Invited Paper

Application of precision diamond machining to the manufacture of micro-photonics components

M. A. Davies*[a], C. J. Evans[c], S. R. Patterson[a], R. Vohra[a], B. C. Bergner[b]
[a] Center for Precision Metrology, University of North Carolina at Charlotte, 9201 University City Boulevard, Charlotte NC, USA 28223
[b] Center for Optoelectronics and Optical Communications, University of North Carolina at Charlotte, 9201 University City Boulevard, Charlotte NC, USA 28223
[c] Zygo Corporation, CT, USA

ABSTRACT

The use of diamonds to generate precision patterns and precision surfaces on a micrometer or nanometer scale has a history that dates back centuries. Uses of diamond in semi-automated machinery can be traced to ruling machines, pantographs, and ornamental turning with "diamond turning" dating back about a century. Poor behavior in machining more common materials (e.g. ferrous alloys) has limited diamond use in traditional industrial machining. The niche of the single crystal diamond is its edge sharpness and the ability to produce near-optical finish in materials such as aluminum, copper and their alloys; however, due to machine limitations, diamond machining remained a novelty until relatively recently. A convergence of machine technologies developed for both weapons and commercial applications led to modern diamond turning. Current turnkey machines can produce contoured surfaces with surface finish in the range of 5 nm R_a and long range accuracy of micrometers or less. Macroscopic scale, three axis, diamond machining is a well-developed technology; machining of features on a micrometer and submicrometer scale is a new and rapidly developing application of single crystal diamond machining. The role of this technology in micro-optics replication has yet to be fully defined.

Keywords: Diamond Turning, Diamond Micro-milling, Micro-optics Replication

Contributors: J. Bryan, E. Brinksmeier, B. Cassin, J. S. Colton, R. H. Hocken, D. A. Lucca, S. Scott, L. Simon, D. Thompson, Y. Tohme, P. Tolley, M. Weck, J. Wyman.

1. INTRODUCTION

Micro-optics ranging from 10s of μm to 100s of μm are a key enabling technology for telecommunications, medical imaging/diagnostics, and surveillance systems. Progress in micro-optics production has been hampered by bottlenecks in manufacturing, testing and metrology. Currently, lithographic techniques dominate industrial production, limiting devices to two-dimensions and generally low-aspect ratio configurations. Unlike in electronics, three-dimensional form accuracy is a necessity for optics, and precision assembly is critical to performance. New manufacturing platforms capable of mass production of fully integrated devices are needed. Any practical method must be capable of rapid, parallel production in order to be cost effective. One method that has been proposed is micro-molding. Molds can be produced by photolithography with binary or stepped techniques, grey scale lithography, LIGA techniques, electron beam lithography and mechanical processes. Standard lithography processes can be applied directly to optical materials or to mold manufacturing. They are well-characterized by years of experience in the electronics industry. However, due to depth-of-field limitations they produce two-dimensional structures with limited aspect ratios. While "curved" surfaces can be approximated by binary structures or steps, the efficiency of such structures is limited. Grey scale lithography can produce structures with continuous three-dimensional profiles and LIGA processes can produce large aspect ratios, but the combination of these capabilities is not currently possible with lithographic techniques, and profile control in gray scale lithography must be done by stringent process feedback . LIGA techniques are limited because they require synchrotron radiation. Electron beam lithography is able to produce accurate structures on a nanometer scale, but making large three-dimensional structures is not cost effective.

An alternative method for manufacturing micro-photonic components is single-crystal diamond machining. In a recent article *Fortune* [1] made the following statement.

> “Ultraprecision machining is doing for light what integrated circuits did for electronics”.

While this may be overstated, it correctly indicates that ultraprecision machining of micro-optics and molds is receiving significant attention. It is clear that diamond machining offers some significant advantages for micro-molding of some optical structures. However, it is likely that solutions to problems in micro-optics will most likely develop from the appropriate combination of existing techniques. For example, binary optics which are particularly suited (by design) for lithographic techniques, while contoured surfaces or macro-scale optics with micrometer or nanometer surface structures/patterns may require diamond machining and/or diamond machining combined with lithographic techniques. The immaturity of the manufacturing methods in this area is evident from a survey of the industry where *similar devices are being manufactured by dissimilar methods.* Mature industries are characterized by similar manufacturing techniques for similar products.

Brinksmeier [2] has suggested that processes for manufacturing of micro-components can be broken into two technological types, microsystem technologies (MST) and micro-engineering technologies (MET). MST consist of MEMs and MEOMs products and devices, while METs consist of mechanical components, micro-molds and microstructured surfaces. MST are well suited for production by processes that have grown out of the electronics industry, photo (UV) lithography, silicon micromachining technologies such as wet etching and thin film deposition. On the other hand, because of their more three dimensional structure, METs are more suited for mechanical processes such as precision machining and micro-engraving processes (micro-ruling). Brinksmeier [2] also argues for a third category of processes that he defines as energy assisted processes such as laser machining; these processes are useful for both MST and MET production. Expanding on this, it is interesting to note the dependence of device design on the designer’s perception of the available manufacturing processes. In our survey of industrial products and production techniques, this seems to be evident, with very similar (if not identical) products being produced by vastly different processes. Of course, some of the perceptions of designers about available processes may be correct and some perceptions may be incomplete due to limited exposure; equally important are the limitations that result from intellectual property that produce non-technical evolutionary forces in any industry.

For the producers and designers of micro-optics, single crystal, ultraprecision, diamond machining offers the following capabilities: (1) true three-dimensional contour generation; (2) accuracy of one part in 10^6 with absolute accuracy of 1 part in 10^8 on a single axis for ideal conditions [3]; (3) surface finish of 5 nm R_a for a range of materials and as good as 1 nm R_z [3]; (4) ability to generate surfaces with variable aspect ratios; and (5) feature sizes that exceed the limits of optical microscopy. However, despite the potential advantages, application of diamond machining to mold production for micro-optics remains in its infancy (Herzig[4]). In this paper, we review the capabilities of single crystal diamond machining and its potential for micro-optics production. We compare the technique to the leading optical lithographic techniques and offer a view of its advantages. We also review recent micro-molding work and its relationship to diamond machining and attempt to suggest directions for future work in this area. Academic research with a longer event horizon seems to be centered in Europe (Weck [5], Brinksmeier[6]) and Japan (Takeuchi [7,8]) while private sector activity worldwide is substantial with significant (and possibly the majority of) activity in the United States. The reason for the differences in the level and type of research activities seems to be primarily policy related with government support agencies placing greater emphasis on non-defense related manufacturing technologies overseas.

2. HISTORICAL PERSPECTIVE

The use of a single natural diamond to shape hard materials dates back centuries. Diamond pantographs and mechanically controlled and/or mechanically compensated ruling and dividing engines have demonstrated since the 16th century that very dense and precise line spacing can be generated by purely mechanical means. With regard to the production of gratings for the calibration of optical microscopes by Norbert, the following statement from Evans [9] illustrates the potential for mechanical methods to compete with optical methods for precision feature production.

> “Norbert adapted Fraunhofer’s idea, producing test plates with bands of lines of different spacing; as microscopes improved, Norbert introduced new test plates with finer spaced rulings, always staying one step ahead of the microscopists until, inadvertently, he exceeded the theoretical limits of optical microscopy.”

