Predictive modelling of cutting force and its influence on surface accuracy in ultra-high precision machining of contact lenses

O. A. Olufayo*, K. Abou-El-Hossein

Precision Engineering Laboratory, Nelson Mandela Metropolitan University (NMMU), Port Elizabeth 6031, South Africa

* Corresponding author. Tel.: +27-61-034-9175 fax: +27-041-504-9067. E-mail address: oluwole.olufayo@nmmu.ac.za

Abstract

The successful application of contact lenses is heavily dependent on their form accuracy and surface integrity. Cutting forces play a key role in the diamond turning of contact lenses as they have direct influence on their form accuracy and surface integrity. In addition, the cutting forces are also important for other aspects of diamond turning of contact lenses such as tool wear. Therefore, the prediction of cutting forces in contact lens manufacturing is deemed essential for the sake of high quality optical surfaces. One way to manage the effect of the cutting force and reduce its negative effect on surface finish could be realised through optimisation and modelling techniques. There are several factors that affect the extent of the cutting force developed in diamond turning. An example of these factors is the selection of cutting parameters. The establishment of a statistical model for the reliable prediction of cutting forces which is linked to a specific optical quality characteristic could be a way for understanding the behaviour of cutting force and its effect. In this study, a cutting force model based on response surface statistical method is developed for reliably predicting the values of cutting force based on its relationship to cutting parameters in the high-precision machining of contact lenses. The model obtained from fifteen experimental tests determines the effects of cutting speed, feed rate and depth of cut on force and how various combinations of parameters affect cutting force and thus surface quality. Results indicate that feed rate is a significant factor in the generation of high cutting force and low surface roughness. The study concludes that high feed rates and high cutting speeds cause an increase in cutting force and thus adversely affect the quality of the diamond-machined surface in the high precision machining of contact lenses.

1. Introduction

Currently, ultra-precision machining (UHPM) based on single-point diamond turning (SPDT) is considered as an effective process for the generation of high quality functional surfaces with minimal defects in the superficial surface layer from various materials [1]. This optical manufacturing method utilises diamond tools to cut optical surfaces with nanometric accuracy.

In the area of precision diamond turning, a number of research studies have embarked on evaluating the general effect of diamond tool wear, effects of tool geometry and influence of machine tools and controlling techniques. These research works have addressed the effects of cutting parameters on the surface quality of various optical profiles made from metallic materials. However, little research works have been devoted for the evaluation of diamond machining when polymeric components are shaped. Precision machining of polymers though has been in existence for few decades now, yet it is still an untapped field and data produced so far is still inadequate. This cutting edge technology with divers’ applications from medical, imaging and micro electrical systems still needs an adequate prognostic system to ensure optimal performance.

The successful application of contact lenses is heavily dependent on their form accuracy and surface integrity. The cutting force produced in contact lenses diamond turning plays a key role as it has a negative influence on the form accuracy and surface integrity. It is recorded from literature that there exists a high influence of cutting parameters such as
feed rate and depth of cut on cutting force and invariably this affects the achievable surface quality [2, 3].

In addition, cutting force is also important for other aspects of diamond turning of contact lenses such as tool wear which also negatively affects surface finish. One way to manage the effect of the cutting force and reduce its negative effect on surface finish could be realised through optimisation and modelling. Therefore the prediction of cutting forces in contact lens manufacturing is deemed essential for the sake of high quality optical surfaces.

This study seeks to address this gap in research and present an experimental approach for the prediction of the influence of cutting force and its independence on cutting parameters in the process of high precision machining of polymers.

1.1. Cutting mechanics in UHPM

Micro-force sensing presents an effective method of force monitoring [4, 5]. During the modelling of micro-cutting forces occurring during diamond machining, it is essential to revisit the cutting mechanics equation linked to this diamond machining experimentation. Also, a brief insight into orthogonal force distribution in diamond turning for negative rake angle tools could assist in understanding the importance of cutting forces in UHPM. For this purpose, the section below modifies the known cutting mechanics equations to suit this experiment.

\[
\varphi = \frac{\beta}{4} + \frac{\alpha}{2} - \frac{\lambda}{2}
\]

Eq. 1 shows the relationship of the Merchant model where \(\alpha\) is the rake angle and \(\lambda\) is the friction angle defined by \(\mu = \tan(\lambda)\), where \(\mu\) is the coefficient of friction.

The Merchant’s model is the most famous approach of orthogonal cutting. It is extensively used in introductive courses on machining. In the model, the cutting edge is perpendicular to the relative cutting velocity between the tool and the workpiece (See Fig. 1). The model could represent all forms of cutting level and the materials are considered as continuous media.

