Effects of Cutting Parameters on Surface Finish Quality of Ultra-high Precision Diamond-Turned Optical Grade Single-Crystal Silicon

Abubakar I. Jumare and Khaled Abou-El-Hossein
Department of Mechatronics, Nelson Mandela University, Port Elizabeth 6031, South Africa
Email: s214199002@mandela.ac.za, khaled.abou-el-hossein@mandela.ac.za

***Abstract*—Ultra-high precision machining (UHPM) is the most suitable manufacturing process for the production of various optical components with high precision requirements and minimal defects in the superficial surface layer from various materials. To get the desired surface finish and dimensional accuracy, single-point diamond turning (SPDT) is preferable. This study is therefore aimed at determining the effects of three (3) machining parameters (cutting speed, feed rate and depth of cut) on the surface finish generated on single-crystal silicon (SCSi) workpiece. Series of diamond turning operations were performed sequentially with 1.5 mm nose radius, –25° rake angle, 10° clearance angle and 1–4° side cutting edge angle SPD tools on a Precitech Nanoform 250 ultra-grind lathe machine based on Box-Behnken Design in Response Surface Methodology by varying the three (3) cutting parameters. Analysis of variance was used to determine the influence of each of the machining parameters and their interactions on the response. The results revealed that feed rate is the most influential factor affecting the surface finish followed by cutting speed. Depth of cut was found to have the least influence on the response. Statistical analysis was used to ascertain the accuracy, adequacy and reliability of the developed model.**

***Index Terms*— diamond turning, cutting parameters, surface roughness, prediction model, single-crystal silicon**

I. Introduction

The field of infrared (IR) optics is one of the fastest growing branches of traditional optics and the new laser sources, fibre optic communications, night vision devices and a host of new detector technologies make the field of IR optics ripe for further growth [1]. The surface of silicon (Si) for IR application requires a good integrity and nanometric roughness devoid of microfractures, scratches and microcracks [2]. Hence, the need for lenses and mirrors to support the growth for IR systems.

Single-crystalline materials such as Si and germanium (Ge) are the principal materials in IR optics and electronic applications for the superior performance [3]. As thermal imaging materials, SCSi has the primary requirement of an IR optical material, and hence, the principal material used for solid-state electronics and IR optical technologies [4]. Therefore, SCSi is regarded as an ideal semiconductor and optical IR material [5] for weight sensitive applications and other high added value products due to its attractive features [6].

Nonetheless, Si as a brittle material, exhibits some difficulties when ultra-precision machined by single-point diamond (SPD) tool due to the excessive tool wear [7]. Process parameters such as cutting speed, feed rate and depth of cut are significant parameters in the investigation of machinability of an element [8] due to their influence on the cutting forces, tool wear, built-up edges (BUE) and surface finish criteria [9]. These pose a serious challenge on the economical and productive machining process to the manufacturing engineers.

However, advances in precision machining made machining of Si possible at a micro and nanometre scales through ‘ductile-regime machining’ (DRM) condition. Silicon and other brittle materials are known for their low machinability unless they are machined in DRM conditions [10], which enable the production of optical quality surfaces on brittle materials [11].

Consequently, Leung *et al.* [11] conducted an experimental demonstration of the possibility of DRM of SCSi under different cutting conditions using cutting fluid. Surface finish in the order of 2.86 nm was achieved. Then, Gerbig *et al.* claimed that information about differences in the brittle-ductile transformation pressure for the various crystallographic orientations in DRM is vital for the best results regarding subsurface damage, form accuracy and surface finish [12]. Hence, achieving ductile cutting mode is of utmost significance for excellent and uniform surface quality of SCSi using SPDT technique.

The SPDT technology is an UHPM process for producing high quality optical surfaces on metals, polymers and crystals [13]. It is a machining process that makes use of a mono-crystal diamond cutting tool (Fig. 1) that possesses nanometric edge sharpness, form reproducibility and wear resistance [14].

