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DIAMOND TURNING - OPENING A NEW LASER DESIGN DOOR(U)
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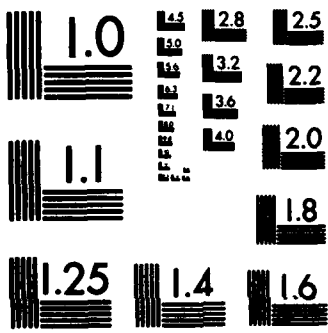


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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS			
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release Distribution Unlimited.			
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE						
4. PERFORMING ORGANIZATION REPORT NUMBER(S) FJSRL-JR-80-0003			5. MONITORING ORGANIZATION REPORT NUMBER(S)			
6a. NAME OF PERFORMING ORGANIZATION Frank J. Seiler Research Lab		6b. OFFICE SYMBOL (If applicable) FJSRL/NH	7a. NAME OF MONITORING ORGANIZATION			
6c. ADDRESS (City, State and ZIP Code) USAF Academy Colorado Springs, CO 80840			7b. ADDRESS (City, State and ZIP Code)			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER			
8c. ADDRESS (City, State and ZIP Code)			10. SOURCE OF FUNDING NOS.			
			PROGRAM ELEMENT NO. 612305	PROJECT NO. 2305	TASK NO. F2	WORK UNIT NO. 70
11. TITLE (Include Security Classification) Diamond Turning - Opening a New Laser Design Door (U)						
12. PERSONAL AUTHOR(S) Saito, Theodore T.						
13a. TYPE OF REPORT Presentation		13b. TIME COVERED FROM Jan 80 to Jul 80		14. DATE OF REPORT (Yr., Mo., Day) 1980 December 18		15. PAGE COUNT 7
16. SUPPLEMENTARY NOTATION Presented to Lasers 80, New Orleans, LA, Dec 80						
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)			
FIELD	GROUP	SUB. GR.	Diamond Turning; Large Optics Diamond Turning Machine (LODTM)			
2005	2006					
19. ABSTRACT (Continue on reverse if necessary and identify by block number) This paper will be of special interest to those wanting to find out about diamond turning. The history and development of diamond turning is reviewed including personal insights from being with the technology from its earliest stages. Applications which have demonstrated the unique capabilities and accuracies for difficult geometries are given. The state-of-the-art review includes accuracies, sizes, and weights. Developing diamond turning production capabilities and the impact of the DOD Manufacturing Technology Transfer program is summarized. Rules of thumb and insights into when diamond turning or other optical fabrication techniques should be used are also given. Future laser resonators may depend on diamond turning for axicon, reflaxicon, and waxicons. The DARPA sponsored Large Optics Diamond Turning Machine (LODTM) is summarized. LODTM will have a capacity for 1.6 m diameter parts to be machined to 2.0 u" (500 A) rms figure accuracy.						
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input checked="" type="checkbox"/> DTIC USERS <input type="checkbox"/>			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED			
22a. NAME OF RESPONSIBLE INDIVIDUAL THEODORE T. SAITO			22b. TELEPHONE NUMBER (Include Area Code) (303) 472-3120		22c. OFFICE SYMBOL FJSRL/CC	

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DIAMOND TURNING-OPENING A NEW LASER DESIGN DOOR

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ABSTRACT

This paper will be of special interest to those wanting to find out about diamond turning. The history and development of diamond turning reviewed including personal insights from being with the technology from its earliest stages. Applications which have demonstrated the unique capabilities and accuracies for difficult geometries are given. The state-of-the-art review includes accuracies, sizes, and weights. Developing diamond turning production capabilities and the impact of the DoD Manufacturing Technology Transfer program is summarized. Rules of thumb and insights into when diamond turning or other optical fabrication techniques should be used are also given. Future laser resonators may depend on diamond turning for exicon, reflexicon, and waxicons. The DARPA sponsored Large Optics Diamond Turning Machine (LODTM) is summarized. LODTM will have a capacity for 1.6 m diameter parts to be machined to 2.0 μ " (500 A) rms figure accur

