ULTRASONIC MACHINING, LAPPING AND POLISHING OF NEODYMIUM DOPED YTTRIUM ALUMINUM GARNET LASER CRYSTAL ROD

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A thesis submitted in fulfillment of the
requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

OCTOBER 2009

Specially dedicated to my beloved grandfather, parents, brothers, family and friends...

ACKNOWLEDGEMENT

First and foremost, I would like to thank especially supervisor PROF. DR. ESAH BINTI HAMZAH and co-supervisor ASSOC. PROF. DR. IZMAN BIN SUDIN for their continuous supervision, guidance, encouragement and advices during my graduate studies at Universiti Teknologi Malaysia.

I would also like to convey my deepest gratitude to Mr. Sazali Ngadiman, Mr. Azizi and other staffs of production laboratory; Mr. Ayob Abu and other staffs of metallurgy laboratory, Mr. Wan Hairul, Mr. Abdul Rahman, and Mr. Rashdan of AOMRG laboratory; and Mr Khalid at metrology laboratory Engineering for their effort in assisting me to solve my problems and made my project a successful one.

Special and infinite thanks goes to the most important people in my life; my parents, for their love, prayers, sacrifice and support. Thanks to all my friends with whom I had the opportunity to learn, and share a good time during my study here.

Finally, special dedication for my grandfather, he’s left too soon, gone yet not forgotten. His memory lies within us, forever in everyone’s heart. May he rest in peace.

ABSTRACT

Fabrication of perfect laser crystal rod is a very challenging work where high shape accuracy and flawless surface are expected. Besides, most improvements in the processes or understanding of the physical process involved in fabrication of laser crystal rod are closely guarded as proprietary information, and specific details can be hardly found in technical journals and other literatures. The main purposes of the study are to investigate the potential of rotary ultrasonic machining (RUM) process to core drill Neodymium Doped Yttrium Aluminum Garnet (Nd:YAG) laser crystal material, and to study the effect of lapping and polishing parameters on the surface finish of the machined end faces of Nd:YAG laser rods. The effect of RUM machining parameters (spindle speed and feedrate) on surface integrity (surface roughness and opaqueness) and defects (ring marks, edge chipping size and chipping thickness) are studied. The feasible parameters to obtain the best surface roughness, opaqueness, straightness and diameter for Nd:YAG laser rod is 3000 rpm spindle speed and 5.4 mm/min, which is at low spindle speed and high feed rate. Nd:YAG crystal reaches the saturation point at fine surface finish of 0.124 micron at rotational speed of 60 rpm at 11 minutes of lapping time. Whilst for polishing process, Nd:YAG laser crystal reaches the saturation point with mirror-like and flawless surface finish of 5 nm at 23 minutes of polishing time. It is concluded that the RUM process exhibits a great potential method in producing laser crystal rods with better controlled machining condition. Meanwhile, LP50 lapping and polishing machine and its equipment is adequate to produce very fine surface finish of less than 10 nm on hard and brittle materials.

ABSTRAK

Fabrikasi rod kristal laser yang sempurna merupakan kerja penuh cabaran khususnya mencapai kualiti ketepatan bentuk yang tinggi dengan permukaan tanpa kecalaran. Majoriti pemahaman tentang pemprosesan fizikal yang terlibat dalam fabrikasi rod kristal laser dikawal ketat oleh pihak pengilang sebagai harta intelek. Malahan informasi perinciannya juga terhad dalam jurnal teknikal dan bahan bacaan lain. Matlamat utama kajian tersebut adalah untuk mengkaji potensi pemesinan *rotary ultrasonic* (RUM) untuk memesin bahan kristal laser, *Neodymium Doped Yttrium Aluminum Garnet (Nd:YAG)*, serta untuk mengkaji kesan parameter pemelasan dan penggilapan terhadap kekasaran permukaan rod laser Nd:YAG yang dimesinkan. Kesan parameter pemesinan (kelajuan spindal dan kadar uluran) atas kekasaran permukaan dan kadar legapannya, serta kecacatan (tanda cincin dan sumbing bahagian tepi rod) yang terhasil telah dikajiselidik. Kelajuan spindal 3000 putaran per minit (ppm) dengan kadar uluran 5.4 mm seminit merupakan kombinasi parameter bersesuaian untuk menghasilkan rod laser Nd:YAG yang bertahap legapan tinggi, kelurusan rod dan kekasaran permukaan yang memuaskan. Kristal laser Nd:YAG mencapai titik tepu pada kekasaran permukaan 0.124 micron setelah dipelaskan selama 11minit pada kelajuan pemelasan 60 ppm. Sementara itu, kristal laser Nd:YAG menemui titik tepu pada 5 nm setelah digilap 23 minit pada kelajuan spindal 40 ppm dengan permukaan selicin cermin tanpa kecalaran. Kesimpulannya, RUM menunjukkan potensi yang memberangsangkan dalam penghasilan rod kristal laser dengan pengawalan parameter yang optimum. Mesin pemelasan dan penggilapan LP50 sesuai diaplikasi untuk penghasilan permukaan halus yang kurang dari 10 nm pada bahan berkekerasan dan kerapuhan tinggi.