Even in the 18th and 19th centuries, the need for diffraction gratings and test gratings for optical microscopes (many of which were actually used by wealthy hobbyists) drove the development of ruling machines capable of generating parallel lines with spacing less than one micrometer. As early as the 1880's, Fasdolt claimed to have a ruling engine that could generate and incredible one million lines per inch equating to a line spacing of 25 nm. This was done by using a mechanical transmission – often the scales on the position-amplified side of the transmission were themselves read with a microscope. Relying on the repeatability of the errors, the periodic imperfections in the line spacing from the drive were removed with a customized cam-corrector system. In the 1940's, mechanical corrections were replaced by feedback from an interferometer and a servomotor. The technology then evolved to the use of software error correction so that today master gratings with thousands of lines per millimeter are generated mechanically and mass produced via replication techniques. According to Cassin [10] and Scott [11], new technologies such as linear motors, precision hydrostatic slideways, glass scales and electronic feedback control allow the production of near frictionless single axis systems with accuracy that now exceeds that of the early ruling engines. Scott [11] points to the generation of lenticulars with a modern ruling engine and a diamond "form tool".

While diffraction gratings are arguably provide the earliest example of the mechanical production of micro-optical elements, ruling machines did not evolve directly into modern diamond turning. For the purpose of ruling, the most important machine characteristic is the ability to produce accurate parallel lines with accurate spacing. Thus, while much energy was spent removing periodic machine errors arising from imperfect drives, other aspects were not as important – indeed even deviation from linearity is forgivable if the curves remain locally parallel. Ruling also involves burnishing to modify the material whereas modern diamond machine use a cutting process based on local plastic deformation. However, the possibility of "drawing" micro-waveguides in molds using a combination of ruling techniques and ultraprecision machines is enticing.

To our knowledge, the first known report on single crystal diamond turning was by Ramsden [13] in 1779, who used a diamond to cut a hardened steel screw for dividing engines. Diamond turning was used at Zeiss to generate an improved surface finish first for aesthetic purposes and later for optical function as early as 1901 [9]. In 1929, Bauch [14] reported an accuracy of one ten thousandth of an inch and "beautiful mirror-like finishes" could be obtained in diamond boring operations. Cooke [9] and Phillips [9] developed methods for precision turning of Schmidt plate masters in World War 2. Rank Taylor Hobson also developed precision machines for the diamond crushing of glass and other uses in the 1950s [9]. Benjamin [15] reported that aspheric generation had been a continuing activity at Bell and Howell from the 1950s Herbert [16] reported that single crystal diamond tools were used to produce better than a 50 nm finish on computer disks using machines with hydrostatic spindles at Mullard in Great Britain. Lewis [17] reported Du Pont had spent 12 years developing the Ultra-precision Positioner and Shaper (UPPS) in collaboration with the Union Carbide Y-12 (nuclear weapons) plant which used both conventional tools and "diamond knives" (the techniques for developing these near theoretically sharp diamond knives was developed by the biologist and physician Fernandez-Moran [18] in the 1950s). According to the history of the Y-12 facility at Knoxnews.com [19], the process of developing a machine tool with Dupont began in 1962 and involved many of the components now associated with modern diamond machining equipment. It is likely that the early experiences with the UPPS at Union Carbide Y-12 [20] were communicated to Lawrence Livermore National Laboratory (LLNL) where they were combined with expertise in measuring machines and provided the impetus for the design and development of modern diamond turning equipment. The Y-12 weapons facility has also continued to develop this technology. An example of such development is the SPACO machine which integrated linear motor and diamond turning technologies, now a common commercial practice. [10,11].

Since the introduction of precision machining into the weapons' laboratories, there has been an acceleration in related technological advances in the areas of: (1) machine design including non-contact spindle bearings (primarily air-bearings), (2) hydrostatic ways, (3) non-contact drive systems, (4) integration of displacement measuring interferometers onto the machine axes, (5) computer numerical control (CNC), (6) numerical compensation for repeatable errors, and (7) precise environmental temperature and vibration control. Coordinate measuring machine design, motivated by inspection of precision hemispherical shells for weapons applications in the 1950s and 1960s, gave the impetus for the design of most modern commercial diamond turning machines [3]. Defense applications developed in parallel with the private sector, often overlapping in areas such as infrared imaging telescope optics, forward looking infrared (FLIR) systems, night vision, heads-up displays and computer disks. After the 1970s, there were many parallel efforts in industry and in the Department of Energy weapons laboratories that were mutually influential. For example, the efforts of Bell and Powell converged with efforts at Lawrence Livermore National Laboratory (LLNL) in the 1970s with the introduction of a number of machines that utilized the Moore 3 measurement base and spindles from Professional