INTRODUCTION

This paper will briefly review diamond turning of optics background the technical stimuli that initiated our interest. A few specific examples of diamond turned components will be given not only to show the accuracies that can be obtained, the resulting design flexibility, but also the wide fields of applications besides optics. I also discuss diamond turning in use. We'll see how cost savings has been a major driver for the DoD's diamond turning commercialization program. I will summarize some of the manufacturing technology programs with details about the Precision Machining Commercialization (PMC) program sponsored by the Air Force and the Army. Results of the commercialization program have been very encouraging as can be seen by the number of organizations that now can do diamond turning and accuracies they achieve. The state of the art will be summarized. Finally I will give a brief description of the Large Optics Diamond Turning Machine, (LODTM) being developed by the Lawrence Livermore National Laboratory. This machine will achieve accuracies of better than 50nm (2 μ) for diameters up to 1.6 meters.

BACKGROUND

Diamond turning of optics is the use of a diamond tool on a precision lathe under very precisely controlled machine and environmental conditions to fabricate a finished optical component. (1, 2, 3, 4) It is also known as micromachining and precision surface generation (PSG). The technology was primarily developed in the Department of Energy (formally the Atomic Energy Commission). There were two major developments which impacted diamond turning. One was the air bearing spindle developed at Y-12. (5) The air bearing provided the crucial very smooth rotation. Rotational accuracies on the order of 25 nm are now possible. A second major development was the incorporation by the

Lawrence Livermore National Laboratory of the air bearing spindle on a Moore Measuring machine (6). Livermore took advantage of the very accurate motions of the X and Z axes and combined that with the accurate rotation of an air bearing spindle. The crucial element of diamond turning is the single point diamond tool. A gem like quality diamond fabricated in the shape of a tool will cut without a built up edge and with minimal tool wear on compatible materials. Wherever the tool is directed a resulting surface (a figure of revolution) is cut. Therefore the accuracies that one can achieve for the motion of the tool relative to the work piece are translated directly into work piece accuracies. This technology now makes components feasible with an accuracy of a few microinches.

In 1973 Dr. Reichelt brought a diamond turned mirror to my laboratory to have the 10.6 micrometer reflectivity measured. We were startled to find the reflectivity of a machined piece of copper to be about 99%. Some of the best 10.6 micron reflectivities that I had measured on metal (even ultra-high vacuum deposited on surfaces smoother than 20 Å rms) were just in excess of 99%. (1) The technical stimulation for diamond turning therefore was the high reflectivity and the exciting possibility of cutting figures of revolution and freeing ourselves from the constraint of conventional optical fabrication techniques. (1) The Los Alamos Scientific Laboratory and the Air Force Weapons Laboratory funded development efforts to improve the figure accuracy and the surface finish of diamond turned optics. These programs centered on the deterministic philosophy to find what portions of the machine were limiting the accuracy and then improving these components to get better accuracy. If the errors were repeatable, they were sometimes compensated for. Of course the preferred technique was error removal. These development programs were primarily at the Y-12 plant at Oak Ridge, Tennessee. There were other developments going on in parallel at the Lawrence Livermore National Laboratory.

EXAMPLES Let us now consider several examples demonstrating the accuracy and flexibility that diamond turning makes available. In conjunction with the University of California at Berkeley, LLNL diamond turned and polished an extreme ultraviolet telescope which was used in astrophysical studies. (7) The optical components of this telescope were first coated with electroless nickel, then diamond turned and finally polished. It was polished to minimize the diamond turning marks and smooth the surface for the very short extreme ultraviolet wave lengths. Another interesting example is a linear compound axicon, also called a waxicon. This 30 cm (12") diameter optic was cut from a single piece of copper. It is composed of two axicons, one concave, the other convex. Both are 90 degrees in angle. The sides are straight to better than 125 nm peak-valley (5 μ"). The angle between the concave and convex cone was accurate to better than 2 arc seconds. This linear waxicon is an interesting demonstration of machining an optic with a single degree of freedom cuts. The concave section was cut using the x-axis drawn in a straight line and then the X-axis was stopped and locked and the convex section was cut using the Z-axis drawn in a straight line. The accuracy of the angle between the concave and concave section results from the accuracy of the alignment of the X & Z axis. The last example is a compacting Gaussian waxicon. This optic transforms an incoming annular beam of uniform intensity into an outgoing beam which is Gaussian in intensity. This waxicon is not described by a closed form equation. In fact the shape was designed by a computer which satisfied the two

