A Study on Machining of Sculptured Surfaces

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ABSTRACT

Current trends in consumer product design are experiencing the increasing use of sculptured surfaces such as Coons' formed by blending of non-uniform rational B-Splines (NURBS). In this research, 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 polynomial regression equations were established which relate the axial depth of cut and feed rate with cutting force, surface finish and machining time. The developed equations can be used for the variable feed rates estimation and regeneration of the machine code. The obtained results from the study show that it is possible to target high surface finish and low machining time while maintaining constant 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 a preliminary investigation [4], it was considered that non-uniform rational B-Splines (NURBS) are the most appropriate approximation for 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 rates yield constant cutting force which gives a better surface finish. The feed rates may be varied to match the required force using a force prediction approach [6]. This may result in less tool deflection, vibration, and reduce surface form errors.

Most of the research work in sculptured surface machining 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. A summary of machining issues is given in Table 1 and Figure 1. The past studies show that the bulk of research being done in the modeling of cutter geometry, with less attention on integration of toolpath and feed rate issues. The cause of this trend may be due to the machining of sculptured surfaces.

Table 1: A Summary of Machining Issues

Cutter Geometry		Toolpath Optimization		Feed Rate Optimization		Toolpath and Feed Rate Integration	
Author(s)	Year	Author(s)	Year	Author(s)	Year	Author(s)	Year
Jerard, Fussell, Hemmett, and Ercan[6]	2000	Imani, Sadeghi, and Elbestawi[19]	1998	Imani, Sadeghi, and Elbestawi[19]	1998	Feng and Su[23]	2000
Engin and Altintas[7]	2001	Sheu[20]	1999	Feng and Su[24]	2000		
Jung, Kim, and Hwang [8]	2001	Chen and Ye[10]	2002	Hemmett, Fussell, and Jerard[25]	2000		
Wang and Zhen[9]	2002	Mansour[11]	2002	Jerard, Fussell, Hemmett, and Ercan[6]	2000		
Chen and Ye[10]	2002	Omirou[21]	2003	Fussell, Jerard, and Hemmett[26]	2001		
Mansour[11]	2002	Chen, Vickers, and Dong[12]	2003	Milfelner, Kopac, Cus, and Zuperl[27]	2005		
Chen, Vickers, and Dong[12]	2003	Chen, Vickers, and Dong[22]	2004				
Lazoglu[13]	2003	Giri, Bezbaruah, Bubna, and Choudhury[23]	2005				
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						

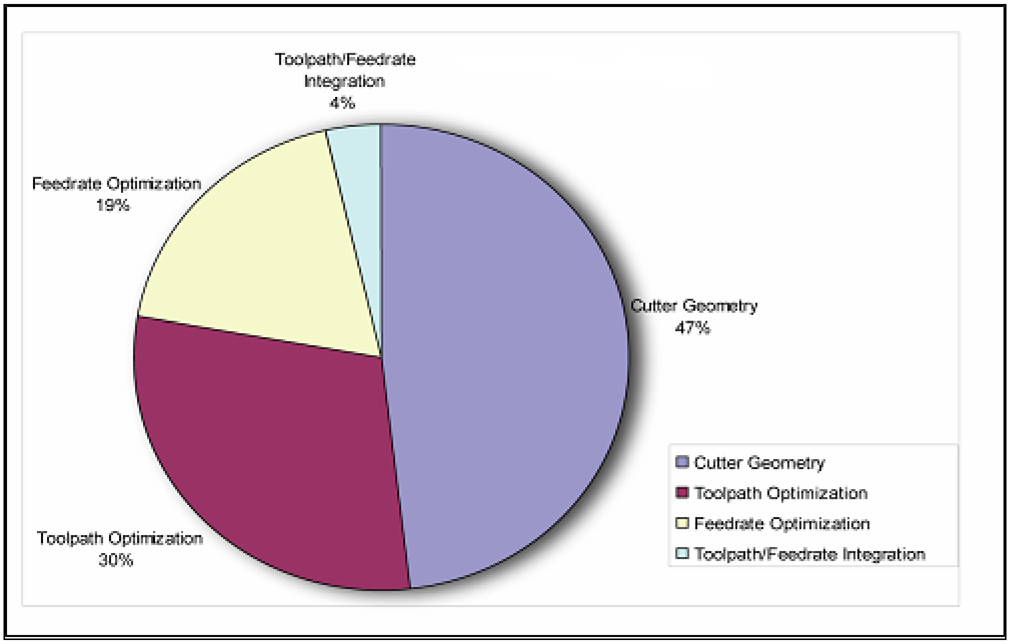
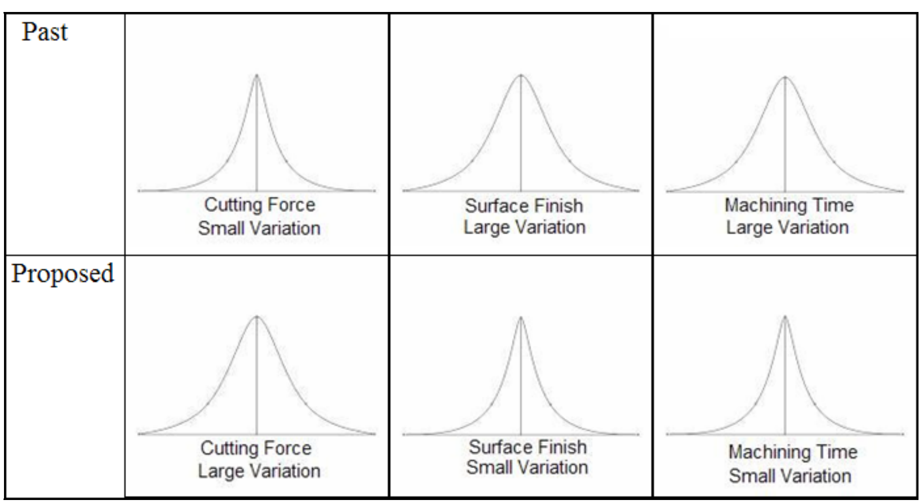