Manuscript received August 5, 2019; revised January 7, 2020.

doi: 10.18178/ijmerr.9.4.541-547

Figure 1. Single-point synthetic diamond tools

Evidently, Goel [15] reiterated that SPDT provides a machining form accuracy and machined surface finish that are among the best ranges obtained through the traditional method of lapping and polishing. Ravindra [16] corroborates that SPDT is famous for its mechanical and optical advantages due to the precision level of the machine and the diamond cutting tool.

To further improve the surface roughness (R_a), it is imperative to fully comprehend the various factors that affect the attained surface roughness and methods of improving surface quality [17, 18]. Generally, these factors are classified into the process factors and material factors. The former involves the cutting conditions like spindle speed, feed rate, tool geometry, environmental conditions and relative vibration between the tool and the workpiece, tool wear and chip formation [19]. The latter involves the machine tools and physical and chemical properties of workpiece and tool materials.

Surface finish issues received serious attention for many years [20], being the widely used indices of product quality and in most cases, the technical requirements for mechanical products. The R_a profile of a machined surface provides a faithful signature of the cutting process and the variation of material properties [21]. It is a measure of the technological quality of a product and a factor that greatly influences manufacturing cost [22].

II. Literature Survey

Si makes up about 25% of the Earth's crust by mass, is the second most abundant element after oxygen [1], and it is safe for the environment [2]. It is a metalloid and crystalline material in nature, with excellent advanced physical and mechanical properties [1, 3]. SCSi is widely used in the manufacturing of integrated circuits and infrared optics [4-7]. It is relatively inexpensive, has a high transmittance and is lightweight due to its less density. Therefore, SCSi is regarded as an ideal semiconductor and optical IR material [8] for weight sensitive applications and other high value-added products owing to its attractive features [9].

Despite being difficult-to-machine, proper selection and control of cutting parameters can lead to maximum material removal rate with smallest possible surface roughness on ultra-precision machined SCSi parts. Such parts have tremendous importance in microelectronics, micromechanical and optical elements manufacturing. Mechanism of nanometric cutting of this important element has been a focused research area because of its high accuracy and high surface finish requirements [10]. Hence, understanding its behaviour and machinability is paramount.

Machinability is the term used to describe the ease with which a work material can be machined using appropriate tooling and under a given set of cutting conditions [11, 12]. It depends on the work material properties and the cutting conditions. Machining is considered to be the best way of producing a prototype, with least effect on the component's metallurgical properties, and for generating the required surface finish within an acceptable tolerance [13]. Machining is also one of the most significant and complicated manufacturing process used for the production of quality components in manufacturing businesses [14]. The main aim is to produce the components within the minimum machining time and at minimal cost.

Owing to the rise in demand for surface perfection in recent years, brought about by the sophistication of aerospace, micro-electronics and optical industries, various efforts have been made to improve defects in Si parts [15, 16]. In another attempt to improve the machinability of Si parts, scholars have deployed different means in an effort to understand the deformation, fracture and microstructural changes of Si [17, 18]. Vodenitcharova *et al.* [18] recommended a scratch test on Si-based devices to eliminate cracks, which resulted in strength degradation. Moreover, these researchers confirmed that the anisotropic nature of Si influenced its fracture upon scratching. This resulted in differences in the cracking resistance and reliability, depending on the direction and the wafer surface. It is a known fact that defects, such as cracks or pores and amorphization/re-crystallization, influence the optical as well as electronic and mechanical performance of Si wafers. Hence, there is need to fully understand the mechanisms of fracture in Si and devise means of eliminating them.

Nonetheless, advances in precision machining have made the machining of SCSi possible at micro- and nanometre scales with the aid of non-conventional, high-stiffness precision machine tools that control the machining parameters and produce what has been termed 'ductile-regime machining' (DRM). It is the process of machining brittle materials, in which the material is removed by plastic flow rather than by brittle fracture, thus leaving a high-quality crack-free surface [19, 20]. The process is a novel means of fabricating unique features in brittle materials that can be achieved under certain chip formation conditions [21].

