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Topic:

"Ultra-High Precision Manufacturing"

Ultra-High Precision Manufacturing

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Abstract

One of the engineering areas focusing on the research and development of high-value components and manufacturing technologies is precision engineering. Precision engineering represents a variety of engineering and science disciplines ranging from areas such as mechanical, electronics and industrial engineering to chemistry, physics, optics and materials science. This paper aims at familiarising the reader with the recent advances in ultra-high precision manufacturing technologies and their applications for the production of various critical components employed in different sectors of the industry. In this paper, the principles of ultra-high precision manufacturing will be discussed followed by examples of its use in various industrial applications. The status of ultra-high precision manufacturing in terms of current research issues and future trends will be discussed. In addition, research activities and projects in the area of precision manufacturing that are currently conducted at the NMMU will be also highlighted. Finally, the author looks forward to presenting herewith comprehensive information that could be useful to the reader and easy to understand by the bigger NMMU's community.

Keywords: Precision engineering, ultra-high precision manufacturing, diamond machining

1. Introduction

The successful economy of a developing country is always associated with the level of its manufacturing sector. South Africa has a well-established manufacturing industry if compared to other economies on the African continent. However, South Africa still needs to look at different ways to enhance its ranking in terms of manufacturing among other industrialised nations outside the African continent.

By focusing on the fabrication of special processing technologies and high-value industrial products, used by strategic and critical manufacturers, we will be able to increase the country's competitiveness in the manufacturing sector. Such an approach will result in the enhancement of especially skilled human capital capable of dealing with high-value technologies used in different manufacturing businesses such as semiconductor, medical, electronics, defence, automotive and aerospace industries.

One of the engineering areas focusing on the research and development of high-value components and manufacturing technologies is precision engineering. Precision engineering represents a variety of engineering and science disciplines ranging from areas such as mechanical, electronics and industrial engineering to chemistry, physics, optics and materials science. Precision engineering provides the necessary technologies required to fabricate various strategic components of critical performance. Using the principles of precision engineering, we will be able to support industries dealing with production of medical devices and implants, life science equipment, semiconductors, photonics, laser machines, optical-mechanical systems and high precision motion control systems. This also includes highly accurate components used by traditional industries such as the automotive, aerospace and military industries.

2. History of Precision Manufacturing

The ultra-high precision manufacturing (UHPM) of critical components has progressed through a number of extended historical stages. However, UHPM has progressed dramatically over the past few years because of the rapid development in computer and information technology and communications engineering.

With the development of UHPM, a great impact has imposed on the advancement of other engineering and science disciplines; and on the development of new materials processing technologies. This is because of the ability of UHPM technologies to produce critical components such as optical elements, precise sensors and other extremely-accurate functioning devices that form part of those processing technologies. Therefore, UHPM is regarded as an important discipline that stimulate the continuous development nanotechnology (De Chiffre et al., 2003).

Professor Norio Taniguchi (1912-1999), a scientist formerly from Tokyo Science University was first to introduce the term nanotechnology. He also defined ultra-high precision manufacturing are those technologies by which the highest possible dimensional accuracy was, or had been achieved (Taniguchi, 1983). Figure 1, adopted from Taniguchi (1983) and modified by McKoewn (1987), shows the progress stages that precision manufacturing technologies have developed through. With the advances in computer control and information technology, combined with the development of property controlled materials, the accuracy of UHPM has progressed from 1 micrometre which was more than 60 years ago and entered into nanometric region just recently.

Because of the ability to combine different forms of energy and integrate different processing technologies on machine-tools, the accuracy level of UHPM technologies will get better down to sub-nanometric levels. For example, the combination of the energy received from ion beam together with mechanical energy results in surface finishes with less than one nanometre (Mahmud et al., 2012).

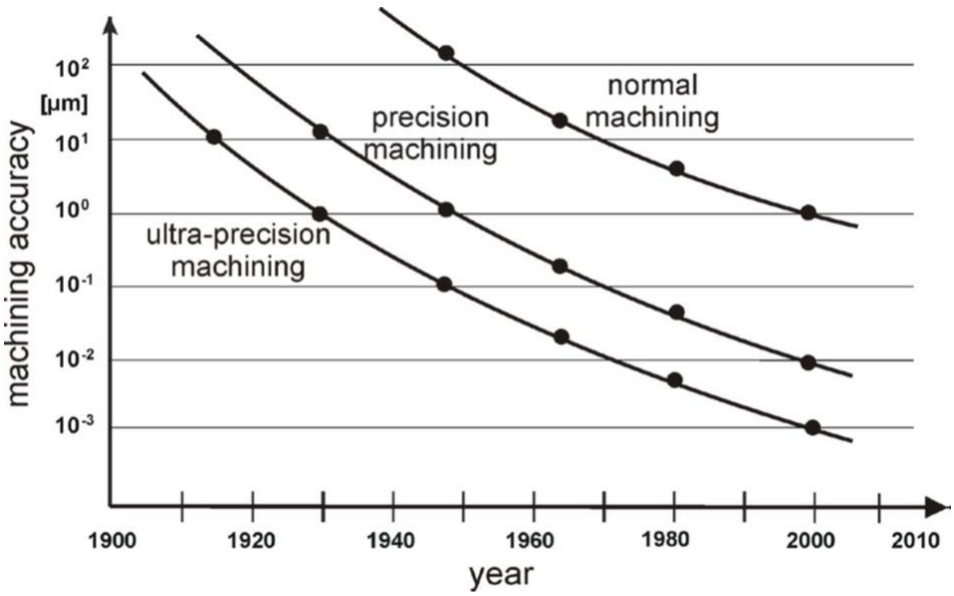

Figure 1: The prediction of accuracy of machining technologies as predicted by Norio Taniguchi in 1983 (Taniguchi, 1983) and modified by McKoewn (1987)

3. Principles of Ultra-High Precision Manufacturing

Manufacturing with ultra-high precision capability can be achieved using different forms of energy ranging from mechanical to thermal. However, in this paper, discussion of UHPM will be limited to those processing technologies that are solely based on the use of mechanical energy to shape components of various levels of complexity. In mechanical-based UHPM processes, components are shaped from stock materials (workpieces) by the chip removal principle (Figure 2), which is based using a sharp cutting tool having particular cutting geometries and specified cutting edge. The tool is driven at a certain speed into the workpiece and penetrates into its surface at a certain depth. This action will cause the generation of a new surface (machined surface) that is generally smoother than the original surface of the workpiece. In addition to the properties of the machined materials, the surface finish of the new surface also depends largely on the tool geometry and machining parameters employed.