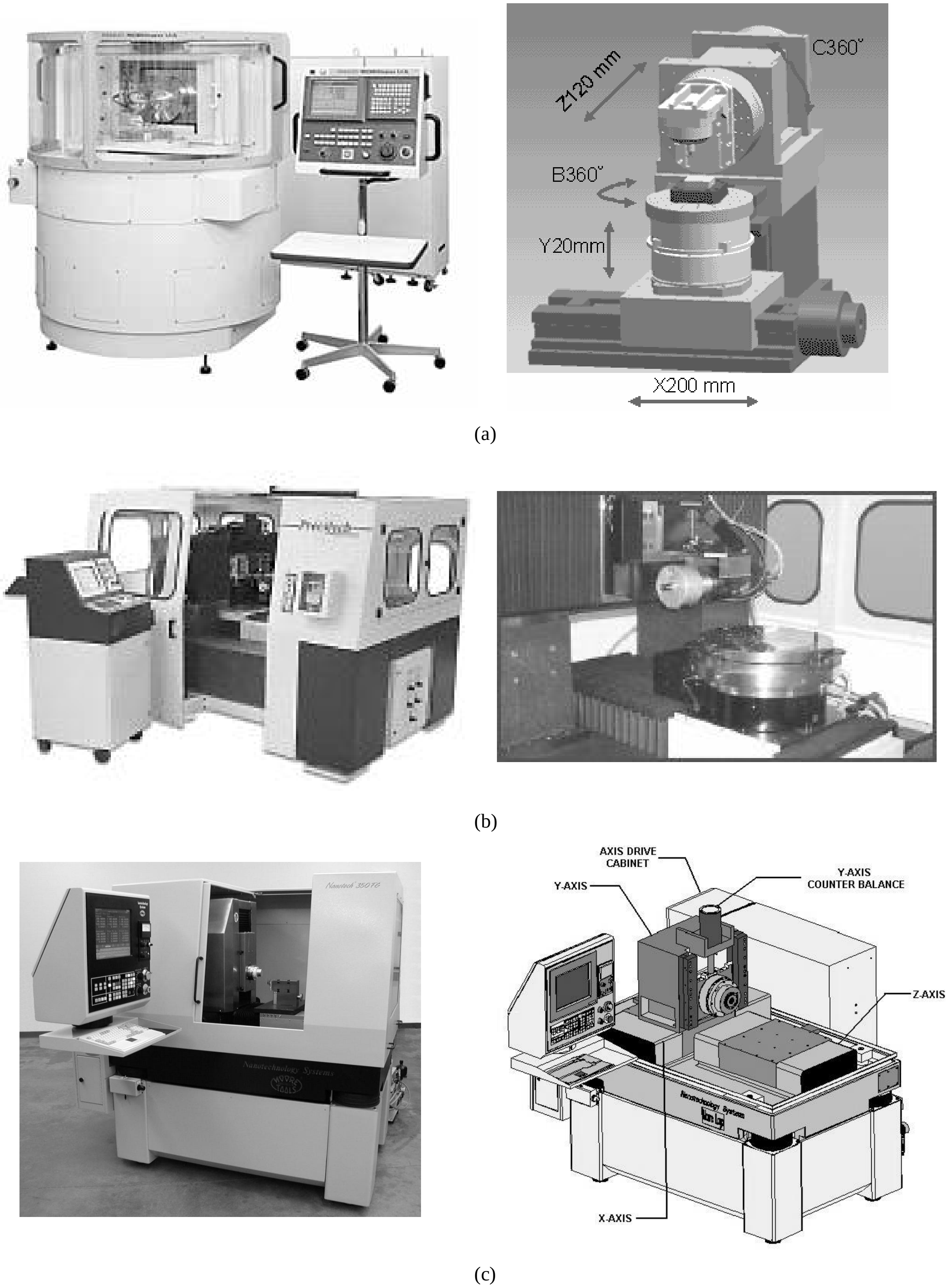

Figure 1 (a) Fanuc robo-nano; (b) Precitech five axis micromachining center; and (c) Moore Nanotechnology 350 five axis machining center and advanced macro-scale machined freeform optics.

Instruments. The “Senior” machine is one example [15]. Efforts at Philips remained relatively independent with the production of optics for compact disks and laser vision [21]. However, being relatively immune to economic fluctuations in the midst of the cold war, the largest sustained development effort was at the DOE Laboratories, particularly LLNL and Y-12. The long-term influence on the industry was substantial.

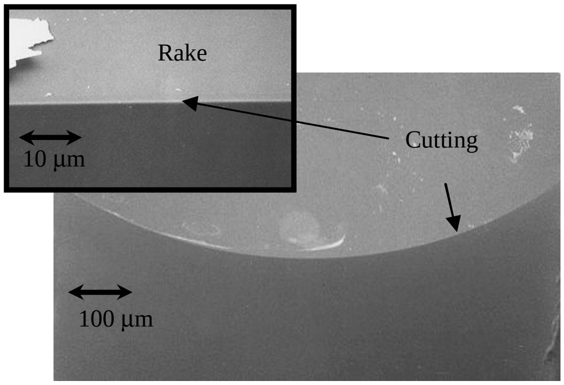

Figure 2: Highly magnification optical image of the edge of a commercially prepared diamond tool.

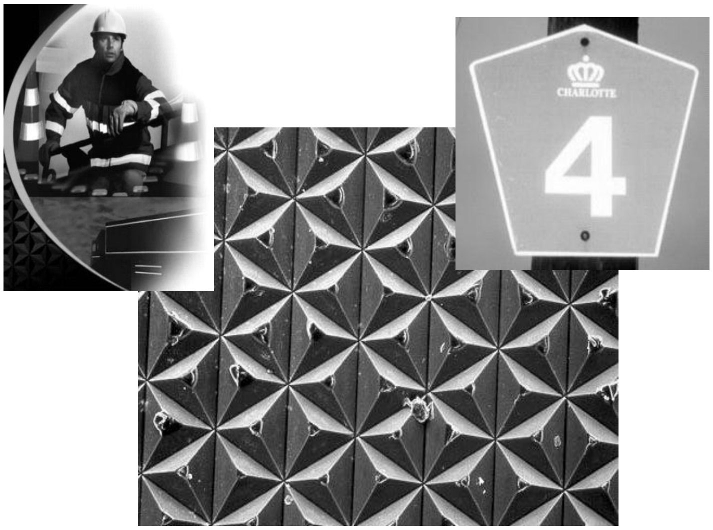

Figure 3: Pyramid array generated by mold produced by the flycutting operation.

Early weapons applications were more concerned with form measurement and generation rather than finish. In nuclear weapons, small deviations from ideal spherical form in the explosive and fissile core lenses causes instability, explaining the early interests at Y-12 and the development of the UPPS machine. However, this work led to the important realization that the design of a precision measuring machine, and the design of a single point diamond turning machine had great similarities. It was the application of the design principles from coordinate measuring machine tools that lead to the development of diamond turning machines (DTMs) 1,2, 3 [22] and the Large Optics Diamond Turning Machine (LODTM) [23] at Lawrence Livermore National Laboratory (LLNL). LODTM was designed in support of the department of defense Space Based Laser and remains the most accurate large machine tool in the world. More recently, emerging technologies of infrared night vision systems have required a range of reflective components such as toroids, polygons, frame mirrors, and cold shields. Currently, the frontiers in conventional diamond machining involve the flycutting of more than 800 precision potassium di-phosphate (KDP) crystal optics for the National Ignition Facility (NIF); the goal of NIF is to produce inertial confined fusion. The fact that macro-scale diamond machining is a mature technology was demonstrated with some humor by Thomson et al. [24] who assembled the Baby Optics Diamond Turning Machine (BODTM) from commercially available components in only two weeks; it is worth noting that modern compact diamond turning lathes (see Figure 1) seem to bear a striking resemblance to the BODTM.

Other components critical to micro-scale diamond machining processes, particularly the tools, have developed more slowly. The art of polishing near theoretically sharp edges on diamonds developed in the 1950s [18]. There was little reason to improve upon this process for macroscopic scale machining. Chemo-mechanical polishing is also used on a limited basis. A diamond tool edge produced by chemo-mechanical polishing is shown in Figure 2; mechanically lapped tools show a more distinct linear structure from the abrasives in the polishing slurry. With an appropriate mechanically or chemo-mechanically polished tool and machine, it is possible to turn surfaces with a finish approaching 2 nm R_a (actually the best recorded is about 1 nm). However, the generation of micro-optical features challenges diamond tool makers to develop processes for manufacturing micro-scale form tools with theoretically sharp edges. The private sector and some academic institutes (mainly in Europe) have lead in the development of molds for inexpensive polymer-optic microstructured surfaces. These institutions have driven the development of small-scale diamond tools, flycutters and drills; this development is likely to accelerate.

3. MACHINE CAPABILITIES

The ultraprecision machining of micro-optic components and molds requires a combination of (1) machine technology; (2) tools; (3) environmental control; (4) appropriate materials. These will be discussed below.

3.1 Machine Capabilities

Relatively few companies supply modern ultraprecision diamond machine tools. In the United States, Precitech and Moore Nanotechnology Systems, both located in Keene, New Hampshire are currently the largest producers of ultraprecision machine tools. According to *Fortune* [1], even in the current economic environment, these companies are experiencing unprecedented growth. Precitech has annual revenues of $20 million and has tripled its sales from 1999-2002. It expects to sell 75 machines this year with prices ranging from $200,000 for two-axis turning machines to $1 million for larger multi-axis systems. Moore expects to sell 25 machines this year and much of the growth is stimulated by the production of micro-optic systems. As is typically true with strategic base industries, the production of these tools leads to much greater end-user production. This is not difficult to believe considering that diamond machining technology is already used for the production of contact lenses, polygon mirrors, aspheric lenses, microlens arrays, microstructured surfaces of pyramids, corner-cubes, and antireflective gratings or channels with individual features of micrometer or now submicrometer dimensions. Applications for these microstructured surfaces and replicas generated from diamond machined molds include antireflective coatings (“moth’s eye” and other structures), retroreflective coatings for road signs, surfaces for light management and control of building environment, directing low-energy semiconductor lighting, diffractive optical elements and 2D and 3D roughness standards.