boundary conditions of (1) having an Gaussian intensity output and (2) having all the rays have the same pathlength to conserve phase. This piece was cut to an accuracy better than $1\frac{1}{2}$ waves in the visible. (7) In addition to optical components another interesting application of diamond turning is millimeter waveguide parts for traveling wave tube (TWT). Diamond turning these parts not only present a possibility of saving money but also reducing assembly time by making each part both more accurately and reproducibly (to better than 250 nm)(10 microinches).

Materials that are presently compatible with diamond turning include metals (aluminum, brass, electroless nickel, copper, beryllium copper, gold, silver, platinum, and lead), transparent materials (plastic and lithium niobate), infrared materials (zinc selenide, zinc sulfide, germanium, NaCl, KCl, CaF₂, SrF₂ and silicon).

Although some work at Livermore to diamond turned glass has been promising, glass optical components have not yet been diamond turned by Livermore. Also ferrous materials are incompatible with diamond turning.

Why does diamond turning save money? Whereas spherics (and flat) are natural geometry for conventional polishing techniques, aspheres and optics with critical geometric specifications require expensive craftsmanship. The hours and hours of time that are required to make special optics can often be saved by diamond turning. Cost saving estimates for diamond turning have run to the millions and millions of dollars. However one must be careful about using diamond turning in all situations. Diamond turning is more economical when, (1) aspherics are required (2) there are unusual geometrical constraints. These unusual geometric constraints are:

a.CENTERING: Spheres are easier and more economical to polish, than diamond turn. However if that sphere must be centered very precisely, for example when it is used in conjunction with an asphere, then diamond turning may be more economical. (9)

b.ANGLES: Consider a rectangular mirror which has sides that are flat to a half wave in the visible. (10) This flatness requirement is not difficult to achieve in polishing, however the sides must also be oriented to each other within 2 arc seconds accuracy. Achieving flatness in conjunction with angular accuracy drives the cost of this mirror up. In fact Honeywell Electro-Optic Center has been able to save \$500,000 (10) using diamond turning instead of polishing.

c.REPEATABILITY AND SIZE: Diamond turning may be more economical to put on simple surfaces such as flat or spheres when the total size of the part are important. Precise and repeatable size makes optical assembly easier. What we are seeing then is that reduced aspheric fabrication costs plus improved accuracy and performance are resulting significant design flexibility. Whereas designers in the past were constrained from including aspherics because of fabrication cost, they are being driven to using aspherics because of the needs for higher resolution and weight reduction. (Reducing the number of spherical components) Diamond turning makes it feasible and in fact attractive to include such aspherics in their systems.

DIAMOND TURNING IN USE

Surveys of various organizations have shown that optics are often times the leading cost driver and schedule constraint for major programs. An Air Force industry-electronics-manufacturing-cost-reduction study estimated that \$120 million savings in electro-optics was possible. In addition to applying diamond turning to lasers there were needs for optics in the Army and the Navy which would benefit from diamond turning. Therefore the Air Force Materials Laboratory established a program "Manufacturing Technology for Precision Machine Tool Technology. A major portion of this program was the Precision Machining Commercialization (PMC) Program at the Lawrence Livermore National Laboratory. The objective of this program, funded by the Air Force and the Army, was to stimulate industry interest in DOD application of diamond turning and to expedite the technology transfer as to reap more immediate cost savings.