In other words, in DRM, an optical quality surface, free of microstructure damage is obtained through a ductile mode material removal process approach [22]. This is made possible by diamond turning, which enables direct fabrication of mirror-like surfaces without subsequent post-processing by controlling the cutting mode to be ductile [23, 24]. It is a preferable method, especially for manufacturing components with complex shapes. This is due to its high machining accuracy and ease of numerical control. The advent of the ductile-mode machining notion from the indentation test established that brittleness is an indentation size effect [25].

However, for a Si workpiece to be machined in the ductile mode, the machining conditions must be carefully chosen, such that the maximum undeformed chip thickness is adequately smaller than the cutting edge radius [26]. Also, the theory of the precision diamond turning of infrared crystals, such as Si, has it that DRM entails very shallow depths of cut [27]. This benchmark, as Uddin *et al.* [6] put forward, is an essential constraint for the attainment of enough hydrostatic pressure to enable plastic deformation in the cutting process to occur.

This study therefore evaluated the effects of cutting parameters (cutting speed, feed rate and depth of cut) on the surface finish quality of ductile regime-machined SCSi. Subsequently, empirical prediction model for surface roughness based on the experimental data was developed, and effects of cutting parameters on the surface roughness were characterized. Statistical analysis was used to determine the extent of the effect of each parameter on the surface roughness.

III. Experimental Setup

Fig. 2 depicts the experimental setup. The turning operations were performed on a Precitech Nanoform® 250 ultra-precision lathe. Diamond tool inserts mounted on tool holder assembly and SCSi workpiece mounted and centred on the pneumatic vacuum chuck with the aid of optical microscope. The workpiece used in this study was a round, sliced blank optical grade SCSi with dimensions – 30 mm diameter x 14 mm thick. The SCSi is the base material for silicon chips used in virtually all electronic equipment today.

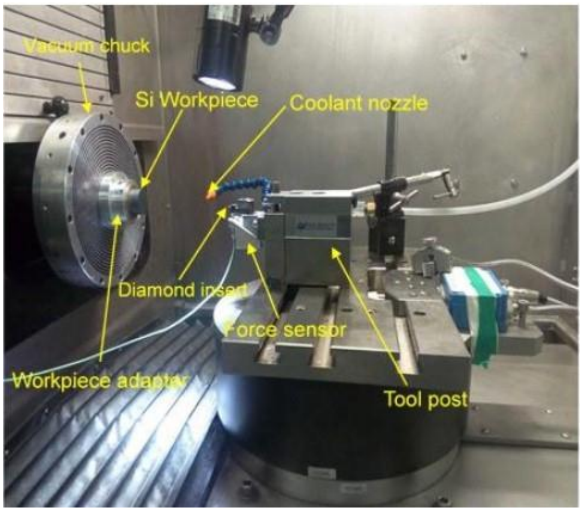

Figure 2. SPDT process setup

SPD tools were used as cutting inserts for this study, each with 1.5 mm nose radius, -25^o rake angle, 10^o clearance angle and $1–4^o$ side cutting edge. This is because, conventionally, round nose cutting tools and low feed rates are preferred to obtain a crack free machined surface while machining brittle materials [24]. Series of facing operations were performed on the surface of SCSi workpiece while surface roughness values of the machined surfaces were measured intermittently at regular interval of cutting distance and recorded. The cutting parameters were selected such that ductile removal mode is achieved [7]. Accordingly, the cutting parameters used in this study were determined by the results obtained in [4]. Nevertheless, the depth of cut was adapted to 10 µm low and 25 µm high to obtain improved surface finish quality. This is because, in finishing operations, depth is set to achieve the final dimensions for the machined parts [28]. The complete passes of cut covered an average of interrupted cutting distance of 2.6 km for each of the 15 trials. The cutting trials were conducted under continuous cooling conditions throughout and full-flood water-based coolant was used for cooling and lubrication during the machining process.