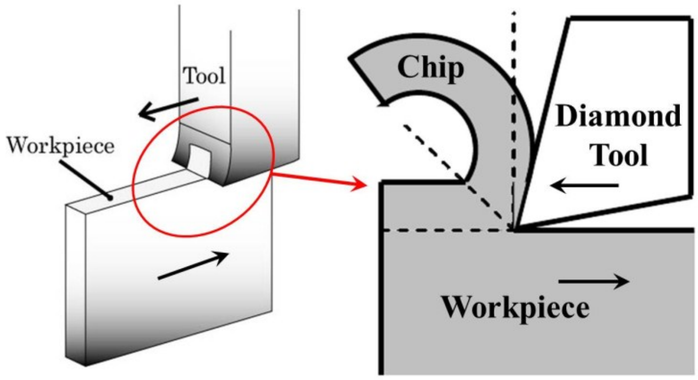

Figure 2: Principle of mechanical precision manufacturing by chip removal

Although, the process of mechanical removal of chips results in a relatively large amount of material wastes, the mechanical version of UHPM has been increasingly seen in a numerous number of applications. This is due to the fact that mechanical manufacturing as a deterministic processing technology is still capable of addressing the high requirements of advanced and high-accuracy components at relatively low cost of machines using absolutely high resolutions of control. On the other hand, in other machining technologies that use other forms of energy (such as ion and laser beams technologies), high accuracy of machined surfaces could be achieved at increased costs resulting from high energy consumption rates.

Contemporary processes that can be used to realise UHPM can be categorised into two groups:

- Ultra-high precision diamond machining
- Ultra-high precision grinding

3.1. Ultra-high precision diamond machining

In ultra-high precision diamond machining, a single-edge cutting tool made from single-crystal natural diamond (Figure 3) is used to generate optical profiles with surface roughness of only a few nanometres and form accuracies in the sub-micrometre range (Brinksmeier et al., 2012). Compared to other UHPM processes that are based on chemical or thermal energies, the use of diamond tools offers a higher degree of freedom and therefore the ability to generate surfaces of special structures and special profiles such as freeform optics (Davies et al., 2003).

A disadvantage of UHPM using diamond tools is the inability of the technology to machine components made from hard and difficult to cut materials such as glass or ceramics. Generally, diamond tools can be employed to processes ductile non-ferrous materials such optical aluminium and copper alloys. In some cases, diamond machining can be successfully used to shape relatively hard and brittle materials such as silicon and germanium crystals if the cutting parameters are selected carefully to provide a ductile mode of cutting rather than brittle regime (Jasinevicius et al., 2013, Pramanik and Basak, 2013).

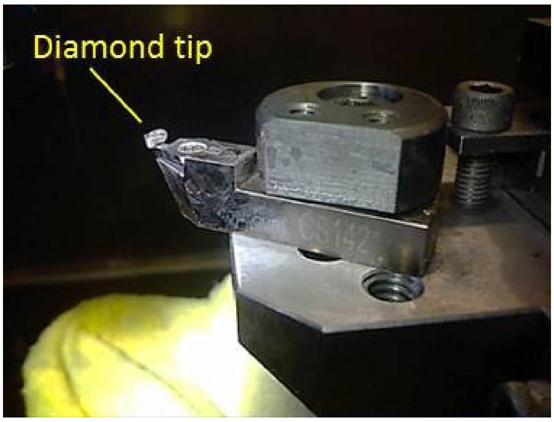

Figure 3: Single-crystal natural diamond tool

3.2. Ultra-high precision grinding

In ultra-high precision grinding, a grinding wheel (Figure 4) that consists of a large amount of strongly bonded abrasive grains is used to achieve high form accuracy (0.1 micromere) and excellent surface finishes (within 10 nanometres) on optical components.

Unlike diamond machining, precision grinding can be used to process ultra-hard and brittle materials such as glass, sapphire and silicon carbide. However, the process should be closely controlled and monitored to avoid surface rupturing and the development of micro cracks which deteriorate the integrity of the machined surface. Therefore, it is always suggested to conduct fine grinding of brittle surfaces using extremely small cutting parameters. This will help realise the mechanism of ductile mode cutting and avoid the pulling action of the material grains.

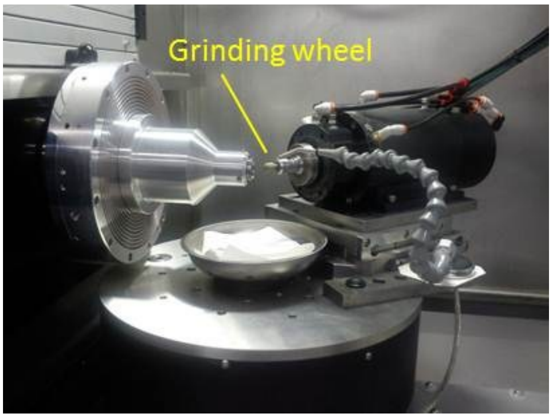

Figure 4: Ultra-high precision grinding process

4. Examples of Applications of Ultra-High Precision Manufacturing

Although UHPM is still a hot research field that is being addressed by many research laboratories worldwide, it has been widely employed in the production of critical components for various industrial sectors. UHPM has found a wide use in the automotive, aerospace and astronomical industries. In addition, UHPM is strongly presents in applications related to health care and bio-engineering. However, it is hoped that the continuous research development in UHPM will help increase its production rates and further simplify process control strategy which is a challenge task sometimes.