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CHAPTER 1

RESEARCH OVERVIEW

1.1 Introduction

Laser, an acronym for light amplification by stimulated emission of radiation, is certainly one of the greatest innovations of twentieth century. Its persisted growth and development has been an exciting division in the history of science, technology and engineering. Laser is distinguished from other electromagnetic radiation mainly in terms of its coherence, spectral purity and ability to propagate in a straight line. As a versatile source of pure energy in a highly concentrated form, laser has emerged as an attractive tool and research instrument with potential for applications in various fields. Figure 1.1 exemplifies a brief overview to show the diversity of application of laser in different fields.

Rapid progress has taken place in the development of solid-state lasers over the last five decades since the invention of the first ruby laser in 1960. Solid-state lasers exhibit many favorable characteristics such as mechanical durability, and long operational lifetime. Solid-state lasers also provide the most versatile radiation source in terms of output characteristics when compared to other laser systems such as average and peak power, pulse width and repetition rate, and wavelength. These remarkable characteristics have put solid-state laser systems among the most preferred candidates for a wide range of applications in science and technology, military industry, and domestic use. Furthermore, the field of solid-state lasers has found new potential application in conjunction with development of electro-optics for alternative energy resources. Progress in crystal growth technology is essential for the development of renewable energy sources like laser-fusion energy where large laser and nonlinear-optic crystals of high radiation hardness are required. In short, the field of solid-state lasers remains a dynamic area and that will continuously advance and broaden into many new areas. Therefore, it is essentially for developing nations to explore this arena for better future development.