The surface roughness values were measured intermittently with the aid of Taylor Hobson's PGI Dimension surface profiler (Fig. 3), which is a contact-type mechanical profiler. The technique involves dragging a conical diamond tip stylus probe over the machined surface (Fig. 3). The stylus moves over the surface to record the height variation along a straight line and at a constant speed while an electrical signal is produced by the transducer. These electrical signals are amplified and undergo analogue to digital conversion. The displacement of the probe provides proportional amplified electric signals, which are then fed into a chart recorder to produce a profile chart of the surface roughness and the corresponding R_a values.

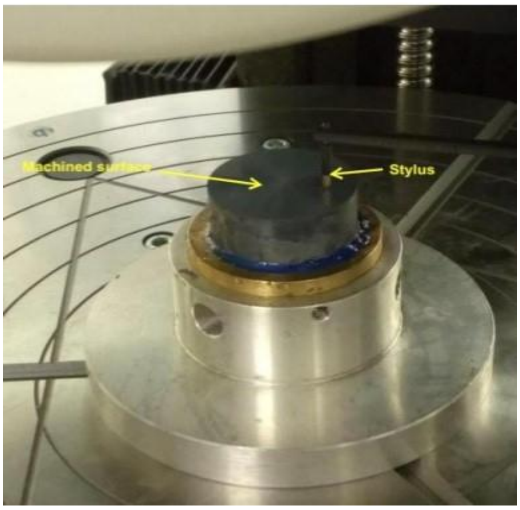

Figure 3. Surface roughness measurement

IV. Design of Experiments

The experimental design used in this study was based on Box-Behnken Design (BBD), which is a type of response surface methodology (RSM). The BBD was used to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. Three-factor three-level parameters and their levels are employed in this study (Table I).

These machining conditions were used for the design of experiment that generated the various machining combinations used for the machining and the corresponding experimental R_a values for each experimental run are as presented in Table II.

TABLE I. MACHINING CONDITIONS FOR THE EXPERIMENTS

Factors	Levels		
	Low (-1)	Medium (0)	High (+1)
Cutting speed (rpm)	250	500	750
Feed rate (mm/min)	2	7	12
Depth of cut (μm)	10	17.5	25

V. RESULTS AND DISCUSSION

The only response considered in this study is the average surface roughness, R_a. Table II depicts all the input variables and the corresponding response.

TABLE II. MEASURED AVERAGES OF SURFACE ROUGHNESS VALUES

Run No.	Cutting speed, v (rpm)	Feed rate, f (mm/min)	Depth of cut, d (μm)	Average roughness, R_a (nm)
1	750	7	10	12.5
2	750	12	17.5	34.3
3	750	2	17.5	2.1
4	500	7	17.5	21.9
5	500	12	25	158.3
6	750	7	25	5.2
7	500	7	17.5	22.6
8	500	12	10	129.8
9	250	2	17.5	5.6
10	250	12	17.5	470
11	500	2	25	2.3
12	250	7	10	122.5
13	500	2	10	2.2
14	250	7	25	192.3
15	500	7	17.5	23.2

The results (Table II) affirmed that large variation in surface finish quality ensued by changes mostly in feed rate and cutting speed. Thus, R_a increases with increasing feed rate and decreases with increasing cutting speed. As none of the poor surface finishes correspond to the high speed and low feed combination. With the reduction of feed rate, the chip removal action is improved and high quality surface is obtained. But in a higher feed rate, surface finish quality deteriorated.

Again, an increase in Ra as a result of increase in feed rate was due to the occurrence of brittle fractures at high feed rates caused by the increased metal removal rate (MRR). Yet, a DRM phenomenon was realized. The observation demonstrates the viability of ultra-high precision diamond turning of optical grade silicon at very high MRR. The finding thus suggests a strong correlation between Ra and feed rate.