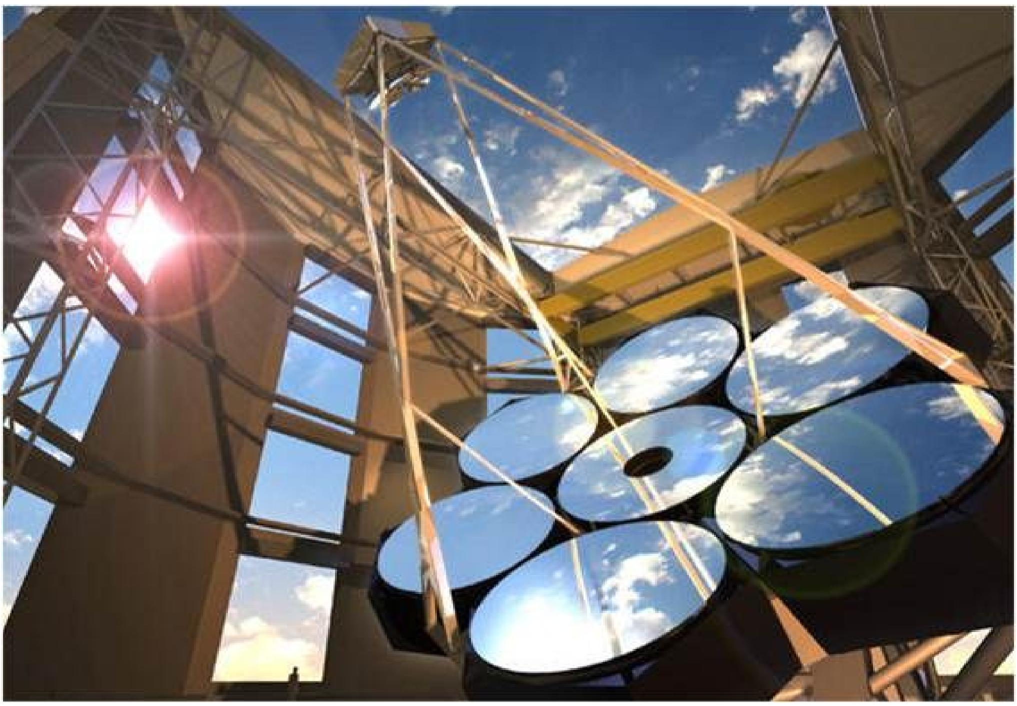

Figure 5: The Giant Magellan Telescope (GMT) *(Courtesy: GMTO)*

4.1. UHPM in aerospace and astronomical applications

The use of UHPM in the aerospace industry has been intensive for the last decade. Aerospace components ranging from micro astronomical sensors to giant telescope mirrors has been fabricated using precision diamond machining and grinding. An example of the successful utilisation of high precision grinding in astronomy is the development of the largest telescope on Earth (Figure 5), the Giant Magellan Telescope (GMT) (GMTO, 2012), which is being built by Steward Laboratory and expected to be in use in 2019. In this laboratory, high accuracy off-axis aspheric shape surfaces are produced with only 15-25 nanometres surface finish on 20-tonne mirrors having a diameter equal to 8.5 m. For the realisation of the grinding process on such large mirrors, high precision grinding heads (Figure 6) attached to huge a machine have been developed (Shore et al., 2010).

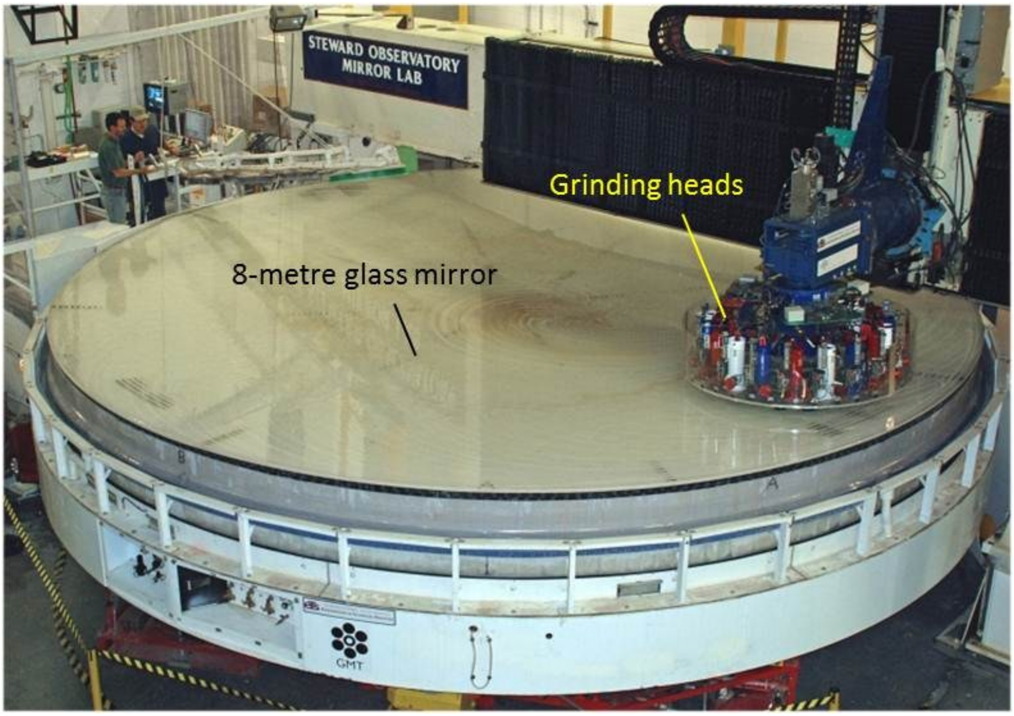

Figure 6: The Giant Magellan Telescope (GMT) (Courtesy: GMTO)

4.2. UHPM for automotive applications

In automotive industry, the manufacturing of car lights from polymer optics is a major activity and is still one of the development areas. Production lines of car lights is always faced by new challenges in terms of tooling and processing machines because of the continuous changes in light designs which nowadays contain more freeform features (Mayer, 2007). The challenge imposed by the production of freeform optics can be resolved using advanced UHPM. Freeform surfaces on mould inserts (Figure 7) used in plastic injection of polymer car lights can be easily produced using multi-axis ultra-high precision machine-tools. Excellent optical profiles with extremely high accuracy can be obtained using diamond tools powered by those machine-tools.

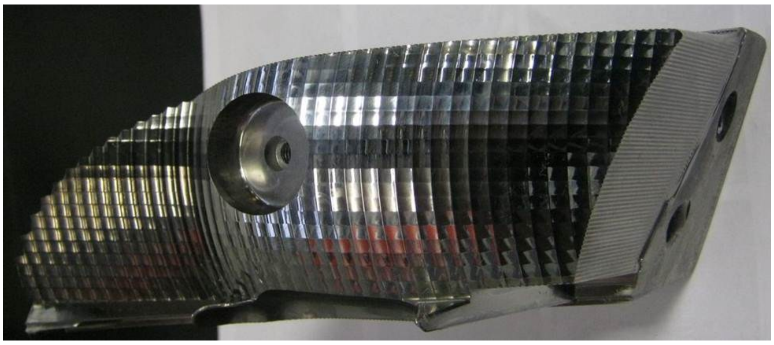

Figure 7: Freeform mould insert for injection of polymer car light (Courtesy: Piazza Rosa)

Figure 8: The first commercial solar plant *(Courtesy: Torresol Energy)*

4.3. UHPM in solar energy harvesting applications

Parabolic mirrors shaped by UHPM from materials such as aluminium, acrylic and glass can be now economically used as solar concentrators to harvest solar power. UHPM can be used directly to shape optical profiles on the surfaces aluminium mirrors. However, for high volume production, UHPM is utilised to first create mould inserts which are used to in plastic injection of acrylic and moulding of glass mirrors

(Chen and Yi, 2011). Figure 8 shows the first commercial-scale solar plant that was built in Spain and commissioned in 2011. The plant employs hundreds of parabolic mirrors for solar power concentration to produce 20 MW.

5. Status of research in Ultra-High Precision Manufacturing

UHPM based on diamond turning and precision grinding has proved to be a feasible fabrication technology of strategic components in terms of cost-efficiency and product quality. The recentness of the research articles listed herein indicates the richness and dynamic nature of the field of UHPM. The research efforts in this field are continuously increasing as a result of the continuous developments of new engineering materials which always impose new challenges when fabricated into high-value components of strategic nature. Working on high-precision machines involves activities that incorporate the need of using knowledge aspects from different disciplines. The increased flexibility of state-of-the-art machine-tools and metrological systems used in UHPM help realise solutions adopted from fields such as physical science; and materials, mechanical, manufacturing, mechatronics, and chemical engineering.