A metal chip and uncut chip thickness is sheared away from the workpiece. The cutting forces are exerted only in the direction of velocity \(v_t\) and uncut chip thickness namely tangential force and feed force [6]. The Merchant’s shear angle can be obtained from the Eq. 1.

![Fig. 1. Diagram of (a) diamond cutting tool (b) cutting force representation](image)

Fig. 1 shows the cutting force interactions during diamond turning operation. From the diagram below \(F_c\), \(F_s\), \(F_n\), \(F_{sn}\), \(F_r\) are the cutting force, shear plane force, normal force, thrust force, normal force along the rake plane of the tool and resultant force during cutting. This orthogonal force diagram was readapted from [7, 8] using the negative rake angle of the tool for application in this research work. \(v_c\) is the cutting speed, \(\varphi\), \(\beta\) and \(\alpha\) are the shear angle, friction angle and rake angle. The orthogonal cutting force \((F_c)\) is interpreted as:

\[
F_c = \tau A_o [\cos(\beta + \alpha) / \sin \cos(\varphi + \beta + \alpha)]
\]

where \(r\) is the shear stress and \(A_o\) is the undeformed chip thickness.

The above derived model represents the factors associated with cutting forces during the UHPM of polymers using a negative rake angle. It could be used to predict the underlining force factors at this scale of cutting responsible for cutting conditions.

The following assumptions are however considered for a cutting model to be applicable in representing machining operations:

* The tool tip is a perfectly sharp edge free of defects and alterations which could represent changes in force vectors
* The deformation is considered in only two planes (2D) for the action and direction of forces for representation
* Stresses on the shear plane are uniformly distributed i.e. considered as equal for the purpose of calculation
* The resultant force on the chip applied at the shear plane is equal, opposite and collinear to the force applied to the chip at the tool-chip interface [6].

1.2. Other influential factors to optical fabrication

There are several factors that affect the extent of the cutting force developed in diamond turning. An example of these factors is the selection of cutting parameters. Influential cutting parameters in UHPM are the speed, feed and depth of cut. These parameters have known associations with optical surface quality and form accuracy in optical fabrication.

Consequently in the establishment of a statistical model for the reliable prediction of cutting forces and recommending the right cutting parameters is deemed useful.

1.3. Measurement instruments

For cutting force acquisition, a highly sensitive Kistler® piezoelectric is used. The micro-force sensor was affixed below the diamond tool to monitor the cutting force experienced during polymer cutting. The force sensor was set to a calibrated range of 0–20N at a sensitivity of -83.68pC/N. This sensor is plugged into Kistler® multichannel charge amplifier which relays sensor charge signals to a proportional output voltage for data acquisition.

The data acquisition system used consists of a Type 5697 Kistler® DAQ station and was processed through Dynoware software.
2. Experimental setup

Machining tests were performed on Precitech Inc. Nanoform Ultragrdn 250 ultra-high precision lathe which is available at the Nelson Mandela Metropolitan University, Precision engineering laboratory (Fig. 3). The Nanoform 250 ultra-grind precision machine is a 4 axis diamond machining system designed for precision manufacturing of optics, optical moulds and mechanical components in ferrous and nonferrous. This precision machine is equipped with a vacuum chuck, ultra-high precision air-bearing spindle, granite base, oil hydrostatic slides and optimally located air isolation mounts [9]. The system is built on sealed natural base to eliminate machine contamination. Self-levelling isolation minimises vibration influences during machining. The system is driven by linear motors and hydrostatic oil bearing sideways with advanced stiffness characteristics which provide ultimate performance. Nanoform 250 ultragnd is also equipped with a spindle that can provide with nanometric runout motion accuracy. The feedback resolution of the machining system is 1.4nm. Additionally, the programming resolution is 1.0 nm.

Fifteen experimental runs were recorded based on the Box Behnken statistical method using cutting parameters shown in Table 1. Three force measurements were collected for each experimental run to ensure accuracy and the average of these three force values was selected for the model. The recorded multiple force values were found to have small variations in the range of 0.001 – 0.0035N.

2.1. Force sensor setup

In Fig. 2, we observe the machining setup used in the manufacture of UHPM contact lenses. In the Figure we can observe the sensor under the tool and the various components of the high precision machining environment.

2.2. Cutting tool and workpiece

Experimental testing was conducted on a range of cutting parameters using diamond tools. Contour® ltd fine tooling monocrystalline diamond tool were employed to machine the polymer. A silicon-acrylate industrial grade contact lens copolymer was used in this research. This polymeric material is a rigid gas permeable polymer with hydrophobic properties. It is also a commercially available contact lens polymer and is well known for its high permeability and wettable properties. Table 2 shows the various properties of the tool and workpiece used in this study.