Then, results of the experiments 1, 5, 8, 12 and 14 in this study substantiated the contentious practical effect of depth of cut on the Ra profile in UHPM of silicon. This requires further research to ascertain the actual trend. While the rapid increase in R_a (run 10) indicates the transition of cutting mode from ductile to brittle.

Analysis of variance (ANOVA) was used to determine the extent of influence of the individual cutting parameters as well as the interaction influence (Table 3). This further substantiated the contribution of each situation on the Ra values.

This shows that it is only depth of cut that is statistically insignificant in the model (p-value > 0.05), with only 0.2% contribution. Feed rate is the most influential factor. Speed–feed interaction also appears significant (Table 3).

The final second-order polynomial response surface (RS) model for Ra prediction in terms of the actual factors is presented as a function of cutting speed, feed rate, depth of cut and their interactions and is given by:

$$R_a = (0.233234 + 0.000671v - 0.088173f + 0.001469d - 0.000054vf + 0.005554f^2)^{-1}. \quad (1)$$

where: R_a = surface roughness, in nm; v = cutting speed, in rpm; f = feed rate, in mm/min and d = depth of cut, in μm.

Based on the prediction model, the recommended combination of cutting parameters to obtain the best Ra value is the usage of high cutting speed with low feed rate and medium depth of cut. Also, to further confirm the adequacy and accuracy of the model, accuracy check is performed on the model. This is done with the aid of the diagnostic plots, which involves the normal probability plot of the studentized residuals (Fig. 4) to check for normality of residuals.

The normal probability plot of the studentized residuals of the model (Fig. 4) shows that the residuals (i.e. error = model value – actual value) closely follow the straight (probability) line. This justifies that the errors are distributed normally and the terms mentioned in the model are significant.

Similarly, the ANOVA result (Table 3) shows that feed rate has the highest effect on the R_a model, with 64.4% total contribution. Increase in feed rate causes sharp decrease in the inverse function of the R_a, thereby causing increase in R_a. On the other hand, the 0.2% contribution of the depth on the response indicated its least significance. However, its presence in the model (Eq. 1) with a positive standardized regression coefficient made it to show a slight effect on the R_a.

TABLE III. ANALYSIS OF VARIANCE FOR SURFACE ROUGHNESS MODEL

Source	Sum of Squares	Degree of Freedom	Mean Square	F Value	p-value	% Contribution	Remark
Model	0.41463	5	0.08293	35.2635	< 0.0001		*significant*
A-Speed	0.04257	1	0.04257	18.1033	0.0021	9.8	
B-Feed	0.28079	1	0.28079	119.404	< 0.0001	64.4	
C-Depth	0.00097	1	0.00097	0.41345	0.5363	0.2	
AB	0.01831	1	0.01831	7.78398	0.0211	4.2	
B^2	0.07199	1	0.07199	30.6123	0.0004	16.5	
Residual	0.02116	9	0.00236			4.9	
Lack of Fit	0.02116	7	0.00302	1840.24	0.0005		*significant*
Pure Error	3.29E-06	2	1.65E-06				
Cor Total	0.43579	14					

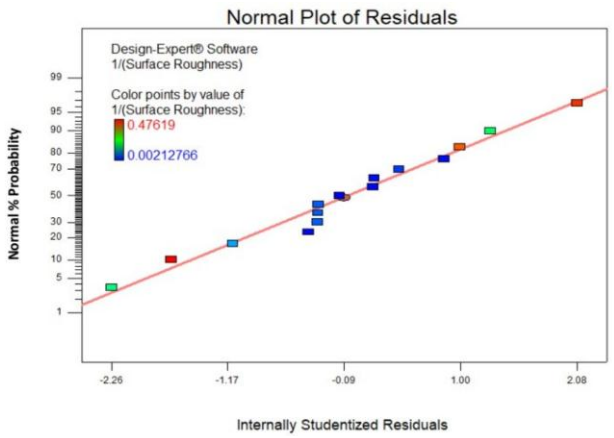

Figure 4. Normal probability plot of the studentized residuals

The linear relationship is such that, huge increase in depth of cut causes a slight increase in the inverse R_a, thereby causing slight decrease in R_a value. For the interaction effect, it indicates that the effect of cutting speed on the R_a is exclusively dependent on the level of feed rate and vice versa.