For the last decade, the advances and development of machine-tool components such as vibration-isolated and high-speed air-bearing spindles, hydrostatic oil slideways, high-speed and high-resolution computer-numerical controllers, and on-machine measuring and error-compensation systems, has resulted in strengthening the presence of UHPM in the industry as a relatively cost-efficient fabrication technology for strategic parts. Although some of the machining challenges, in terms of precision and quality, have been extensively addressed in the literature, ultra-precision machining will continue to grow as a result of the development of new engineering materials featured by special properties that make these materials challenging when they are precisely machined.

An extensive study of the available literature reveals that the number of research works focusing on UHPM has increased recently. This is due to the increasing demand for strategic components with tighter profile accuracy and special surface finish. Such products are usually made from advanced materials having critical properties that will negatively affect the performance of UHP machining. It is noticed that the publications related to UHPM could be categorised under one of three research scopes: (a) increasing the efficiency of the UHPM by optimisation, modelling or process monitoring with a focus on tool wear and machined surface roughness; (b) observation of machined material characteristics and quality; and (c) development and modification of UHPM systems including the incorporation of other fabrication methods (hybrid machining) and development of new tools.

Researchers following the first scope have aimed at finding relationships between the UHPM processing variables and output parameters in order to improve the process efficiency and increase its productivity. Examples of that are the studies conducted in (Roy, 2006, Basheer et al., 2008). The authors performed modelling of machined surfaces of metal-matrix composites in precision machining to understand the effect of material particle size, machining feed rate, depth of cut, and tool nose geometry on machined surface roughness.

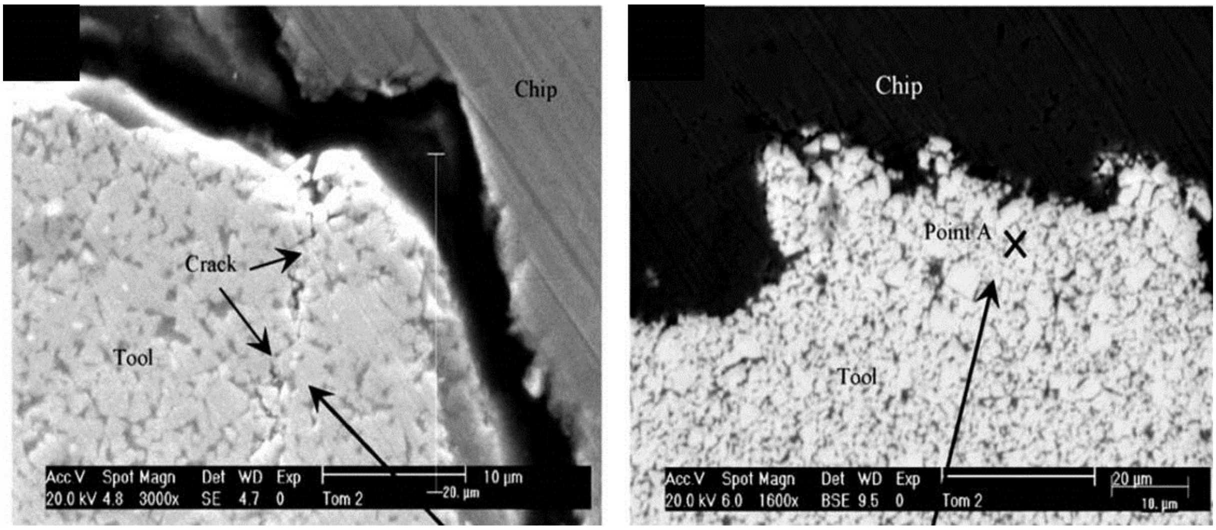

Figure 9: Tool edge wear caused by micro-cracks (Abou-El-Hossein and Yahya, 2005)

In terms of tool wear, Yingfei et al. (2010) found that tool wear mechanisms such as chipping and cleavage actions were dominant in the diamond tools used in ultra-precision turning of a silicon aluminium matrix composite. An example of tool wear resulting from micro crack of the tool edge is shown in Figure 9 (Abou-El-Hossein and Yahya, 2005). In another study by Abou-El-Hossein et al. (2013), it was reported that abrasive wear was a dominant mechanism when diamond machining materials with ultra-fine grains (Figure 10). Mamalis and Lavrynenko (2007) also reported on the tool wear of diamond turning tools when machining polymeric materials. They found that adhesion wear was quite noticeable. Ultra-precision grinding was also investigated along with ultra-precision turning by other researchers to find out the performance of UHPM of some special ceramic (Arai et al., 2009, Namba and Takahashi, 2010).

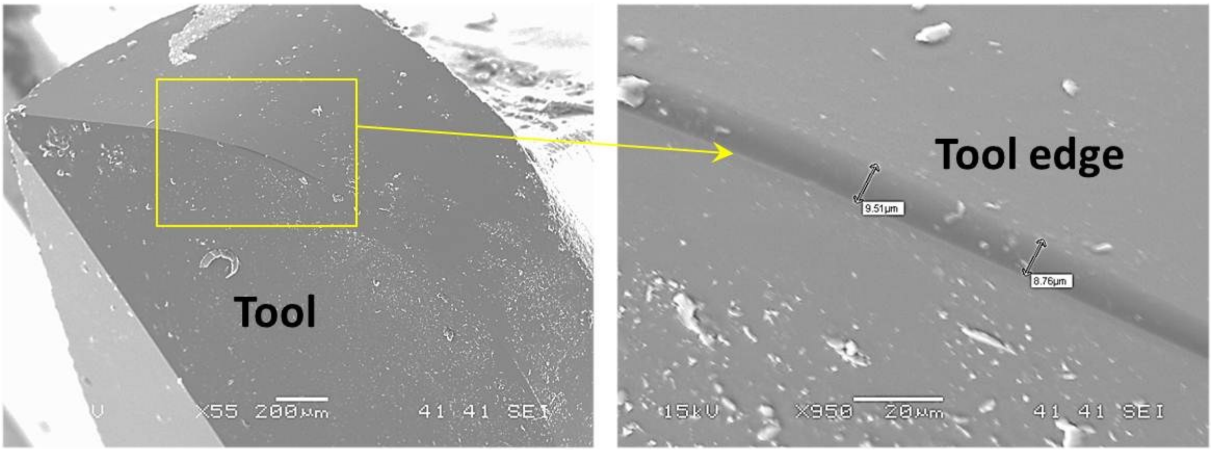

Figure 10: Example of abrasive wear on diamond tool (Abou-El-Hossein and Yahya, 2005)

Other properties of the machined surfaces, different from surface roughness, are vital if the component is planned to be used in critical applications such as electro-optical systems. Therefore, some researchers followed the second focus in their works by looking at the variation in the microstructure of sub-surface layers as a result of ultra-high precision turning and grinding. To et al. (To et al., 2005, To et al., 2006) investigated the microstructure change and phase decomposition of a Zn–Al after being ultra-precision machined. They noticed that micro-plastic deformation occurred at the machined surface. In addition, they indicated that the UHP machining process induced some stress at the surface. This resulted in phase decomposition acceleration. Jasinevicius (2006) also investigated the material microstructure variation of semiconductor crystal as a result of high-precision diamond turning. Zhao et al. (2009) published a study where the effect of the ultra-precision diamond machining on potassium dihydrogen phosphate (KDP) crystal was investigated. They found that the diamond tool geometry played a significant role in affecting the anisotropic character of the KDP crystal.