Many in the industry believe that ultraprecision machining will be fundamentally improved by the development of linear motor technology, precision hydrostatic slideways and glass scales that now have 8.6 nanometer resolution (while many would dispute the use of glass scales over DMIs). This combination of technology allows the reduction of the unrepeatable errors caused by stick-slip friction that have plagued precision instrument designers for centuries. The commercial specifications on the linear positioning accuracy of a single axis with 300 millimeters of travel, assuming a reasonably well-controlled thermal environment (0.1 degrees C, according to one manufacturer), is 200 nanometers with 50 nm of repeatability [12]. Those with experience in the use of these machines would say that this estimate is conservative; for example LODTM has an accuracy approaching 25 nm over the entire 1.5-meter diametral work zone and can produce a surface finish in the range of 50-100 Angstroms rms [23]. However, this level of performance comes at a cost: (1) careful separation of the structural and metrology loops; (2) environmental temperature control to 0.005 degrees Celsius; (3) low CTE on passive components; (4) interferometric feedback on all axes with 0.6 nm resolution; and (5) circulation of temperature controlled water through the most critical machine components with a stability of 0.0005 degrees Celsius [25]. Under the best conditions, a surface finish of 1 nm R_z has been attained in OFHC copper on a Precision Engineering Research Lathe at LLNL providing a view of what can be done with enough investment and understanding.

However, for the production of micro-optical components, the linear global positioning accuracy is often not as relevant as for other components. For example, for a micro-lens array, the relative and not the absolute position of the features is the critical parameter. Thus, when examining this technology for micro-optics production, it is critical (as in all components) to understand the sources and types of manufacturing errors and determine whether those errors can be removed by relatively simple subsequent operations or corrections. Also, if optics are to be replicated, subsequent replication processes will be the dominant source of errors in the final components. Currently, fully programmable five axis machine tools that can produce contoured surfaces of optical quality are available from a number of companies worldwide. Representative examples are shown in Figure 1. It is always necessary when constructing a precision machining facility to weigh the costs of environmental control with the requirements.

3.2 Tools

The performance of diamond machining is partially dependent on the ability to produce an extremely sharp edge on a diamond tool via mechanical or chemo-mechanical polishing. This has been possible for several centuries via trial and error methods. However, because the edge radii are too small to be measured via optical microscopy (see Figure 2), it has not been possible until recently to measure the actual edge profile of single crystal diamond tools with certainty.

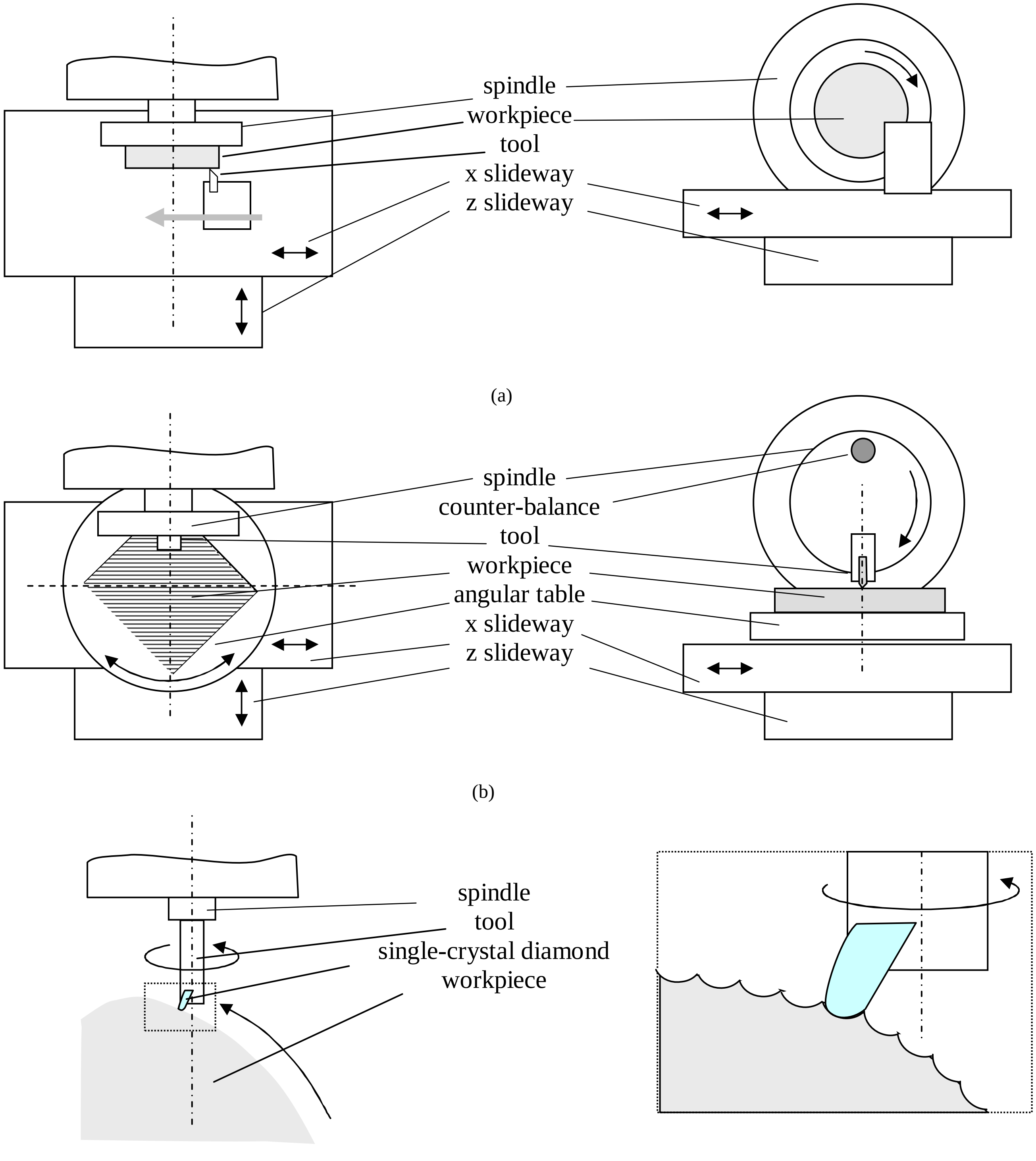

Figure 4: (a) Turning, (b) flycutting, and (c) single-flute contour milling.