The developed model was used to generate the 3D response surface plot to pictorially show the effect of each parameter of the R_a. The 3D plot (Fig. 5) depicts the alliance of lowest R_a with the high cutting speeds and low feed rates (the blue regions). From the figure, it can be seen that a combination of high cutting speed and low feed rate generated better surface quality. On the other hand, combination of high cutting speed–high feed rate and low cutting speed–high feed rate led to the deterioration of the machined surface. However, a combination of low cutting speed–low feed rate also generated fairly good surface.

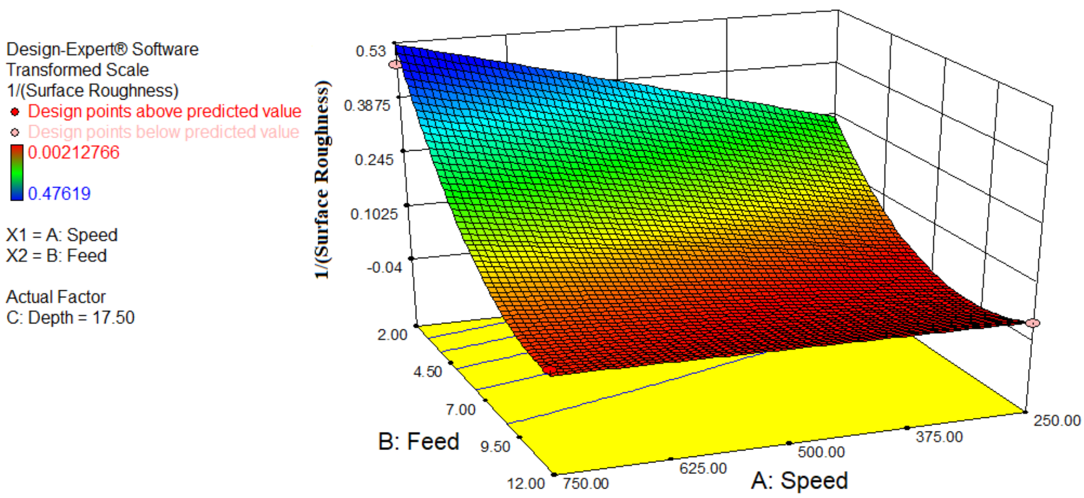

Figure 5. Normal probability plot of the studentized residuals

VI. CONCLUSIONS

The study revealed that feed rate is the most influential factor affecting surface roughness in UHPDT of silicon followed by the feed rate, while depth of cut has the least influence. The cutting process can be characterized as consistent and repeatable as well as huge enhancement of cutting performance of the diamond tool within the experimental domain. Since most of the surfaces generated satisfied the highest surface roughness requirement over the entire IR region for silicon. Values of the regression coefficients signified a considerable correlation between the cutting parameters and the response with good degree of estimation. Hence, the reliability, adequacy and accuracy of the developed empirical model are confirmed. It can therefore be used to determine the optimum cutting parameters for minimum surface roughness generation and make predictions within the range of the actual experimentation. The constructed 3D plots can also be used by researchers and manufacturers of silicon optical lenses to find the best combination of machining parameters for the desired surface quality.

Conflict of Interest

The authors declare that there has been no conflict of interest in carrying out the research activities related to this article.