The defects induced in surfaces as a result of machining and the relatively low process efficiency as a result of tool wear have fostered researchers to follow the third scope by considering developing complimenting and hybrid technologies for

UHP turning and grinding based on existing UHPM centre platforms. This has included the development of advance diamond turning (Zong et al., 2010) and new grinding tools (Gäbler and Pleger, 2010); ultra-precision spindles (Lu et al., 2009); special mechanisms to improve productivity by using fast tool servo systems (Rakuff and Cuttino, 2009); modified set-ups and techniques to measure and compensate for UHPM errors (Gao et al., 2010), special relative movement of diamond tool with respect to the workpiece (Cheung et al., 2007); application of phosphorous suppression mechanisms to reduce carbon content and save diamond tools from erosion by graphitising (Yan et al., 2010); and hybrid ultra-precision systems (Furushiro et al., 2010).

6. Research in UHPM at NMMU

A number of research projects in the area of UHPM have been embarked on in the NMMU. NMMU has obtained a machining centre for UHPM with single-point diamond tools and high-speed grinding (Figure 1). This facility, which is unique of its kind in Africa, is capable of producing components with form accuracy in the submicron region with surface nano-finish (less than 1 nm). The facility is also equipped with a powerful software for 3D lens design which can be used to design lenses of complicated optical surfaces and freeforms. In addition, by the end of 2013, NMMU will commission one of the most advanced 3D profilers worldwide. This instrument will be able to characterise profiles with accuracy down to 0.05 micrometre and surface roughness with resolutions down to 0.2 nanometre. The NMMU has been involved in UHPM projects. Examples of these projects are mentioned below.

6.1. Molecular dynamics modelling of nano-scale machining of optical materials

In this project, the brittle-ductile transition in nanometric machining of mono-crystalline optical materials with precise tool specifications and parameter choices is accessed. Due to its brittle nature, monocrystalline materials such as silicon and germanium requires a ductile-mode machining for improved surface quality. Molecular dynamics (MD) methods are thus applied to investigate the atomistic reaction at the tool-workpiece surface to clearly expose the ductile transition response of this nanometric process. However, the need for experimental validations to determine the accuracy of these simulation models is essential. This research is particularly concerned with the application of the molecular dynamics simulation approach to the atomistic visualization of the plastic material flow at the tool/workpiece interface during orthogonal cutting. Simulated MD acting force and temperature outputs are evaluated to access the accuracy of the model. Figure 11 (Olufayo and Abou-El-Hossein, 2013) shows some simulation results of the process of cutting a monocrystalline silicon workpiece with a single point diamond tool

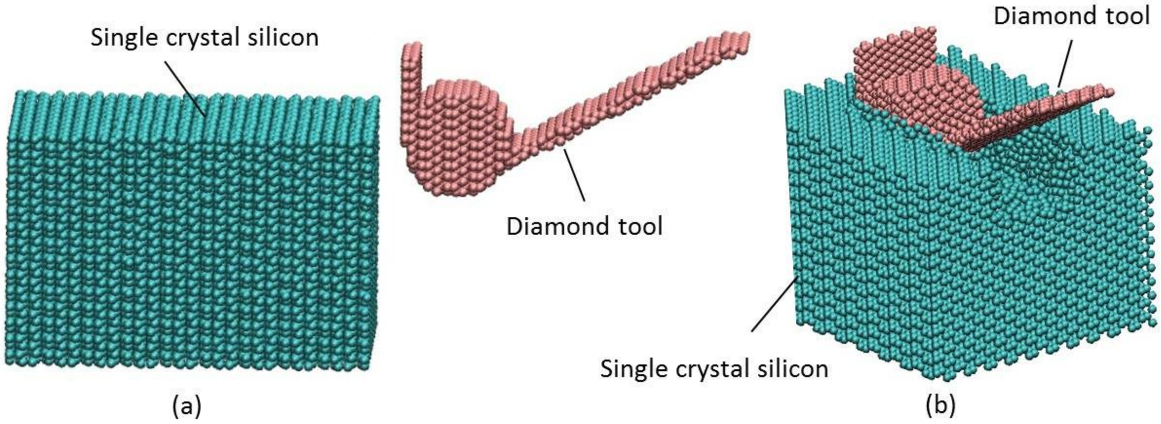

Figure 11: Example of MD simulation: a) before cutting; b) after tool penetration (Olufayo and Abou-El-Hossein, 2013)

6.2. UHPM of modified optical aluminium used for optical mould inserts

The purpose of this research is to investigate the performance of diamond turning in UHPM in terms of tool wear when machining RSA905 rapidly solidified aluminium. RSA 905 aluminium enjoys better mechanical properties compared to other traditional aluminium alloys such as Al6061. Therefore, RSA905 could be a promising candidate for making optical mould inserts. Because of the rapid solidification process, RSA905 possesses a highly refined microstructure which results in the increased ultimate strength of the material compared to other optical aluminium grades. The ultimate tensile strength of RSA 905 is 600 MPa which is much higher than that of other aluminium grades (Al6061 has 350-MPa tensile strength). In addition, the hardness of RSA 905 is HB 180 which is also high in comparison with that of similar aluminium.

The initial observations from this preliminary study indicate the clear independence of tool wear on the feed rate of the diamond tool. Figure 12 shows the diamond tool edge at the three feed rate conditions: a) low, b) middle and c) high. It was found that the increase in the feed rate resulted in a dramatic increase in the wear area observed on the tool flank face. This could be explained by the relatively high tensile strength of the material in addition to the presence of hard iron particles in its microstructure. The wear pattern was different for different feed rates. For high feed values, the wear mechanism was probably according to abrasive action while at the middle feed values the wear was characterised mainly by chipping mechanism. At the smallest feed rate, the wear was not observed except for some scratches on the flank face.