![Fig. 2. Precitech Nanoform 250 ultra-high precision machine](image)

![Fig. 3. Diamond machining setup of contact lens polymers on UHPM](image)

| Run | Factor 1 | Factor 2 | Factor 3 | Response 1 |
|-----|----------|----------|----------|------------|
| A: Speed (m/s) | B: Feed (µm/rev) | C: Depth of cut (µm) | Cutting force (N) |
| 1 | 2.50 | 2.00 | 25.00 | 0.06 |
| 2 | 0.15 | 7.00 | 40.00 | 0.06 |
| 3 | 1.33 | 7.00 | 25.00 | 0.054 |
| 4 | 1.33 | 2.00 | 40.00 | 0.074 |
| 5 | 2.50 | 7.00 | 40.00 | 0.098 |
| 6 | 2.50 | 12.00 | 25.00 | 0.074 |
| 7 | 0.15 | 2.00 | 25.00 | 0.061 |
| 8 | 0.15 | 7.00 | 10.00 | 0.054 |
| 9 | 1.33 | 12.00 | 40.00 | 0.126 |
| 10 | 2.50 | 7.00 | 10.00 | 0.045 |
| 11 | 1.33 | 7.00 | 25.00 | 0.079 |
| 12 | 1.33 | 2.00 | 10.00 | 0.042 |
| 13 | 1.33 | 12.00 | 10.00 | 0.141 |
| 14 | 1.33 | 7.00 | 25.00 | 0.067 |
| 15 | 0.15 | 12.00 | 25.00 | 0.109 |

| Workpiece | Silicon acrylate co-polymer |
|-----------|-----------------------------|
| Diameter  | 12.7 mm                     |
| Thickness | 5 mm                        |
| Tool      | Single-crystal diamond      |
| Rake angle| -5°                         |
| Relief angle | 15°                        |
| Tool nose radius | 0.508mm                   |
3. Predictive modelling of cutting force and the influence of cutting parameters

In this study, a cutting force model based on the response surface statistical method is developed for the reliable prediction of cutting forces in the high-precision machining of contact lenses. The model obtained from fifteen experimental tests determines the effects of cutting speed, feed rate and depth of cut on force and how various combinations of parameters relate to surface quality.

Via a set of polynomial mathematical equations, RSM analysis is utilised to define the relationship between the input variables (speed, feed and depth of cut) and the output variable (cutting force).

3.1. Determination of appropriate polynomial equation to represent RSM model

An RSM data analysis was carried out using a statistical software. The determination of a suitable polynomial equation to represent the relationships between input parameters and the cutting force (output response) was done by carrying out sum of squares sequential model and lack of fit statistical tests. A linear source modelling approach was then utilised for modelling the cutting force.

3.2. ANOVA analysis of the Response surface Quadratic Model for cutting force

The ANOVA have been performed to check whether the model is adequate as well as to check the significance of the individual model coefficients. Table 3 shows the ANOVA for cutting forces. The Model F-value of 11.26 implies the model is significant. The percentage chance of the occurrence of this “F-value” to originate from noise within the analysis is only a 0.52 percent.

Table 3 ANOVA for model coefficient for Cutting Forces in UHPM of contact lens polymer

| Source       | DF | Seq SS     | Adj MS | F     | P     | Remark     |
|--------------|----|------------|--------|-------|-------|------------|
| Model        | 1  | 5.671E-003 | 5.671E-003 | 11.26 | 0.0052 |            |
| B-Feed       | 1  | 5.671E-003 | 5.671E-003 | 11.26 | 0.0052 | significant |
| Residual     | 13 | 6.546E-003 | 5.035E-003 | 11.26 | 0.0052 |            |
| Lack of fit  | 11 | 6.233E-003 | 5.666E-003 | 3.62  | 0.2360 | Not- significant |
| Pure         | 2  | 3.127E-003 | 1.563E-004 |       |       |            |
| Error        | 14 | 3.127E-003 | 1.563E-004 |       |       |            |

The "Lack of Fit F-value" of 3.62 implies the Lack of Fit is not significant relative to the pure error. In the same manner, there is only a 23.60 percent chance that a “Lack of Fit value” could result from noise interference during analysis. Non-significant lack of fit is a desired trait for a fitting model.