Author Contributions

The main author, Mr. A. Jumare wrote that article and performed the experiments explained in this study, including the analyses and discussion. Prof. K. Abou-El-Hossein is the promoter of the study conducted by Mr. Jumare as part of his PhD degree All the authors approved the final version.

Acknowledgement

The authors would like to acknowledge the National Research Foundation (NRF) of South Africa for the invaluable support given to the Precision Engineering Laboratory of Nelson Mandela University. Also, support of the Research Capacity Development unit of the University is hereby acknowledged.

References

[1] W. C. O’Mara, Herring, R. B., and L. P. Hunt, *Handbook of Semiconductor Silicon Technology*: Noyes Publications, William Andrew, Inc., 1990.
[2] T. Saga, "Advances in crystalline silicon solar cell technology for industrial mass production," *NPG Asia Materials,* vol. 2, pp. 96-102, 2010.
[3] R. Hull, *Properties of Crystalline Silicon*, IET, London, 1999.
[4] M. Ayomoh and K. Abou-El-Hossein, "Surface finish in ultra-precision diamond turning of single-crystal silicon," in *SPIE Optifab*, 2015, pp. 96331I-96331I-6.
[5] C. L. Chao, K. J. Ma, D. S. Liu, C. Y. Bai, and T. L. Shy, "Ductile behaviour in single-point diamond-turning of single-crystal silicon," *Journal of Materials Processing Technology,* vol. 127, pp. 187-190, 2002.
[6] M. S. Uddin, K. H. W. Seah, M. Rahman, X. P. Li, and K. Liu, "Performance of single crystal diamond tools in ductile mode cutting of silicon," *Journal of Materials Processing Technology,* vol. 185, pp. 24-30, 2007.
[7] W. J. Zong, T. Sun, D. Li, K. Cheng, and Y. C. Liang, "XPS analysis of the groove wearing marks on flank face of diamond tool in nanometric cutting of silicon wafer," *International Journal of Machine Tools and Manufacture,* vol. 48, pp. 1678-1687, 2008.
[8] S. To, H. Wang, and E. V. Jelenković, "Enhancement of the machinability of silicon by hydrogen ion implantation for ultra-precision micro-cutting," *International Journal of Machine Tools and Manufacture,* vol. 74, pp. 50-55, 2013.
[9] S. Goel, X. Luo, and R. L. Reuben, "Wear mechanism of diamond tools against single crystal silicon in single point diamond turning process," *Tribology International,* vol. 57, pp. 272-281, 2013.
[10] O. A. Olufayo and K. Abou-El-Hossein, "Molecular dynamics modeling of nanoscale machining of silicon," *Procedia CIRP,* vol. 8, pp. 504-509, 2013.
[11] M. A. Dabnun, M. Hashmi, and M. El-Baradie, "Surface roughness prediction model by design of experiments for turning machinable glass–ceramic (Macor)," *Journal of Materials Processing Technology,* vol. 164, pp. 1289-1293, 2005.
[12] J. P. Davim, "Machinability of advanced materials," ed: John Wiley & Sons, 2014.
[13] S. Goel, L. Xichun, Agrawal, Anupam and R. L. Reuben, "Diamond machining of silicon: A review of advances in molecular dynamics simulation," *International Journal of Machine Tools and Manufacture,* vol. 88, pp. 131-164, 2015.
[14] S. K. Tamang and M. Chandrasekaran, "Integrated optimization methodology for intelligent machining of inconel 825 and its shop-floor application," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* pp. 1-13, 2016.
[15] J. Yan, T. Asami, and T. Kuriyagawa, "Response of machining-damaged single-crystalline silicon wafers to nanosecond pulsed laser irradiation," *Semiconductor Science and Technology,* vol. 22, p. 392, 2007.
[16] L. Zhou, H. Eda, J. Shimizu, S. Kamiya, H. Iwase, S. Kimura, and H. Sato, "Defect-free fabrication for single crystal silicon substrate by chemo-mechanical grinding," *CIRP Annals - Manufacturing Technology,* vol. 55, pp. 313-316, 2006.