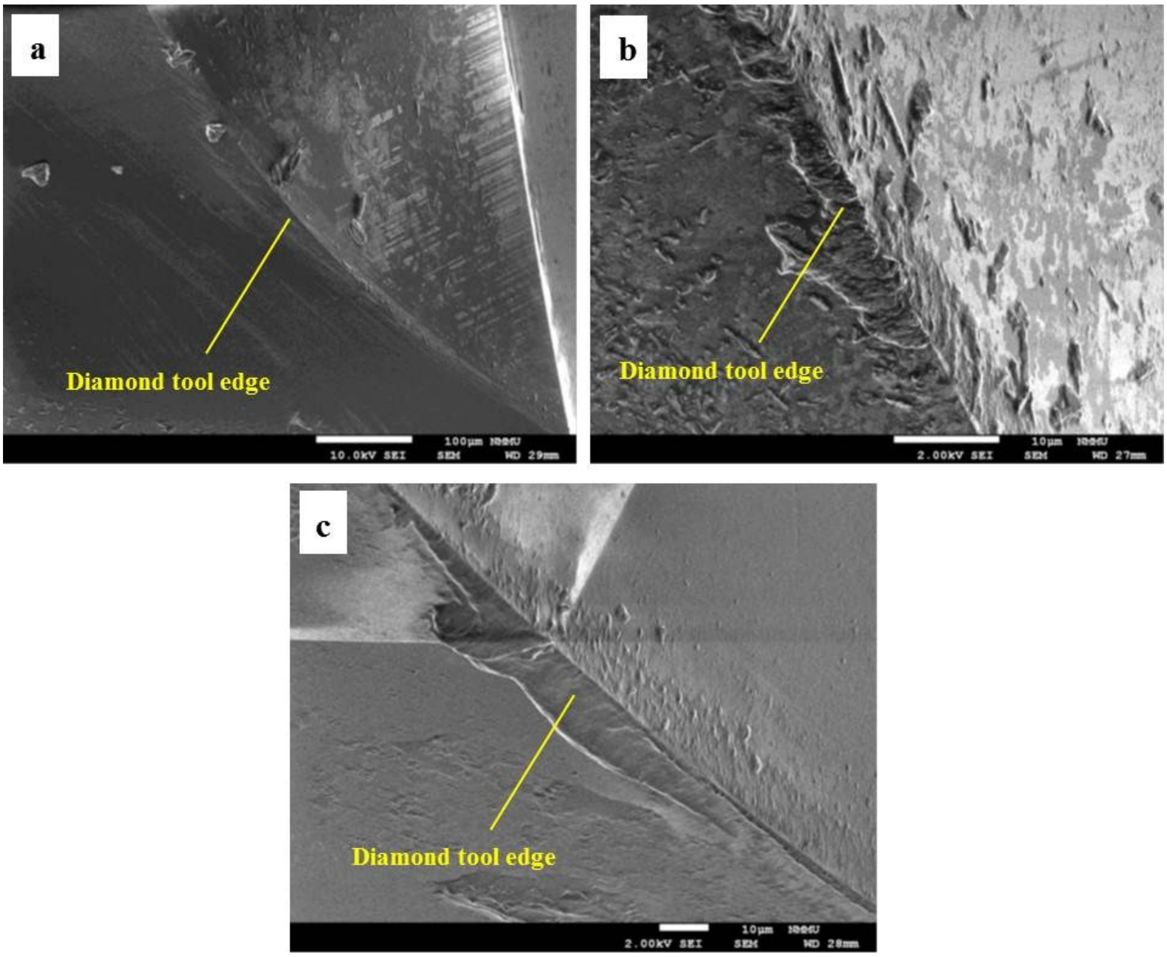

Figure 12: Diamond tool edge condition after 3.5-km cutting distance at three feed rates: a) 5 mm/min, b) 15 mm/min and c) 25 mm/min

In terms of surface finish, Figure 13 shows the surface roughness values for the three feed rates measured using atomic force microcopy. A surface roughness of Ra equal to 3.7 nm was achieved for the lowest feed rate, and 2.7 nm for the high feed. However, because of the tool wear chipping mechanism that resulted in an irregular tool edge, the surface quality deteriorated for the middle feed rate (15 mm/min) and only 16 nm was obtained.

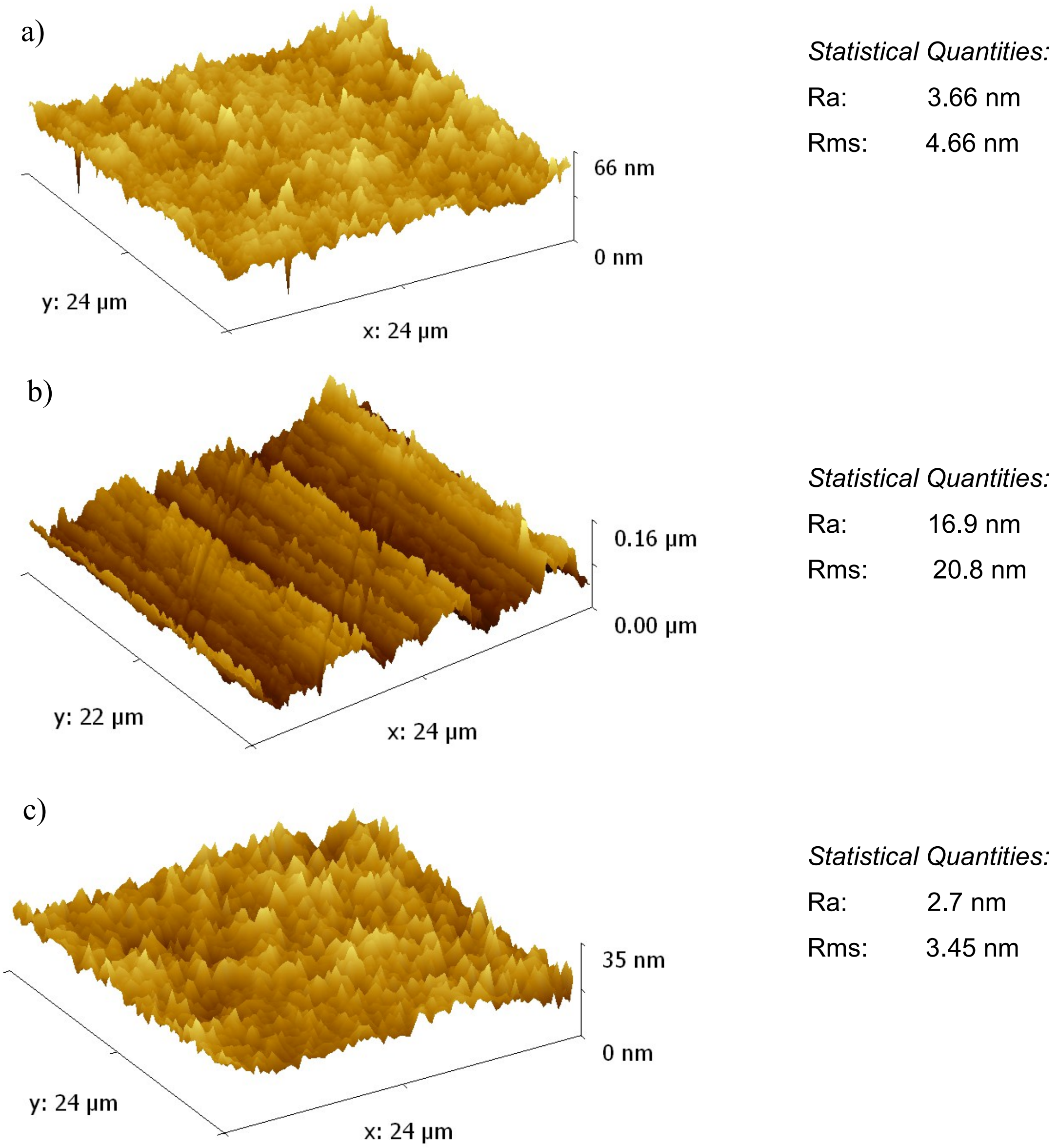

Figure 13: Surface roughness values after 3.5-km cutting distance at three feed rates: a) 5 mm/min, b) 15 mm/min and c) 25 mm/min