Figure 1: Critical Research in Sculptured Machining Area

The objective of this paper is to develop multi-variable polynomial regression equations that relate axial depth of cut and feed rate with cutting force, surface finish and machining time based on an existing force prediction model [6]. Using these equations, variable feed rates are calculated and then the NC code is regenerated to attain cutting time and surface finish estimates while maintaining constant cutting forces. The main differences among the approaches dealt in the past and proposed study for feed rate estimation can be seen in Figure 2.



Legend:

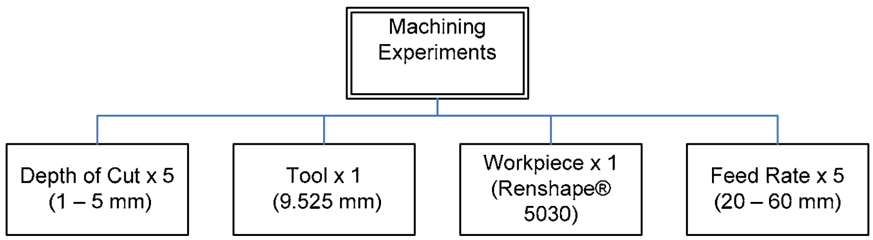
Past approach: Minimize cutting force variation with hope of achieving good surface finish and short machining time, through feed rate variation.
Proposed approach: Target good surface finish and low machining time with hope of minimizing cutting force variation, through variable feed rates.

Figure 2: Summary of the Past and Proposed Approaches for Feed Rate Estimation

METHODOLOGY

To establish relationships between cutting parameters (feed rate and axial depth of cut) and cutting force, surface finish and machining time, we used the following three-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 way similar to Fussell et al. [26].



Legend: Total number of experiments = 5 x 1 x 1 x 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
- feed rate: 20 - 60 mm/s
- tool diameter: 9.525 mm.

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: Establish the multi-variable regression equations
The multi-variable regression equations for cutting force, surface finish and machining time are established 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 as a function of feed rate and axial depth of cut in the machining of sculptured surfaces 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 since, the cutting forces recorded for these (12) experiments fell within the acceptable range of a previous study results [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 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.