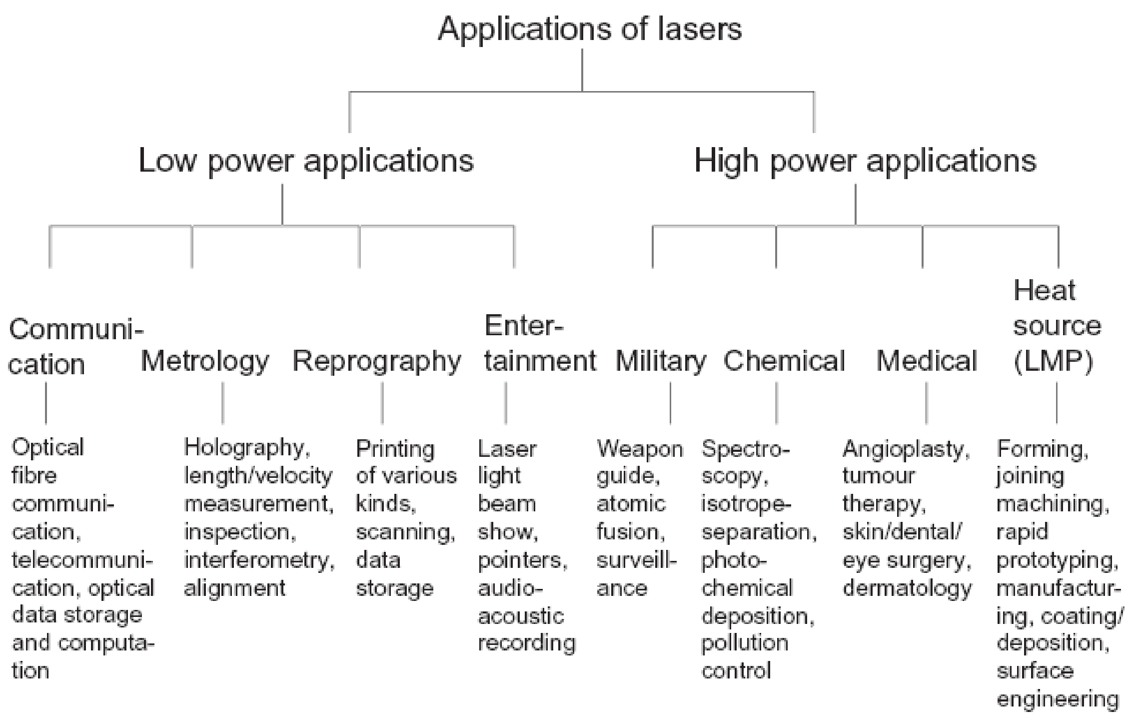

Figure 1.1 Application spectrum of lasers (Steen, 1991)

1.2 Research Background

Electro-optics is a branch of technology involving components, devices and systems which operate by modification of the optical properties of a material by an electric field. It concerns the interaction between the electromagnetic (optical) and the electrical (electronic) states of materials. Solid-state lasers are widely used for high technology electro-optical and laser applications and have found a number of new potential applications. Nowadays hard and brittle oxide materials such as Ruby, Alexandrite ($BeAl_2O_4$), Yttrium Aluminium Garnet (YAG, $Y_3Al_5O_{12}$), Lithium Niobate ($LiNbO_3$) and Sapphire (Al_2O_3) have become important host laser materials.

Hard solids are invariably stiff, high strength and wear resistant. On the other hand, hard solids typically exhibit statistically variable brittle fracture and high sensitivity to machining damage. When loaded with tensile stresses, hard solids transform from elastic to fracture behavior and invariably fail by crack extension. Thus, hard solids are usually brittle, i.e., they have small capacity to convert elastic energy into plastic deformation at room temperature (Dieter, 1981). Thus, an optimum technology for industrial fabrication of specific crystals is required in conjunction with the scientific development of crystal growth technology and high demands of various crystals.

In the field of materials processing, the precision machining technologies have been developed for the manufacture of cost-effective and quality-assured precision parts produced by brittle and hard solids. Examples of machining techniques are diamond turning, ion and electron-beam machining, laser-beam machining and abrasive machining processes (Snoyes 1986, Nakazawa 1994). For electro-optic applications, the functional devices built with single crystals frequently show monolithic structures with complexes shapes that cannot be achieved during the process of crystal growth. Thus, high precision machining process is required in order to produce these hard and brittle materials into perfect crystal (Anantha Rumu, B.L., et. al, 1989).

1.3 Problem Statement

The science and technology combine the state-of-the-art of crystal growth and fabrication techniques of these oxide materials, however, have only been circulated in the developed nations. In recent years, industrial applications of electro-optical and lasers are growing rapidly. Such a high demand of various crystals for today's wide ranges of applications and purposes, and thus it is extremely crucial for industrial-based developing nations to gain such knowledge and technology. Therefore to gain such technology it is important to gain a paramount understanding the knowledge and have the hands-on experience that art and passion of the crystal growth and fabrication techniques.

Neodymium doped yttrium aluminum garnet (Nd:YAG) crystals have been widely used as solid-state laser materials due to its attractive combination of its physical, chemical, mechanical, thermal and optical properties. The Nd:YAG lasers have found many industrial field applications include material processing in manufacturing fields, medical operations in several medical disciplines and in military field.

Many researchers have reported their studies on designations, generations and characterizations of various Nd:YAG laser systems and their performances in various applications. However, studies related to the machining processes of Nd:YAG were not widely reported. Furthermore, laser crystal, for some unknown reasons, had been given less attention compared to other hard and brittle materials such as advanced ceramics, matrix composites and glasses.