[17] O. Borrero-López, T. Vodenitcharova, and M. Hoffman, "Anisotropy effects on the reliability of single-crystal silicon," *Scripta Materialia,* vol. 63, pp. 997-1000, 2010.
[18] T. Vodenitcharova, O. Borrero-López, and M. Hoffman, "Mechanics prediction of the fracture pattern on scratching wafers of single crystal silicon," *Acta Materialia,* vol. 60, pp. 4448-4460, 2012.
[19] W. K. Neo, A. S. Kumar, and M. Rahman, "A review on the current research trends in ductile regime machining," *The International Journal of Advanced Manufacturing Technology,* vol. 63, pp. 465-480, 2012.
[20] S. Venkatachalam, "Predictive modeling for ductile machining of brittle materials," Doctor of Philosophy Dissertation, Doctor of Philosophy thesis, George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, 2007.
[21] W. Sawangsri, "An investigation on micro cutting mechanics: Modelling, simulations and experimental case studies," Doctor of Philosophy, PhD. thesis, School of Engineering and Design, Brunel University, 2014.
[22] M. Zhou, B. K. A. Ngoi, Z. W. Zhong, and C. S. Chin, "Brittle-ductile transition in diamond cutting of silicon single crystals," *Materials and Manufacturing Processes,* vol. 16, pp. 447-460, 2001.
[23] T. P. Leung, Lee, W. B. and X. M. Lu, "Diamond turning of silicon substrates in ductile-regime," *Journal of Materials Processing Technology,* vol. 73, pp. 42-48, 1998.
[24] J. Yan, Syoji, K. Kuriyagawa, Tsunemoto and H. Suzuki, "Ductile regime turning at large tool feed," *Journal of Materials Processing Technology,* vol. 121, pp. 363-372, 2002.
[25] B. Lawn, T. Jensen, and A. Arora, "Brittleness as an indentation size effect," *Journal of materials science,* vol. 11, pp. 573-575, 1976.
[26] S. Asai and A. Kobayashi, "Observations of the chip producing behavior in ultraprecision diamond machining and study of mirror-like surface generating mechanism," *Precision Engineering,* vol. 12, pp. 137-143, 1990.
[27] E. R. Marsh, Sommer, J. Edward, Deakyne, R. S. Theodore, Kim, George A. and J. A. Simonson, "Detection of orientation-dependent, single-crystal diamond tool edge wear using cutting force sensors, while spin-turning silicon," *Precision Engineering,* vol. 34, pp. 253-258, 2010.
[28] M. P. Groover, *Principles of Modern Manufacturing,* Fifth, SI Version ed.: John Wiley & Sons Singapore Pte. Ltd., 2013.

Abubakar Jumare is a PhD student in the Department of Mechatronics of the Nelson Mandela University in Port Elizabeth. He is an active team member of the Laboratory of Precision Engineering.

He has published extensively in the field of high precision diamond turning of optical silicon. He obtained his bachelor and master degrees in the area of mechanical engineering.

Mr. Jumare is also a faculty staff who has taught extensively, courses related to mechanical and mechatronics engineering.

Khaled Abou-El-Hossein has obtained his Master of Science in Engineering and PhD from Ukraine in the areas of machine building technology and advanced manufacturing.

He is currently a full professor at the Nelson Mandela University in South Africa. During his academic career, he occupied a number of administration positions. He was the Head of mechanical engineering Department in Curtin University (Malaysia). He was also the Head of Mechatronics Engineering and Director of School of Engineering in Nelson Mandela University. He published extensively in the areas of machining technologies and manufacturing of optical elements using ultra-high precision diamond turning technology.

Prof Abou-El-Hossein is registered researcher in the National Research Foundation of South Africa (NRF SA). He is also a registered professional engineer in the Engineering Council of South Africa (ECSA).