3.3. Determination of significant factors influencing cutting force

In determining the cutting parameters influential to the cutting force the results from the ANOVA Table 3 were studied. Based on a probability value greater than F-value and less than 0.005, significant terms to the model were identified. In this case the feed was identified as the only significant model term linked to the cutting force. The behaviour of cutting force in response to variations of feed rate was also compared to research work compiled by other researchers to support the validation of the model. The feed rate line in Fig. 5 indicates that as the feed increase from 2 to 12µm/rev, the cutting force increases from 0.45 to 0.102N. A direct correlation is shown to exist with increase in feed.

4. Results and discussion

From the surface response modelling the linear polynomial model equation developed to relate the input parameters to the cutting force is shown in Eq. 3.

![Fig. 4. Normal probability plot of residuals in cutting force modelling](image)  
![Fig. 5. Behaviour of force in response to variation in feed](image)
Cutting Force (N) = 0.038992 + 5.32500E – 003 * Feed

From the graphical perspective of the model equation using a 3D surface plot, in Fig. 6, the effects of varying the depth of cut and feed while keeping the speed constant is shown. Fig. 6 shows that as the feed increases a corresponding increase in cutting force is observed. However, the depth of cut shows no effects on the force values.

Fig. 6. 3D Plot of the influence of feed and depth of cut on cutting force

5. Model validation

The validation of the model is used to ascertain if the developed model can sufficiently predict the output cutting force generated during cutting. Using the point tool from the statistical software, three set of parameters were chosen for validation. As seen in Table 4 below, the actual predicted values are compared using the residual error. A margin of 20 percent is used to determine the adequacy of the model at a confidence prediction level of 80 percent. From the table, it can be seen that the results fall within the 20 percent margin of model adequacy but below the 10 percent confidence prediction level.

Table 4 Experimental run and results of cutting force

| Run | A: Speed | B: Feed | C: Depth of cut | Predicted force | Actual force |
|-----|----------|---------|-----------------|-----------------|--------------|
| 1   | 2.50     | 12.00   | 25.00           | 0.0953          | 0.078        |
| 2   | 2.09     | 10.57   | 22.81           | 0.0953          | 0.061        |
| 3   | 1.33     | 7.00    | 30              | 0.0762          | 0.062        |

6. Summary

In this research work, we identify the feed rate as the main influential factor on cutting force generation in diamond machining of polymers. The RSM model implemented also postulates that negligible or no influence is perceived from variations in both depth of cut during UHPM of polymer. However, the validation of the model falls below a 10 percent confidence prediction level needed in general statistics despite a prior modelling of the exact force at the tool tip. This value indicates an underlining challenge in the model. This could be attributed to challenges in micro-force acquisition based on the scale of machining. It is recommended that more tests be conducted with a combination of multiple sensors to predict force effects on cutting parameters.

In conclusion, it can be seen that higher feed rates and high cutting speeds cause an increase in obtained cutting force and thus adversely affect the quality of machined lenses in the high precision machining of contact lenses.

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References

[1] Olufayo, O.A; Abou-El-Hossein, K., “Preliminary investigation of surface finish of a contact lens polymer in ultra-high precision diamond turning,” Robotics and Mechatronics Conference (RobMech) , Durban South-Africa, 2013 6th , vol., no., pp.117,122, 30-31 Oct. 2013, http://dx.doi.org/10.1109/RoMech.2013.6685502
[2] Lin WS, Lee BY, Wu CL. Modeling the surface roughness and cutting force for turning. Journal of Materials Processing Technology. 2001;108(3):286-93.
[3] Özel T, Hou T-K, Zeren E. Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel. Int J Adv Manuf Technol. 2005 2005/02/01;25(3-4):262-9, English.
[4] Risbood KA, Dixit US, Sahasrabudhe AD. Prediction of surface roughness and dimensional deviation by measuring cutting forces and vibrations in turning process. Journal of Materials Processing Technology. 2003 1/10/;132(1–3):203-14.
[5] de Agustina B, Rubio E, Sebastián M. Surface roughness model based on force sensors for the prediction of the tool wear. Sensors. 2014;14(4):6593-408. PubMed PMID: doi:10.3390/s140406393.
[6] Oluwajobi AO. Nanomachining technology development [Doctorate thesis]: University of Huddersfield; 2012.
[7] Xiao K, Zhang L. The role of viscous deformation in the machining of polymers. International journal of mechanical sciences. 2002;44(11):2317-36.
[8] Luo X, Cheng K, Holt R, Liu X. Modeling flank wear of carbide tool insert in metal cutting. Journal of Wear. 2005;259(7):1235-40.
[9] Chapman G. Ultra-precision machining systems; an enabling technology for perfect surfaces. Moore Nanotechnology Systems. 2004.