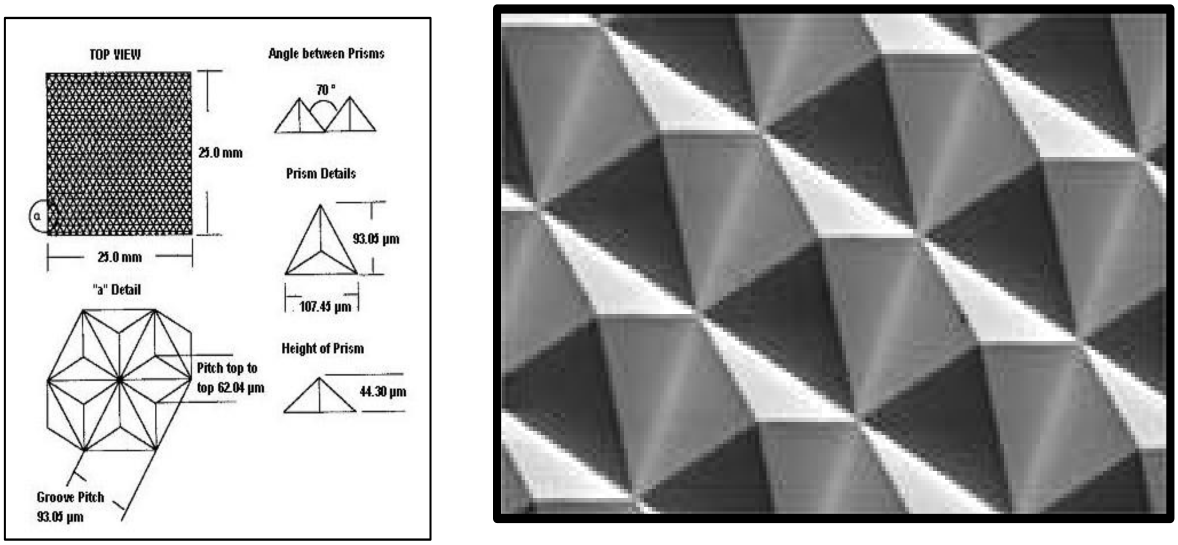

Figure 5: Multiprism structures generated by crossed flycut channels.

According to Lucca et al. [26], the edge radii of newly sharpened single crystal diamond tools can range from several hundred nanometers for commercially prepared tools down to tens of nanometers for specially prepared edges; these edge radii were measured using an atomic force microscope and provide valuable data on the true sharpness of diamond tools. Other data from SEM images suggest that edge radii on commercial tools are typically ten to fifty nanometers. The need to generate more complex surfaces has driven the development of form tools; in this context, a form tool is one that has a desired shape, perhaps on a micrometer scale that can be transferred from the tool to the workpiece. An example of this is the manufacturing of lenticulars by using a diamond form tool in a ruling configuration [11]. Takeuchi et al. [7] demonstrate multiple-axis ruling to generate microgrooves using triangular shaped tools; they point to the use of this method to generate holographic optical elements (HOEs). Another more typical use of a simple form tool is flycutting with a "dead sharp" tool as shown in Figure 5(b). This allows the machining of triangular channels of various profiles that depend on the included angle of the tool and the angle of the spindle relative to the workpiece. By rotating the workpiece and cutting intersecting channels, various patterns can be generated (see for example Brinksmeier et al. [6]). This is the preferred method for producing the molds for the rolling of polymer retroreflective tapes and sheets now available at very low cost [11,27]; Figure 3 shows an example of adhesive plastic sheet used on road signs [27]. Appropriate tooling will be critical to successful widespread application of ultraprecision machining. Already, tool manufacturing is being challenged by the production of micro-optical arrays where complex geometric forms are calling for the development of precise form tools. More controlled and scientific methods for generating these tools are critical for the development of complex optical forms on a micro- and nano-scale.

3.3 Materials

Within the diamond turning community, materials are divided in an almost binary manner: those that are "diamond turnable" and those that are not. While "diamond turnability" is subjectively defined based on the (perceived) cost-effectiveness of using a single crystal diamond tool, the determination is often black and white because of the high-cost of the diamond and the relatively dominant effect of chemical wear.

In general, wear mechanisms in machining include stress related phenomena such as fracture, abrasion [28], spalling, delamination (coated tools) and plastic deformation, and thermally activated phenomena such as dissolution, diffusion, chemical reactions [29], and adhesion. While all of these mechanisms are active in diamond turning, the relatively dominant effect of the chemical wear has given rise to the term "diamond turnability". Paul et al. [29] provide an explanation for the "diamond turnability" of materials that attributes the chemical wear of diamond tools to the presence of unpaired d-shell electrons in the sample being machined. The mechanisms for wear vary but all are linked to the formation of an intermediate carbon-metal compound that facilitates the diffusion of carbon out of the tool and into the workpiece material; the formation of the intermediate compound is related to the presence of unpaired d-shell electrons.

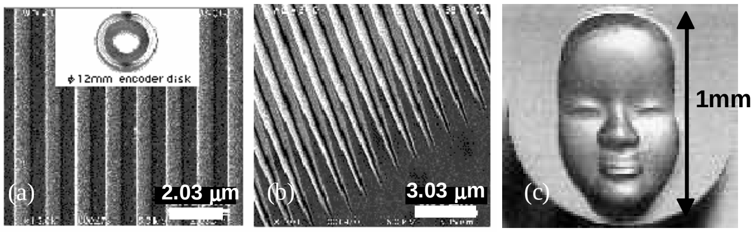

Figure 6: Examples of micro-machined structures: (a) a 1 µm grating with nanometer scale surface roughness, (b) tapered ends with V-grooves showing the absence of burrs, (c) a 1 mm contoured mask with surface roughness (on the forehead) of approximately 60 nm R_a. (Fanuc Web Site)

This theory explains the observation that metals such as aluminum, copper, gold and silver are "diamond turnable" while materials such as nickel, iron, titanium and chromium are not "diamond turnable". Unfortunately, the harder materials and alloys traditionally used for molding are not "diamond turnable". Electroless nickel plating is the most notable exception. While pure nickel is not diamond turnable, a phosphorous content of at least 10%-12% in electroless nickel substantially reduces the wear rates experienced in machining. Paul et al. [29] justify this with a heuristic argument that the unpaired d-shell electrons in the nickel are tied up by the phosphorous. The crystalline electroless nickel coatings are less "diamond turnable" because each phosphorous atom is linked to three nickel atoms while in the amorphous nickel coatings, each phosphorous atom has nine nearest neighbors; thus, the amorphous electroless nickel coatings are more "diamond turnable". Alternate theories for the change in the effect of phosphorus content on wear rate are based upon the phase diagram of nickel and phosphorous and the formation of hard nickel phosphides [30,31]. Taylor et al. [30] is extremely detailed and remains a critical reference for designing electroless nickel coatings for diamond machined optics. More recently, phosphorus-bearing electroplated coatings have been developed with similar properties. Regardless of the mechanisms, the hardness of phosphorus-bearing nickel coatings make them the preferred material for many diamond-machined optics and molds..

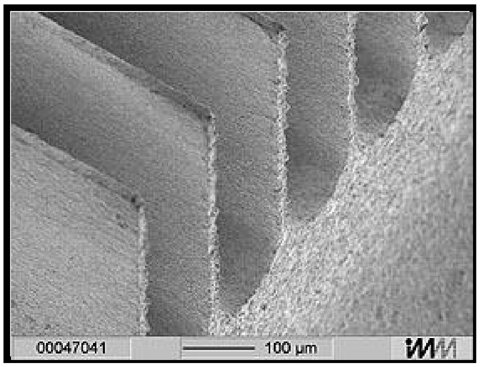

Figure 7: Thin walled structures with large aspect ratio.