6.3. UHPM of contact lenses

Contact lens (CL) manufacture requires a high deal of accuracy and surface integrity. Amidst numerous optical manufacturing techniques, single-point diamond turning is widely employed in the making of CLs due to its capability of producing optical surfaces of complex shapes and nanometric accuracy. This manufacturing technique is however affected by chemical and/or tribo-electric tool wear, which are known as dominant wear mechanisms found in precision turning of polymeric materials. Therefore, an adequate analysis of this manufacturing process and a cross-examination of factors affecting surface finish could aid in ensuring lenses optical quality. This research work is aimed at examining the surface finishes resulting from applying various combinations of cutting parameters during ultra-high precision machining of CLs. Figure 14 shows the process of UHPM of a contact lens. Using a well selected machining parameters a surface finish of 12 nanometres (Figure 15) was achieved in this study.

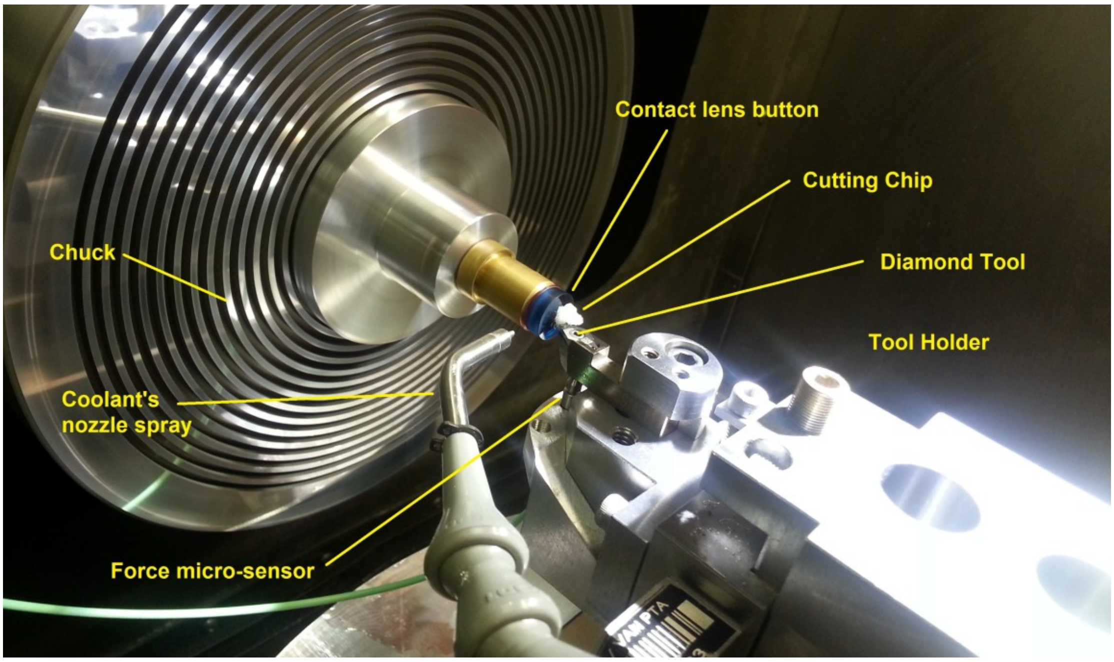

Figure 14: Setup of UHPM of contact lens

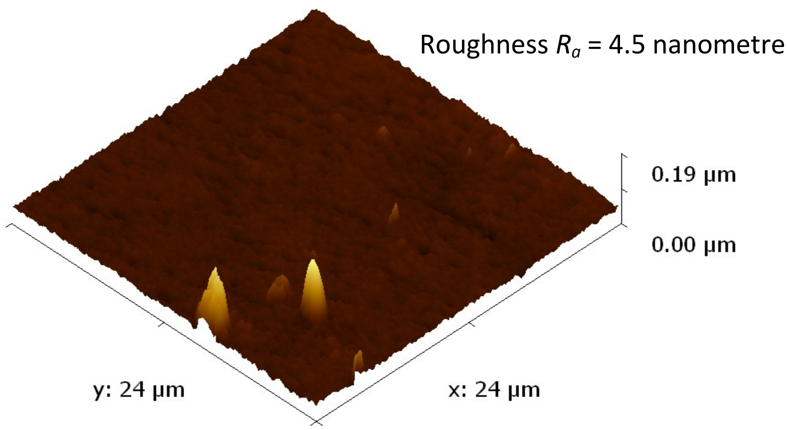

Figure 15: Surface finish of contact lens

7. Conclusion remarks

The following conclusion remarks can be withdrawn:

- UHPM has effectively contributed to the development of other engineering and science disciplines. This is because of the ability of UHPM to fabricate advanced components such as optical sensors that are used by other advanced technologies that other disciplines are based on.
- UHPM has undergone extensive developments in response to the continuous development in engineering materials. The achievements in computer and control technologies and the ability to integrate a number of processing operations in one setup on a machine tool has resulted in a technology capable of achieving nanometric level of product accuracy.
- Although UHPM has been a dynamic technology that has been effectively utilised in various critical industries, it is still going through continuous research efforts. Researchers will continue to address a number of issues in UHPM for at least another decade as there is a great deal of aspects in UHPM that have not been yet fully disclosed.

References

ABOU-EL-HOSSEIN, K., OLUFAYO, O. & MKOKO, Z. 2013. Diamond Tool Wear when Ultra-High Precision Machining of Rapidly Solidified Aluminium RSA 905. *Wear*.

ABOU-EL-HOSSEIN, K. & YAHYA, Z. 2005. High-speed end-milling of AISI 304 stainless steels using new geometrically developed carbide inserts. *Journal of Materials Processing Technology,* 162**,** 596-602.

ARAI, S., WILSON, S. A., CORBETT, J. & WHATMORE, R. W. 2009. Ultra-precision grinding of PZT ceramics—Surface integrity control and tooling design. *International Journal of Machine Tools and Manufacture,* 49**,** 998-1007.