This study is designated to produce Nd:YAG laser crystal rod by core drilling using Rotary Ultrasonic Machining (RUM) and study the influence of machining parameter (feedrate and spindle speed) on core drilling performance. Besides, this study also intended to produce flat end of Nd:YAG laser rod practicing LP50 Lapping and Polishing Machine and investigate the effect of lapping and polishing parameters (rotational speed) on surface finish of flat end of Nd:YAG laser rod.

1.4 Objective of Study

The objectives of the study are as follows:

1. To investigate the feasible machining parameters for core drilling laser crystal rod.

2. To evaluate the effect of lapping and polishing table speeds on crystal rod end surface finish.

1.5 Scope of the Study

The research is confined to the following limits:

1. Fabrication on Nd:YAG and lithium niobate laser crystal ingot including the core drilling, lapping and polishing processes. BK7 optical glass was used as preliminary study to simulate and establish machining parameters.

2. Core drilling was carried out on CNC Rotary Ultrasonic Machine. The machining parameters to be varied were limited to feedrate and spindle speed. The interested output parameters are straightness, diameter variation, desired lateral surface roughness and opaqueness for laser crystal rods.

3. Investigation of feasible machining parameter and time for lapping and polishing to obtain excellent mirror-like surface finish on laser crystal rods.

4. Lapping and polishing were carried out on LP50 Lapping and Polishing Machine. The applied load was fixed during lapping and polishing operations. The machined crystal rod end surface finish was interested.

5. The cast iron plate and alumina (Al_2O_3) abrasive slurry with grit size of 9µm were used in the lapping operation. The lapping parameter to be varied was limited to table speeds, i.e. 40 – 60 revolutions per minute (rpm).

6. The stainless steel plate with mounted polyurethane pad and SF1 polishing suspension with dissolved alkaline colloidal silica were used in the polishing operation. The polishing parameter to be varied was limited to table speeds, i.e. 20 – 40 revolutions per minute (rpm).

1.6 Significance of the Study

The main emphasize in this study has been given on the great potential of rotary ultrasonic machine (RUM) to produce laser rods with desired matt surface by using metal impregnated diamond abrasive core drilling tool in conjunction with well controlled machining parameters, as well as demonstrates high potential in replacing the conventional method for producing Nd:YAG laser rods. In conventional production, large Nd:YAG ingot single crystal was first cut into near-net shape, and then continuously ground on fine diamond grains to produce Nd:YAG laser rods with desired geometry and surface finish. Such method took lengthy processing time and high dependence on well-trained manpower. Core drilling method is therefore capable to overcome the drawbacks of conventional method to produce laser rods within shorter machining time and low dependence on manpower, and fulfilling the need to industrialize the fabrication for mass productions. Besides, the LP50 lapping and polishing machine shows exciting potentials to produce flawless flat end of Nd:YAG laser rod with excellent mirror-like surface finishes. The main idea of the study is as an initiatory step to explore and gain the hands-on experience for machining the laser materials, and posterior for the possibility of commercialization.

1.7 Organization of the Thesis

This chapter begins with the background of the research study, followed by the problem statement, objective and scope of the study, significance of the study. Chapter two includes the background of Nd:YAG crystal and standard specifications for Nd:YAG laser rod, overview the principles of ultrasonic core drilling, lapping and polishing processes, and critical reviews of machining performance for these processes. Third Chapter details out methodology and experimental works. Results and discussions are elaborated in the chapter four. Thesis ends with conclusions drawn for this research and recommendations for future work.

REFERENCES

Adithan, M. and Venkatesh, V.C. (1974). Parameter Influence on Tool Wear in Ultrasonic Drilling. *Tribology*. 7(6): 260-264.

Adithan, M. (1974). Tool Wear Studies in Ultrasonic Drilling. *Wear*. 29(1974): 81-93.

Adithan, M. (1976). Abrasive and Tool Wear in Machining Glass and Ceramics. *Journal of the Institution of Engineering (India), Part MC: Mechanical Engineering Division*. 57(1): 27-32.