The theory of Paul et al. [29] gives a general method for determining which materials will diamond turn well with anomalies resulting from other types of wear such as adhesion or abrasion. While less research on the direct diamond turning of polymers is available, polymethylmethacrylate and polystyrene have been found to diamond turn without difficulty.

3.4 Environment

In order to ensure the accuracy of precision diamond turning machines, careful environmental control must be implemented. Software error correction in modern CNC controllers is capable of eliminating, in large part, the repeatable errors in the machines. However, deviations in temperature from the original calibration conditions and gradients in the machine structure cause uncompensated errors. Fortunately, thermal enclosures that approach 0.01 degree Celsius temperature control are available commercially – the area for LODTM at LLNL has 0.005 degree Celsius control. However, care must be taken to control thermal gradients by eliminating striation and ensuring that the entire machine structure remains at the same temperature. Bryan advocates doing this by exposing the entire machine to a continuous shower of oil circulated through an isothermal reservoir. Care must also be taken to minimize Joule-Thompson cooling as the air exits the bearings. Oil for the hydrostatic ways must also be carefully controlled. Such temperature control is critical if sub micrometer positioning accuracy is to be maintained.

4. MICRO-OPTICAL COMPONENT APPLICATIONS

The number of applications of ultraprecision machining in micro-optics manufacture has been steadily growing over the past decade. To be cost effective, ultraprecision machining must be coupled with a bulk parallel process such as molding. While there have been some attempts to directly mold glass at high temperatures, the greatest success has been achieved in the molding of polymers.

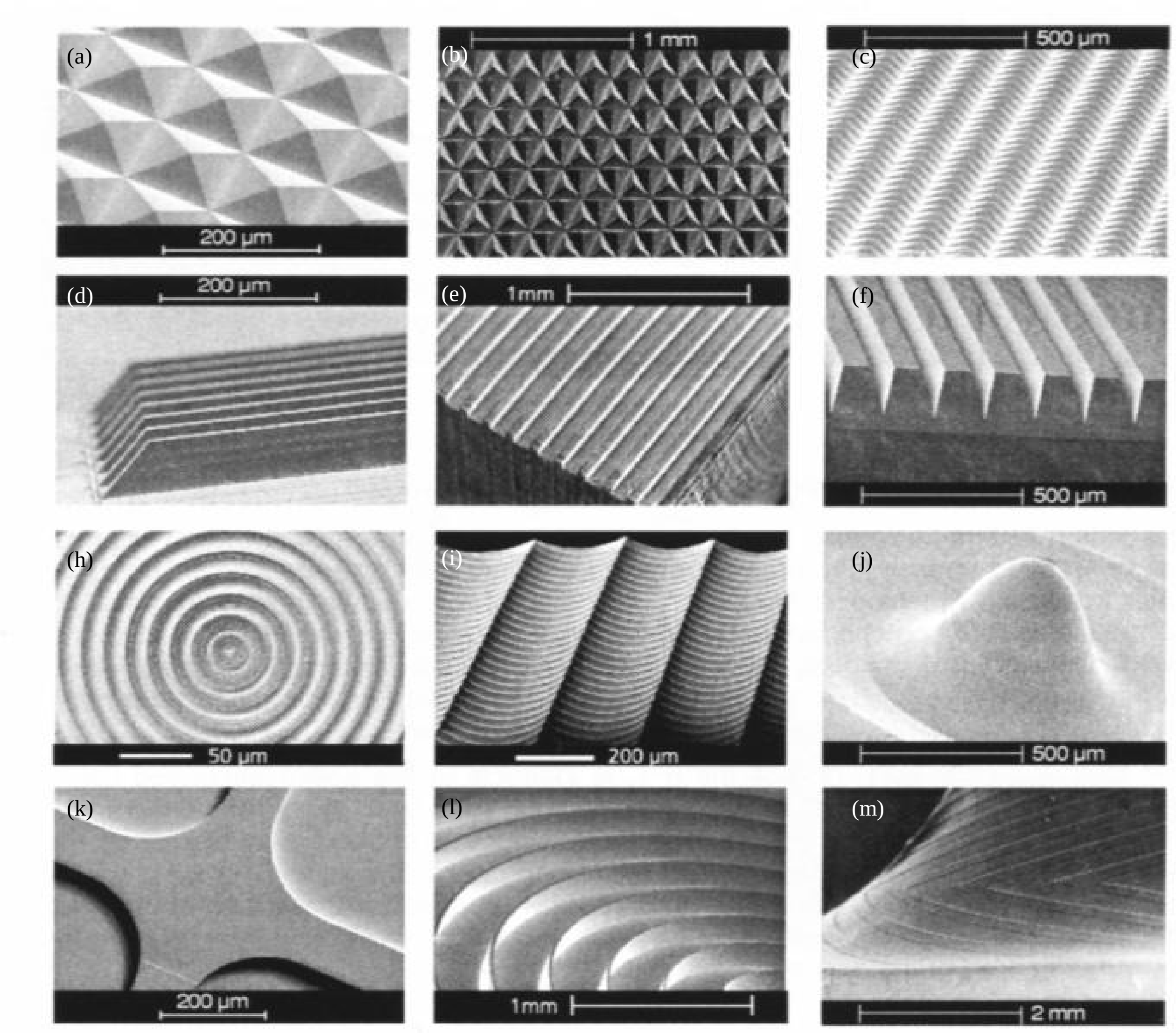

Figure 8: Images of diamond turned micro structures (Courtesy, Fraunhoffer Instituute for Production Technology IPT, Aachen Germany.

Manufacture of the molds for polymer optics is accomplished by a range of machining methods as shown in Figure 4. These include: (1) turning; (2) flycutting (Figure 4(b)); (3) contour machining using a single flute cutter with a radius; (4) ruling with a form tool. These methods can generate a range of three-dimensional geometric forms with optical quality surface finish.

The flycutting geometry is extremely useful for generating repeated prism arrays, pyramid arrays and other structures used in the generation of special reflective coatings, sheets and tapes. Figure 5 shows prism and pyramid structures generated by flycutting electroless nickel [10]. Similar prismatic arrays with as small as 20 micrometer bases, diffractive gratings with 160 nm pitch and accurate step heights as small as 30 nm have also been generated [34]. Impressive contoured structures also generated by a commercial machine (Figure 1 (a)) are shown in Figure 6.

Using a milling geometry (Figure 5(c)) it is possible to cut deep slots and thin walls as well. Figure 7 shows a structure with wall spacing of 100 micrometers, thickness of approximately 10 micrometers and an aspect ratio of approximately thirty to one [10]. This type of structure can be used to manufacture antireflective coatings or could be used for non-optical functions such as micro-heat exchangers. Tools with diameters as small as 10 micrometers have been fabricated using ion milling.