BASHEER, A. C., DABADE, U. A., JOSHI, S. S., BHANUPRASAD, V. & GADRE, V. 2008. Modeling of surface roughness in precision machining of metal matrix composites using ANN. *Journal of Materials Processing Technology,* 197**,** 439-444.

BRINKSMEIER, E., GLÄBE, R. & SCHÖNEMANN, L. 2012. Review on diamond-machining processes for the generation of functional surface structures. *CIRP Journal of Manufacturing Science and Technology,* 5**,** 1-7.

CHEN, Y. & YI, A. Y. 2011. Design and fabrication of freeform glass concentrating mirrors using a high volume thermal slumping process. *Solar Energy Materials and Solar Cells,* 95**,** 1654-1664.

CHEUNG, C., LI, H., LEE, W., TO, S. & KONG, L. 2007. An integrated form characterization method for measuring ultra-precision freeform surfaces. *International Journal of Machine Tools and Manufacture,* 47**,** 81-91.

DAVIES, M. A., EVANS, C. J., VOHRA, R. R., BERGNER, B. C. & PATTERSON, S. R. Application of precision diamond machining to the manufacture of microphotonics components. Optical Science and Technology, SPIE's 48th Annual Meeting, 2003. International Society for Optics and Photonics, 94-108.

DE CHIFFRE, L., KUNZMANN, H., PEGGS, G. & LUCCA, D. 2003. Surfaces in precision engineering, microengineering and nanotechnology. *CIRP Annals-Manufacturing Technology,* 52**,** 561-577.

FURUSHIRO, N., TANAKA, H., HIGUCHI, M., YAMAGUCHI, T. & SHIMADA, S. 2010. Suppression mechanism of tool wear by phosphorous addition in diamond turning of electroless nickel deposits. *CIRP Annals-Manufacturing Technology,* 59**,** 105-108.

GÄBLER, J. & PLEGER, S. 2010. Precision and micro CVD diamond-coated grinding tools. *International Journal of Machine Tools and Manufacture,* 50**,** 420-424.

GAO, W., LEE, J. C., ARAI, Y., NOH, Y. J., HWANG, J. H. & PARK, C. H. 2010. Measurement of slide error of an ultra-precision diamond turning machine by using a rotating cylinder workpiece. *International Journal of Machine Tools and Manufacture,* 50**,** 404-410.

GMTO. 2012. *Giant Magellan Telescope* [Online]. Available: www.gmto.org [Accessed 20 August 2012].

JASINEVICIUS, R., DUDUCH, J., CIRINO, G. & PIZANI, P. 2013. Diamond turning of small Fresnel lens array in single crystal InSb. *Journal of Micromechanics and Microengineering,* 23**,** 055025.

JASINEVICIUS, R. G. 2006. Influence of cutting conditions scaling in the machining of semiconductors crystals with single point diamond tool. *Journal of Materials Processing Technology,* 179**,** 111-116.

LU, X.-D., PAONE, M., USMAN, I., MOYLS, B., SMEDS, K., ROTHERHOFER, G. & SLOCUM, A. 2009. Rotary-axial spindles for ultra-precision machining. *CIRP Annals-Manufacturing Technology,* 58**,** 323-326.

MAHMUD, S., FUKABORI, T., PAHLOVY, S. & MIYAMOTO, I. 2012. Low energy ion beam smoothening of artificially synthesized single crystal diamond chips with initial surface roughness of 0.08–0.4 nm rms. *Diamond and Related Materials,* 24**,** 116-120.

MAMALIS, A. & LAVRYNENKO, S. 2007. On the precision single-point diamond machining of polymeric materials. *Journal of Materials Processing Technology,* 181**,** 203-205.

MAYER, R. 2007. Precision injection molding. *Optik & Photonik,* 2**,** 46-51.

MCKEOWN, P. 1987. The role of precision engineering in manufacturing of the future. *CIRP Annals-Manufacturing Technology,* 36**,** 495-501.

NAMBA, Y. & TAKAHASHI, H. 2010. Ultra-precision surface grinding of PMN-PT relaxor-based ferroelectric single crystals. *CIRP Annals-Manufacturing Technology,* 59**,** 589-592.

OLUFAYO, O. & ABOU-EL-HOSSEIN, K. 2013. Molecular Dynamics Modeling of Nanoscale Machining of Silicon. *Procedia CIRP,* 8**,** 503-508.

PRAMANIK, A. & BASAK, A. 2013. Ductile mode turning of brittle materials and its practical aspects. *Advanced Materials Research,* 651**,** 350-354.

RAKUFF, S. & CUTTINO, J. F. 2009. Design and testing of a long-range, precision fast tool servo system for diamond turning. *Precision Engineering,* 33**,** 18-25.

ROY, S. S. 2006. Design of genetic-fuzzy expert system for predicting surface finish in ultra-precision diamond turning of metal matrix composite. *Journal of Materials Processing Technology,* 173**,** 337-344.

SHORE, P., CUNNINGHAM, C., DEBRA, D., EVANS, C., HOUGH, J., GILMOZZI, R., KUNZMANN, H., MORANTZ, P. & TONNELLIER, X. 2010. Precision engineering for astronomy and gravity science. *CIRP Annals-Manufacturing Technology,* 59**,** 694-716.

TANIGUCHI, N. 1983. Current status in, and future trends of, ultraprecision machining and ultrafine materials processing. *CIRP Annals-Manufacturing Technology,* 32**,** 573-582.

TO, S., ZHU, Y. & LEE, W. 2005. Ultra-precision machining induced micro-plastic deformation in Zn–Al based alloy. *Journal of Materials Processing Technology,* 167**,** 536-541.

TO, S., ZHU, Y. & LEE, W. 2006. Ultra-precision machining induced phase decomposition at surface of Zn–Al based alloy. *Applied Surface Science,* 253**,** 2165-2170.

YAN, J., ZHANG, Z. & KURIYAGAWA, T. 2010. Tool wear control in diamond turning of high-strength mold materials by means of tool swinging. *CIRP Annals-Manufacturing Technology,* 59**,** 109-112.

YINGFEI, G., JIUHUA, X. & HUI, Y. 2010. Diamond tools wear and their applicability when ultra-precision turning of SiC< sub> p</sub>/2009Al matrix composite. *Wear,* 269**,** 699-708.

ZHAO, Q., WANG, Y., YU, G., DONG, S. & ZHANG, X. 2009. Investigation of anisotropic mechanisms in ultra-precision diamond machining of KDP crystal. *Journal of Materials Processing Technology,* 209**,** 4169-4177.

ZONG, W., LI, Z., SUN, T., CHENG, K., LI, D. & DONG, S. 2010. The basic issues in design and fabrication of diamond-cutting tools for ultra-precision and nanometric machining. *International Journal of Machine Tools and Manufacture,* 50**,** 411-419.