PMC had four major tasks. The first task was documentation. It was necessary to have written descriptions of important diamond turning components and technologies. Another very important aspect of documentation was an estimate of the associated cost. This data was needed by management considering diamond turning, since the estimated cost was about \$1 million. The second task was seminars and workshops. These seminars got experts in the field together with engineers and appropriate management people to discuss the technology and the advisability of getting involved in diamond turning. Workshops were designed to give hands-on experience in the how-to's of diamond turning. Attendance was limited to 15-20 attendees to foster personal interaction and individual instructions. To stimulate the participation of machine tool builders, one workshop was held at each of the major diamond turning machine manufacturers. The third task was technical assistance which included specific advice on diamond turning demonstration parts or one-on-one discussions of diamond turning applications. The fourth task was consulting. This involved actual machine tool checkouts and real time problem solving which was holding up production.

The results of PMC have been very encouraging. Honeywell has benefited from PMC inputs and is now producing diamond turned optics. Kollmorgen has formed the (IntOp) division devoted to diamond turning. In addition there are now two major organizations offering turnkey diamond turning machines. One is the Moore Special Tool Company and the other is Pneumo Precision Inc. Present diamond turning capabilities are summarized in Table 1.

THE LARGE OPTICS DIAMOND TURNING MACHINE

The large optics diamond turning machine is a next generation machine being built especially for axicon-like optics. Dr. Robert Donaldson of the Lawrence Livermore National Laboratory is the project leader for this program which is being funded by the Defense Advanced Research Project Agency (DARPA). The goal is to machine a 1.6 meter diameter optic to an accuracy of better than 50 nanometers (microinches) rms. The maximum weight of the work piece and fixture is 1000 kilograms (2200 pounds). LODTM incorporates state-of-the-art technology. This will include a vertical spindle axis, a bridge construction and real time tool path methodology with laser interferometry. It also will include a metrology frame from which measurements will be taken to achieve this extremely tight accuracy

tolerance. Interesting innovations for LODTM are a traction drive roll positioning system and the possible use of a control system to compensate for spindle error on each revolution for the spindle errors.

CONCLUSIONS

Diamond turning is an accepted optical fabrication technology. Today designers are starting to take advantage of the flexibility it gives. Commercial production capability for infrared optics now exist as especially well demonstrated by Honeywell. In the future optical designs will be incorporating more and more aspherics. Because of these unusual shapes that will now be possible, optical metrology will become more complicated. Finally LODTM will push the state-of-the-art accuracies to bigger dimensions and have spin off improvements for smaller diamond turning optics.

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TABLE 1

"SUMMARY OF DIAMOND TURNING CAPABILITIES"

SURFACE FINISH (P-V) ORGANIZATION CURVED	MAX		MAX		NUMBER		FIGURE ACCURACY	
	DIAMETER	WEIGHT	OF MACHINES	W/NC	W/UNC	(P-V)	FLAT	CONTOUR
m	MM	KG	W/O	W/O			m	m
	m							
	W/NC	NC	W/NC	NC				
APPLIED OPTICS S.M.D. DIVISION 6 3	280 25	400	23	45	2 4	3	0.08	0.08
BATELLE PACIFIC 7.5 NORTHWEST LAB (-X)	1,000 7.5	-	230	-	1	0	0.5	0.5
BELL & HOWELL -	380 20	-	35	-	2	0	0.5	0.5
HONEYWELL 2.5 ELECTRO-OPTICS	400 75	360	45	45	2	1	0.3	0.5
INTOP 10	300 20	460	90	90	1	4	0.1	0.1
LOS ALAMOS 25 SCIENTIFIC LAB	810 50	-	180	-	3	0	0.1	0.15
LAWRENCE LIVER- MORE NATIONAL LAB 50	1070 75	305	180	68	2	2	0.1	0.1
MOORE SPECIAL 35 TOOL	- 100	-	90	90	1	1	0.1	0.5
PNEUMO PRECISION 25	360 75	500	45	68	1	3	.3	.6
TINSLEY ?	2,600 ?	?	135	?	1	?	?	?
Y-12 PLANT 7.5	2,032 50	-	545	-	6	1	0.8	0.8

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