Anantha, B.L.R., Krisnamurthy, R., and Gokularathnam, C.V. (1989). Machining Performance of Toughened Zirconia Ceramic and Cold Compact Alumina in Ultrasonic Machining. *Journal of Meachanical Working Technology*. 20(Sept. 1989): 365-375.

Bach, H. and Neuroth, N. (1995). *The Properties of Optical Glass*. Berlin Heidelberg: Springer-Verlag.

Barrett, S.F., Wright, C.H.G., and Welch, A.J. (2002). Laser Ophthalmology. In: Vij, D.R. and Mahesh, K. eds. *Medical Applications of Lasers*. Boston: Kluwer Academic. 59-90.

Belkhir, N., Bouzid, D. and Herold, V. (2007). Correlation between the Surface Quality and the Abrasive Grains Wear in Optical Glass Lapping, *Tribology International*. 40(2007): 498-502.

Brown, N.J. (1990). *Optical Fabrication*, Report MISC-4476 Rev. 1., Lawrence Livermore National Laboratory.

Bruckner, D.K. (1960). Remarks on the Wearing Process in Grinding. *Industrie-Anzieger*. 82: 23–28.

Buijs, M. and Korpel-van Houten, K. (1993). *A Model for Lapping of Glass*. London: Chapman & Hall. 3014–3020.

Buijs, M. and Korpel-van Houten, K. (1993). Three-Body Abrasion of Brittle Materials as Studied by Lapping. *Wear*. 166(1993): 237–245.

Chuang, H. and Tso, P. (2006). An Investigation of Lapping Characteristics for Improving the Form Error of an Aspheric Lens. *Journal of Materials Processing Technology*. 176(2006): 183-190.

Dagnall, H. (1980). Exploring Surface Texture. Rank Taylor Hobson.

Dahotre, N.B. and Harimkar, S.P. (2008). *Laser Fabrication and Machining of Materials*. New York: Springer.

DeYoung, J.M. (1996). *Properties of Tabulated BRDF*. The University of British Columbia: M.Sc. Thesis.

Dieter, G.E. (1981). *Metalurgia Mecânica*. Rio de Janeiro, Brasil: Ed. Guanabara Dois.

Doi, T.K. (2007). Polishing Technology. In: Marinescu, I.D., Uhlmann, E. and Doi, T.K. eds. *Handbook of Lapping and Polishing*. Boca Raton: CRC Press. 281-340.

Doy, T.K. (1988). Colloidal Silica Polishing Based on Micromechanical Removal Action and Its Applications. *Sensors and Materials*. 3(1988): 153–167.

Fang, T., Gordon, L. and Jundt, D.H. (2002). Preparation of LiNbO3 wafers. In: Wong, K.K. *Properties of Lithium Niobate*. London : INSPEC. 277–280.

Farago, T.F. (1980). *Abrasive Methods Engineering*. New York: Industrial Press.

Galinetto, P., Marinone, M., Grando, D., Samoggia, G., Caccavale, F., Morbiato, A. and Musolino, M. (2007). Micro-Raman Analysis on $LiNbO_3$ Substrates and Surfaces: Compositional Homogeneity and Effects of Etching and Polishing Processes on Structural Properties. *Optics and Lasers in Engineering*. 45(2007): 380-384.

Gåsvik, K. J. (2002). *Optical Metrology*. 3rd ed. England: John Wiley & Sons Ltd.

Guzzo, P.L., Raslan, A.A., and De Mello, J.D.B. (2003). A Comparative Study on Ultrasonic Machining of Hard and Brittle Materials, *Wear*. 255(2003): 67-77.

Hecht, J. (1992). *Understanding Lasers: An Entry-Level Guide*. NewYork: IEEE Press.

Hecht, J. (1992). *The Laser Guidebook*. 2nd ed. New York: McGraw-Hill, Inc.

Hitz, B., Ewing, J.J. and Hetch, J. eds. (2001). *Introduction to laser Technology*. 3rd ed. New York: IEEE Press, 192-193.

Hocheng, H., Tai, N.H. and Liu, C.S. (2000).Assessment of Ultrasonic Drilling of Boron Fiber Composite Material. *Composites: Part A*. 31(2002): 132-142.