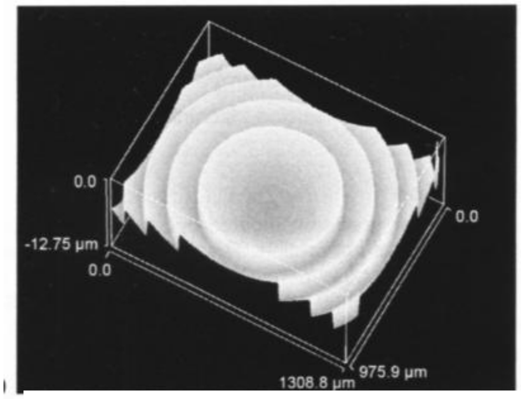

Figure 9: Interferogram of a phase matched Twyman sphere with groove depths of 6.33 µm.

Weck and co-workers [2] have generated many structures using the methods shown in Figure 4 with potential applications as optical molds. Figure 8 shows structures that demonstrate a number of important advantages of ultraprecision diamond machining including the manufacture of true three dimensional contours. While not shown here, it is possible to generate features on countered surfaces as well; for example one could imagine covering a large spherical contour with a microprismatic pattern thus combining multiple length scales. This would allow the generation of larger optics with integrated surface microstructures. This is extremely difficult if not impossible using photolithography. Of course, a simpler but extremely useful example of this type of patterning is the Fresnel lens. A Twyman sphere with groove heights of only 6.33 micrometers generated by Brinksmeier and co-workers using diamond machining as shown in Figure 9 [3].

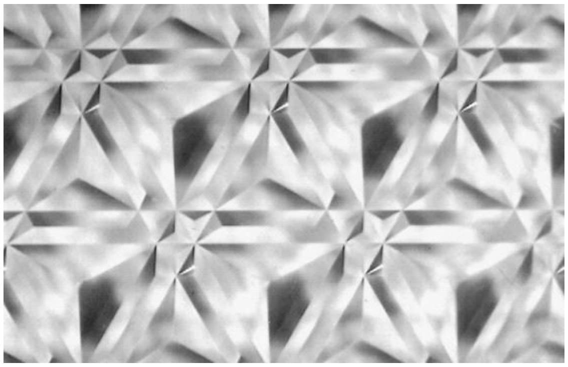

Figure 10: Structured surface of a luminaire for lighting applications.

Using combinations of crossing flycuts, it is possible to generate even more complex surfaces. Figure 10 shows such a complex surface used for luminaries [11]. These complex optical surfaces can be used for light management: (1) coatings that regulate the transmission or reflection of solar radiation based on angle of incidence; (2) films for altering the reflection of light on louvers; and (3) light management for enabling low energy solid state lighting. According to Scott [11] it is also possible to generate integrated optics such as large optics with antireflective (moth's eye type) surfaces integrated into a macro-scale optical mold.

5. MOLDING & MACHINING

Three major shaping operations have been applied to polymer micro-optic components: (1) hot embossing; (2) compression molding; and (3) injection molding. There is significant experience using these methods in conjunction with photolithography to generate the master molds. As described by Gale[32,33], silicon masters generated by photolithography are coated with a conducting layer. Nickel is then electroplated on the silicon to make a second mold. This can then either be used to emboss a polymer or transferred to another mold. This process has been shown to produce nanometer scale features on replicas. The possibility of using diamond turned structures to produce high-quality molded lenses has been demonstrated by Gill and Dow as shown in Figure 11. Some of the challenges with the use of diamond machined molds are: (1) the identification of suitable materials and manufacturing parameters to generate sharp edges and features; (2) the identification of appropriate material combinations for the transfer of the masters to transfer molds and the minimization of errors in these processes; (3) the optimization of three dimensional mold geometries to include draft angles and other features to facilitate molding; (4) identification of releasing agents for metal polymer embossing and other processes. These problems become more important as the advantages of diamond turning are incorporated into designs – particularly high-aspect ratio structures and the incorporation of multiple length scales and aspect ratios in the same component. According to Reflexite Corperation, the molds for embossing of polymer sheet via rolling are produced by diamond machining. The pattern is then transferred to nickel by electroplating. The final production molds are produced by coating the nickel with a polymer that is then UV cured and peeled away from the nickel. The production molds are made from polymer to reduce the costs associated with mold damage due to mishandling which is the leading cause of mold failure. The limitations of using diamond turning for the production of molds is parameter development to reduce burr formation, the reduction of errors induced by the transfer of molds, the production of suitable diamond tools and the design of molds to take advantage of the high aspect ratios and three dimensional structures that can be machined. More research is needed to address these issues.

Another advantage of the use of diamond machining to produce molds is the ability to incorporate long-range kinematic alignment features on the molds. The accuracy of current diamond machine tools could allow alignment of different parts of a mold or the alignment of a second mold and a previously molded part is possible. Interferometric measurements could be made to aid in the alignment of mold components with other devices – perhaps the alignment of a molded lens array with an array of VCELs is a possible example.

6. DISCUSSION

Diamond machining is being applied to the production of molds for microoptic arrays such as retroreflecting polymer tape or adhesive sheet, lenticulars, antireflective surfaces, and systems for light management. Light management guidelines and regulations for the workplace, such as glare reduction for computer screens and management of solar radiation are becoming fairly prevalent in Europe with the United States and the Pacific Rim further behind. Other current high-volume applications include LCD display quality and optics for low energy solid state lighting [11]. Developing and lower-volume applications include the integration of microstructures onto monolithic optical structures, optical fiber alignment, and micro-Fresnel optical arrays (Figure 12): diamond turned molds for macroscopic Fresnel lenses have already had tremendous success in overhead projectors and automotive applications. However these applications do not yet take advantage of many of the capabilities of ultraprecision machining. In particular, all of these structures could still be classified as 2 ½D. As such, they do not take advantage of: (1) the ability to produce true three dimensional structures with an accuracy that can approach 10s of nanometers; (2) the ability to incorporate kinematic alignment features into molds; (3) the ability to generate surfaces with features across multiple length scales and aspect ratios on the same component. Current manufacturing techniques such as photolithography and LIGA do not have all of these capabilities. For example, while gray scale lithography can generate three dimensional smooth contours, the relationship between the resist thickness and the final geometry must be determined empirically. If the geometry can instead be defined in CAD/CAM software, design and modeling capabilities and the ability to develop and test prototypes is greatly enhanced. While LIGA techniques and reactive ion etching can produce high aspect ratio structures, it is difficult to produce components that combine features with vastly different aspect ratios. Unlike in microelectronics, the form of the components is critical to the function of

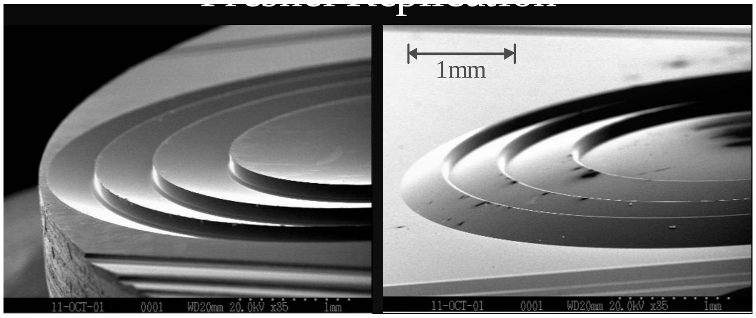

Figure 11: (a) Diamond machined mold and (b) molded PMMA Fresnel optic.

