feed rate will lead to a larger roughness value, meaning that there is a worst surface finish. This can be seen from the following equation:

$$\begin{aligned}&Surface\ Finish = 0.2599E+02 \times Feed\ Rate^{\left(-0.1804E+00+0.1959E+00\ln\left(Axial\ Depth\ of\ Cut\right)\right)}\\&+\left(-0.6555E+01 \times Axial\ Depth\ of\ Cut\right)\end{aligned}.$$

Also, Figure 6 shows the relationship of machining time with depth of cut and feed rate. For the machining parameters used in these experiments, an increase in feed rate has a much larger effect on the machining time than depth of cut. This is expected, and can be seen through examination of the following equation:

$$Machining\ Time = 0.4270E-13\left(Axial\ Depth\ of\ Cut\right)^{\left(-0.2491E+01+\frac{0.7747E+01}{\ln\left(Feed\ Rate\right)}\right)} + \frac{0.1200E+03}{Feed\ Rate}.$$

Figure 7 (a-e) shows the relationship of feed rate with surface finish and machining time for axial depths of cut in the range of 1 – 5 mm with intervals of 1 mm. For the machining parameters used in these experiments, a high feed rate causes shorter machining times, and worst surface finishes. Based on the multi-variable equations generated from these experiments, there is a small decrease in feed rate as the depth of cut increases, while there is an increase in cutting force as depth of cut increases. The average cutting force observed in the study was low (37 N) when compared to the maximum force.

Conclusions and Future Research

The results of the study tend to support the work of [6], where they were able to show that a low cutting force would yield a good surface finish. The current research also indicates that it is possible to target surface finish and machining time while maintaining low cutting forces. This method encourages the delivery of robust machining of sculptured surfaces.

It must be noted that these results are applicable only under some conditions, since there may be other factors, which need to be considered. In particular, the material of the workpiece (Renshape® 5030) has some initial roughness, which might affect the final surface finish values. Other factors such as machine vibration, tool wear, and working conditions may also have had some effect on the experiments, although efforts were made to minimise their effects. Further research in this direction is in progress.

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Biographies

ANTON GITTENS is a Graduate Research Assistant in the Department of Mechanical and Manufacturing Engineering at the University of the West Indies. He holds a BSc. degree in Mechanical and Manufacturing Engineering, and is currently pursuing his MPhil. Degree. His research interest is in the field of Computer Aided Design and Manufacturing.

BOPPANA V. CHOWDARY is Faculty Member of the Department of Mechanical and Manufacturing Engineering at the University of the West Indies, St. Augustine, Trinidad. His research interests are in the areas of Flexible Manufacturing, Product Design and Development and CAD/CAM.