Hu, P., Zhang, J.M., Pei, Z.J. and Treadwell, C. (2002). Modeling of Material Removal Rates in Rotary Ultrasonic Machining: Designed Experiments. *Journal of Materials Processing Technology*. 129(2002): 339-344.

Hu. P, Zhang, J.M., Jiao, Y. and Pei, Z.J. (2003). Experimental Investigation on Coolant Effects in Rotary Ultrasonic Machining. *NSF Workshop on Research Needs in Thermal Aspects of Material Romoval Processes*. June10-12 Stillwater, OK, p.8.

Instrument Systems Div. (2005). Colorimetry: How to Measure Color Differences. Konica. Minolta Photo Imaging U.S.A., Inc.,

Izumitani, T. (1979). Polishing, Lapping and Diamond Grinding of Optical Glasses. In: M. Tomozawa, M. and Doremus, R. H. eds. *Treatise on Materials Science and Technology*. vol.17. New York: Academic Press Inc. 115–172.

Koechner, W. (1976). *Solid-State Laser Engineering*. New York : Springer-Verlag.

Koechner, W. (2007). *Solid-State Laser Engineering*. New York : Springer-Verlag.

Kramer, D. (1995). Ultrasonically assisted machining *Mech. Ind. Mater.* 48 (1995): 15–21.

Kubo, T. (1971). *Introduction to Mechanochemistry*. Tokyo: Tokyo Kagaku Dojin Co. p.5.

Kubota, M., Tamura, Y. and Shimamura, N. (1977). Ultrasonic Machining with a Diamond Impregnated Tool. *Bulletin of the Japan Society of Precision Engineering*. 11(3): 127-132.

Jahanmir, S. (1998). Tribology Issues in Machining. *Machining Science and Technology*. 2(1): 137–154.

Jiao, Y., Liu, W.J., Pei, Z.J., Xin, X.J. and Treadwell, C. (2005). Study on Edge Chipping in Rotary Ultrasonic Machining on Ceramics: An Integration of Designed Experiment and FEM Analysis. *Journal of Manufacturing Science and Engineering*. 127(4): 752-758.

Le, X. and Peterson, M.L. (1999). Material Removal Rate in Flat Lapping. *Journal of Manufacturing Processes*. 1(1): 71-78.

Leyland II, J.T., Albrecht, D.F. and Selman, S.H. (2003). Lasers in Urology. In: Vo-Dinh, T. ed. *Biomedical Photonics Handbook*. Boca Raton, FL: CRC Press. 45-1 – 45-19.

Li, Z.C., Jiao, Y., Deines, T.W., Pei, Z. J. and Treadwell, C. (2005). Rotary Ultrasonic Machining of Ceramic Matrix Composites: Feasibility Study and Designed Experiments. *International Journal of Machine Tools & Manufacture*. 45(2005): 1402-1411.

Li, Z.C., Liang, W.C., Pei, Z.J. and Treadwell, C. (2006). Edge-Chipping Reduction in Rotary Ultrasonic Machining of Ceramics: FEA and Experimental Verification. *International Journal of Machine Tools & Manufacture*. 46(2006): 1469-1477.

Luxon, J.T. and Parker, D.E. (1992). *Industrial Lasers and Their Applications*. 2nd ed. Englewood Cliffs, New Jersey: Prentice Hall.

Malkin, S. (1996). *Grinding Technology: Theory and Applications of Machining with Abrasives*. Dearborn, MI: Society of Manufacturing Engineering.

Marinescu, I., Benea, I. and Pruteanu, M. (2007). Lapping of Brittle Materials. Marinescu, I.D., Uhlmann, E. and Doi, T.K. eds. *Handbook of Lapping and Polishing*. Boca Raton: CRC Press. 123-264.

Markov A.I. (1966). *Ultrasonic Machining of Intractable Material*. London: ILIFFE Books Ltd.

Markov, A.I. and Ustinov, I.D. (March 1972). A Study of the Ultrasonic Diamond Drilling of Nanometallic Materials. *Industrial Diamond Review*. 97-99.