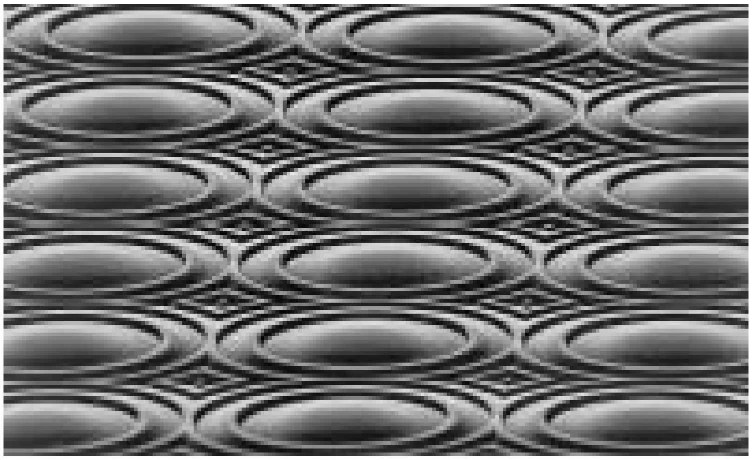

Figure 12: Fresnel optic array (Kodak)

micro-optics and the capabilities of ultraprecison machining are compelling.

One area that does not seem to have been addressed is the use of ultrapresion machining to produce thermooptic and electrooptic devices that would form the basis for electrooptic integrated circuits. Figure 14 provides a perspective on the state-of-the-art telecommunications systems as compared to VLSI technology. The level of integration of today's photonics industry is comparable to that of the electronics industry 30 years ago. In the electronics industry, the development of the integrated circuit through the implementation and continued improvement of photolithography techniques resulted in household solutions that were cost-effective to the average consumer and rendered electronics portable, lightweight, cheap, and reproducibly manufactured.

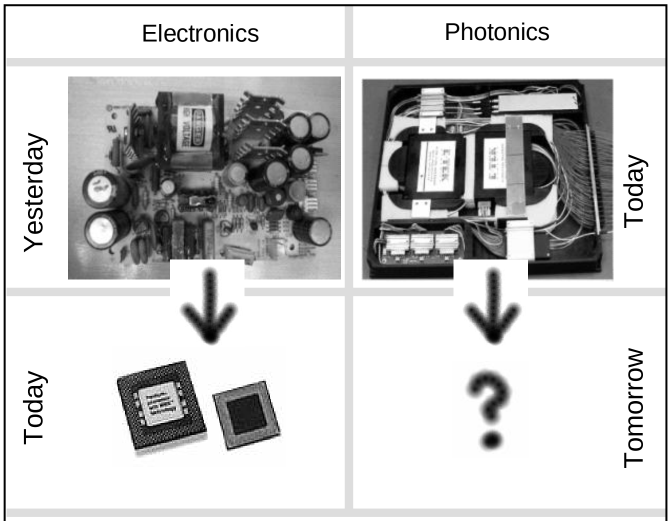

Figure 14: Illustration of the contrast between integrated optics and integrated microelectronics.

While it is natural to think that photolithography or some derivative technology may do for photonics what it has done for electronics, there are significant differences between the two fields. In optics, the *three dimensional* form of the devices is critical to their function while in micro-electronic devices consist of two-*dimensional* conducting lines between essentially *two-dimensional* devices. Photlithography thus lends itself naturally to the production of VLSI devices but not to the production of integrated optics components where three dimensional contours, variable shapes and accurate form are of prime importance. We believe that some combination of mechanical techniques and replication of polymer optics may make a suitable platform for optical integration.

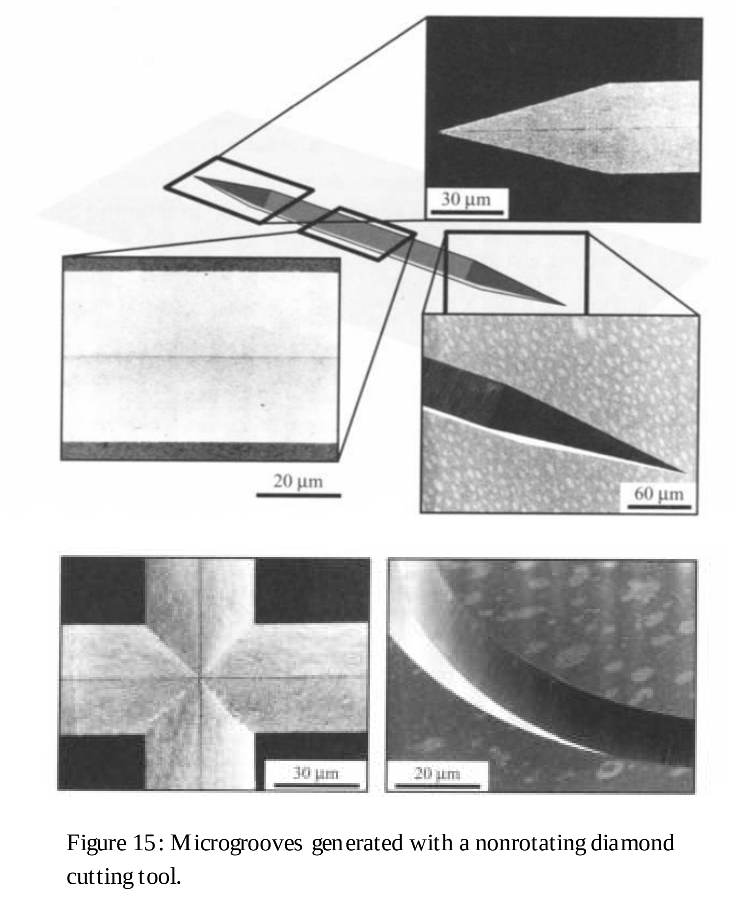

Figure 15: Microgrooves generated with a nonrotating diamond cutting tool.

One possible key to integration is the incorporation of accurately located global kinematic alignment features on macroscale molds that facilitate the alignment of microscale molded optical devices with devices on a substrate. An obvious example that is already receiving some attention is to align microoptics with VCSELs and then to a waveguide array. Takeuchi et al. [8] have demonstrated the ability to generate structures that could be used to mold waveguides using a nonrotating tool. In a method similar to that used in ruling they have produced sharp linear trench structures with widths of 10s of micrometers by slowly moving a single crystal diamond along a surface with two degrees of freedom. Thus one could imagine "drawing out" waveguide structures on a mold with arbitrary geometry under computer control, a method that would be certain to have entertained Ramsden [13].

A final advantage of diamond machining in the molding of optics is the ability to put structures on the surface of three dimensional objects. For example, we have been considering the idea of a vibration sensor or a cylindrical encoder that involves molding of optical structures on the inside and outside of cylindrical structures that make up a rotor and a stator. The rotor optics would reflect light to the stator that would then collect and channel it into waveguides that lead to electronic sensors. The advantage would be that micro-optic sensor structures could be made much more densely than the larger electronic sensors that need to placed a distance away from the system being measured. This could allow the cost effective measurement of the vibrations of objects rotating at high-speed. It obviates the need for expensive lasers or sliprings that would limit the rotational speed or diameter of the structure being measured. It does however require the accurate molding of micro-optic structures on the inner/outer surfaces of cylinders. Sensor applications such as these are of extreme interest due to their immunity to electrical noise.

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