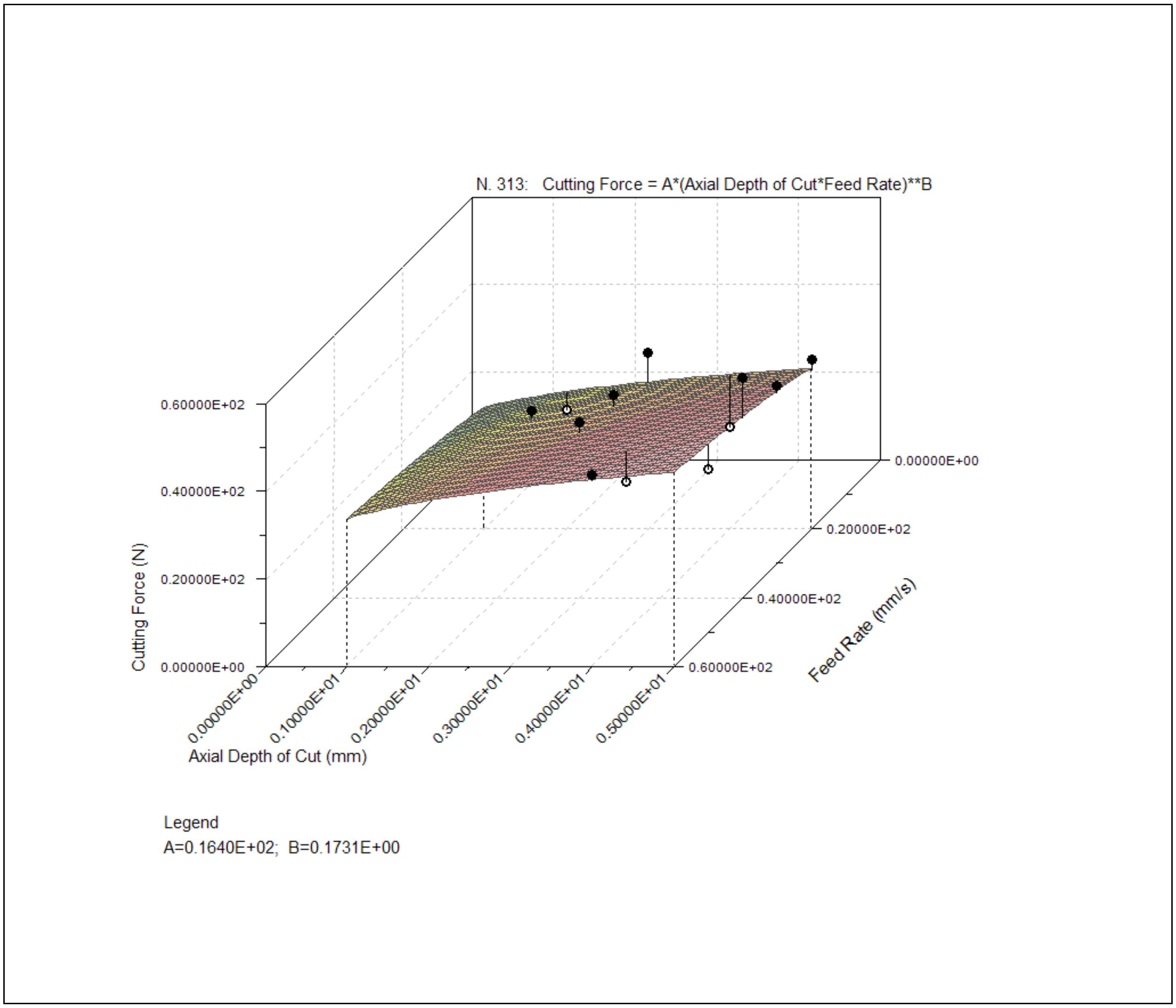


Figure 4: Relationship between Axial Depth of Cut and Feed Rate with Cutting Force

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 verified through the following equation:

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

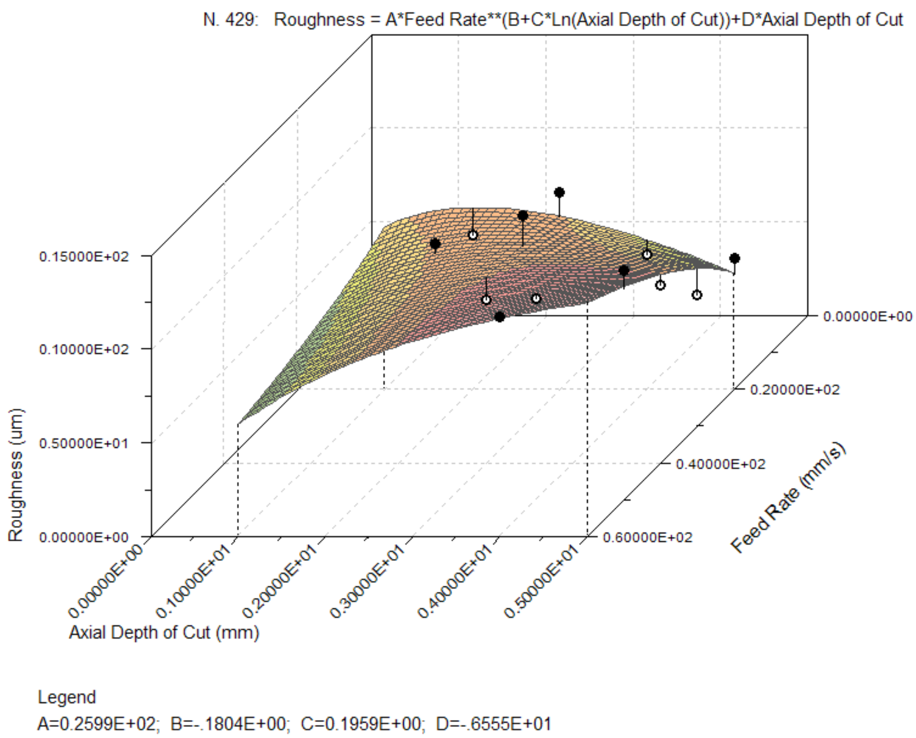


Figure 5: Relationship between Axial Depth of Cut and Feed Rate with Surface Finish

From the experimental results it was noticed that 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 a poor surface finish. This is depicted in Figure 5, and is represented by the equation:

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

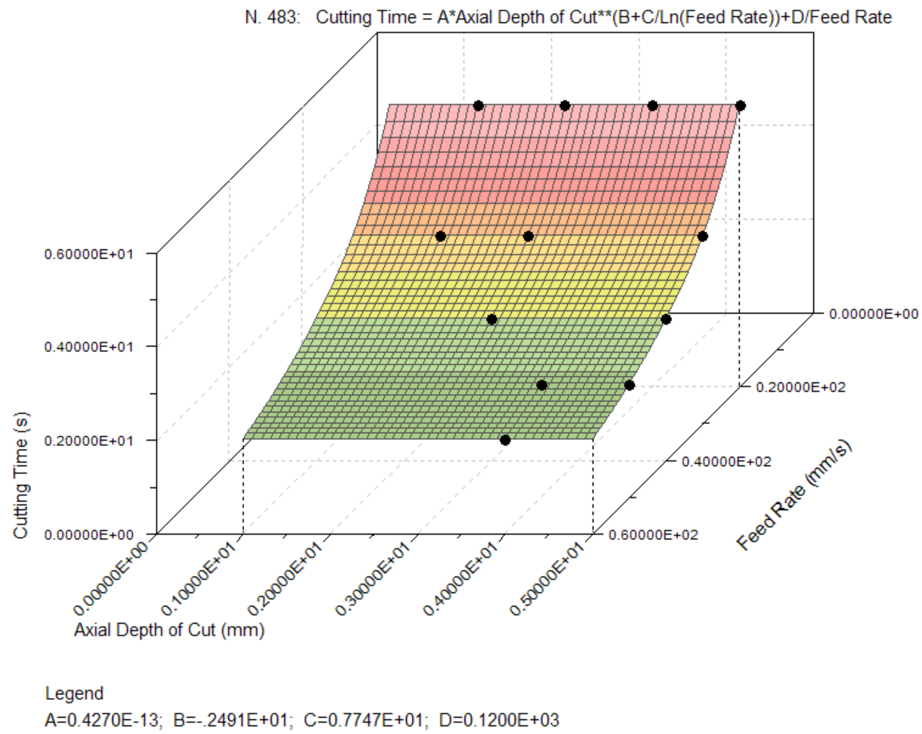


Figure 6: Relationship between Axial Depth of Cut and Feed Rate with Machining Time

This study results further indicate that the machining time was shortest when machining with a high feed rate, while a low feed rate yielded the longest machining time. This trend is presented in Figure 6, and is given by the equation:

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

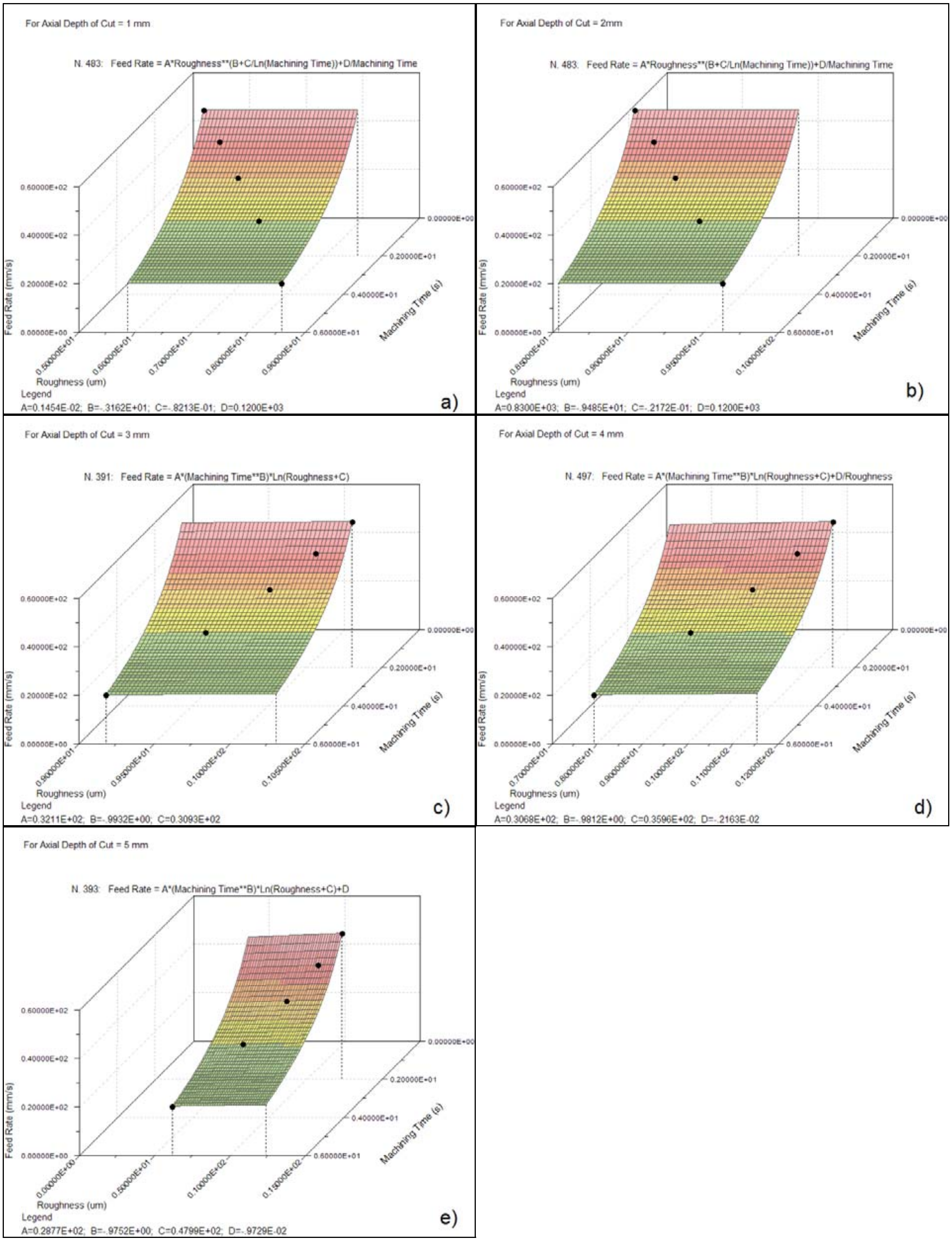


Figure 7 (a-e): Relationship between Surface Finish and Machining Time with Feed Rate

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 machining of sculptured surfaces are investigated. Multi-variable relationships were developed based on Taguchi's design of experiments. Multi-variable regression constants were derived from the Labfit® [[28]] graphs for each set of relationships. The derived multi variable regression constants will reflect the effect of various factors such as vibration and tool wear.

Figure 4 shows the relationship of cutting force with axial depth of cut and feed rate. For the machining parameters used in these experiments, axial depth of cut and feed rate have similar effect on the cutting force, since both are driven 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 relates to the surface finish with axial 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 poor surface finish. This can be seen from the equation:

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

Also, Figure 6 explains the relationship of machining time with axial depth of cut and feed rate. For the machining parameters used in these experiments, an increase in feed rate has a much greater effect on the machining time than depth of cut. This is expected, and can be confirmed through 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) shows the relationship of feed rate with surface finish and machining time for axial depth of cut in the range of 1 – 5 mm with an interval of 1 mm. For the machining parameters used in these experiments, a high feed rate causes shorter machining times, and poor job finish. 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.

CONCLUSION

The results of the study tend to support the work of Jerard et al. [6], where it was revealed 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 constant 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 must be considered for completeness of the study. 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 these effects. Further research in this direction is in progress.

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