Markov et al., (1977). Ultrasonic Drilling and Milling of Hard Non-metallic Materials with Diamond Tool. *Machine & Tooling*. 48(9): 45-47.

May A.B. (1993). Continuous Wave and Q-Switched Nd:YAG Lasers. In. Crafer, R.C.C. and Oakley, P.J. eds. *Laser Processing in Manufacturing*. London: Chapman & Hall. 91-114.

McKinley, D.A. (1996). *Cost Effective Process Control for Flat Lapping*. Colorado State University: M.Sc. Thesis.

Minolta CR-241 Chroma-meter Users Manual.

Muncheryan, H.M. (1983). *Principles & Practices of Laser Technology*. Blue Ridge Summit, P.A.: TAB Books Lunc.

Nakazawa, H. (1994). *Principles of Precision Engineering*. London, UK: Ed. Oxford University Press.

Nardo, D. (2003). *Lasers*. San Diego, California: Lucent Books.

Ng, S., Le, D., Tucker, S. and Zhang, G. (1996). Control of Machining Induced Edge Chipping on Glass Ceramics. *Proceedings of the 1996 ASME International Mechanical Engineering Congress and Exposition*. November 17–22. Atlanta, GA, USA: Manufacturing Engineering Division, MED(4), 229–236.

Panjehpour, M. and Overholt, F.O. (2003). Therapeutic Applications of Lasers in Gastroenterology. In: Vo-Dinh, T. ed. *Biomedical Photonics Handbook*. Boca Raton, FL: CRC Press. 46-1 – 46-12.

Pei, Z.J. (1995). *Rotary Ultrasonic Machining of Ceramics*. University of Illinois at Urbana-Champaign: Ph.D. Thesis.

Pei, Z.J., Khanna, N. and Ferreira, P.M. (1995). Rotary Ultrasonic Machining of Structural Ceramics: A Review. *Ceramic Engineering and Science Proceedings*. 16(1): 259-278.

Pei, Z. J., Ferreira,P.M., Haselkom M. (1995). Plastic Flow in Rotary Ultrasonic Machining of Ceramics. *Journal of Materials Processing Technology*. 48(1995): 771-777

Pei, Z.J., Prabhakar, D., Ferreira, P.M. and Haselkorn, M. (1995). A Mechanistic Approach to the Prediction of material Removal Rates in Rotary Ultrasonic Machining. *Journal of Engineering for Industry, Transactions of the ASME*. 117(2): 142–151.

Prabhakar, D., Ferreira, P.M., and Haselkorn, M. (1992). An Experimental Investigation of Material Removal Rates in Rotary Ultrasonic Machining. *Transactions of the North American Manufacturing Research Institute of SME*. 20: 211-218.

Petrukha, P.G., et al. (1970). Ultrasonic Diamond Drilling of Deep Holes in Brittle Materials. *Journal of Russian Engineering*. 50(10): 70–74.

Rastogi, P.K. (1997). *Optical Measurement Techniques and Applications*. London: Artech House, Inc. p. 341-361.

Rostoker, D. (1987). How Users can Optimize Machine Performance in Production Lapping Operations. *Microelectr Manuf Test*. 9–10.

Rostoker, D. (1990). Improving Lapping Performance with Micron Slurry. *Ceramic Bulletin*. 69(9): 1469-1471.

Rubin, J.S. (1993). Reduction of Process Variability in lapping Magnetic Recording Heads. Cambridge, MA: Massachusetts Institute of Techonology. MS Thesis.

Saha, J., Roy Choudhury, P.K., Lahiri, B.N. and Mishra, P.K. (1977). Ultrasonic Machining of Glas and Ceramics. *American Ceramic Society Bulletin*. 72(8): 102-106.

Sharma, S.K. and Hemal, A.K. (2002). Laser in Urology. In: Vij, D.R. and Mahesh, K. eds. *Medical Applications of Lasers*. Boston: Kluwer Academic. 195-226.

Shaw, M.C. (1996). *Principles of Abrasive Processing*. New:York: Oxford University Press.

Snoyes, R. (1986). Non-conventional Machining Techniques: The state of art. *Advances in Non-Traditional Machining, ASME*. 1-20.

Sreejith, P.S. and Ngoi, B.K.A. (2001). Material removal mechanisms in precision machining of new materials. *International Journal of Machine Tools and Manufacture*. 41:1831–1843.

Steen, W.M. ed. (1991). *Laser Material Processing*. NewYork: Springer Verlag.

Sudarshan, T.S. and Radhakrishnan, R. (2000). Polishing Techniques for Optical Grade Sapphire. *Materials Science and Technology*. 16(9): 958-960.

Tam, H.Y., Cheng, H.B. and Wang, Y.W. (2007). Removal Rate and Surface Roughness in the Lapping and Polishing of RB-SiC Optical Components. *Journal of Materials Processing Technology*. 192-193(2007): 276-280.

Thoe, T.B., Aspinwall, D.K., and Wise, M.L.H. 1998. Review on ultrasonic machining. *International Journal of Machine Tools and Manufacture*. 38(4): 239-255.

Thwaite, E.G. (1982). The Measurement of Surface Roughness. *Technical Proceeding of the Regional Workshop on Metrology for Developing Countries*. Sydney, Australia.

Treadwell, C., and Pei, Z.J. (2003). Machining Ceramics with Rotary Ultrasonic Machining. *Ceramic Industry*. 153(6): 39-42.

Uhlmann, E. (2007). Fundamentals of Lapping. In: Marinescu, I.D., Uhlmann, E. and Doi, T.K. eds. *Handbook of Lapping and Polishing*. Boca Raton: CRC Press. 7-92.

Verspui, M.A. and de With, G. (1997). Three-Body Abrasion: Influence of Applied Load on Bed Thickness and Particle Size Distribution in Abrasive Processes. *Journal of European Ceramic Society*. 17(1997): 473-477.

Waynant, R. W. and Ediger, M. N. (2000). *Electro-Optics Handbook*. 2nd ed. New York: McGraw-Hill.

Weaver, L.A. (1971). Machining and Welding Applications. In: Ross, M. ed. *Laser Applications*. New York: Academic Press. 218.

Whitehouse, D.J., Bowen, D.K., and Venkatesh, V.C. (1994). Gloss and Surface Topography. *Journal of CIRP*. 43(2): 1-8.

Williams, R. L. (1982). *Machining Hard Materials*. Michigan: Society of Manufacturing Engineering.

Ya, G., Qin, H.W., Yang, S.C. and Xu, Y.W. (2002). Analysis of the Rotary Ultrasonic Machining Mechanism. *Journal of Materials Processing Technology*. 129(2002): 182-185.

Yoshikawa, H. and Sata, T. (1963). Study on Wear of Grinding Wheels. *Journal of Engineering for Industry*. 85(1): 39–43.

Yoshikawa, H.Y. (1963). Fracture Wear of Grinding Wheels. *ASME Production Engineering Research Conference*. 209–217.

Yoshikawa, H.Y. (1963). Criterion of Grinding Wheel Tool Life. *Bulletin Japan Society of Grinding Engineers*. 3(1963): 29–32.

Yuan, J.L., Zhao, P., Ruan, J., Cao, Z.X., Zhao, W.H. and Xing, T. (2003). Lapping and Polishing Process for Obtaining Super-Smooth Surfaces of Quartz Crystal. *Journal of Materials Processing Technology*. 138(2003): 116-119.

Zeng, W.M., Li, Z.C., Pei, Z.J. and Treadwell, C. (2005). Experimental Observation of Tool Wear in Rotary Ultrasonic Machining of Advanced Ceramics. *International Journal of Machine Tools & Manufacture*. 45(2005): 1468-1473.

Zhang, Q.H., Zhang, J.H., Jia, Z.X. and Ai, X. (1998). Fracture at the Exit of the Hole during the Ultrasonic Drilling of Engineering Ceramics. *Journal of Materials Processing Technology*. 84(1-3): 20-24.

Zhang, Q.H., Wu, C.L., Sun, J.L. and Jia, Z.X. (2000). Mechanism of Material Removal in Ultrasonic Drilling of Engineering Ceramics. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 214(9): 805–810.