Enabling Technology:

A 3 meter capacity diamond turning machine will be enabling technology for low cost fabrication of x-ray telescope optical components.

Three Meter Capacity Diamond Turning Machine For X-Ray Telescope Components

Submitted by:
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The technology readiness level (TRL) for this technology is 5 to 6.

Based on previous experience of building a similar machine and facility the rough order of magnitude cost to establish the proposed capability to manufacture and certify x-ray mirror glass slumping mandrels meeting IXO specifications will not exceed $300M.

Identification and Significance of the Enabling Technical Innovation

The ranking of IXO as the fourth-priority large space mission in the National Academy Astro2010 Decadal Report reflects the technical, cost, and programmatic uncertainties associated with the project at the current time. A major emphasis in achieving a successful IXO is reducing the cost of the grazing incidence mirrors.

Diamond turning has been proven to be able to produce highly aspheric optical contours to visible wavelength tolerances with extremely smooth surfaces. Diamond turning has the additional enabling capability to not only produce extremely smooth and accurate optical surfaces but also mechanical attachment surfaces and datums which allow extremely fast and complex optical components to be quickly and easily aligned. The productivity of diamond turning allows the production of quantities of optical components with exacting duplication of optical surfaces and metrology datums. Diamond turning has been utilized to produce X ray and synchrotron radiation grazing incidence optical components for many years.

The majority of grazing incidence optics made by diamond turning have involved diamond turning metal substrates that are plated with high phosphorus electroless nickel. Electroless nickel can be directly diamond turned to a roughness of 50nm rms and subsequently polished to better than 30nm rms.

The IXO Wolter-Type I x-ray telescope optical design consists of about 14,000 0.4mm thick glass mirror segments densely packed into a 3.2m diameter and supported with micron level accuracy and stability. These grazing incidence surfaces are made of thin borosilicate glass sheets that are slump formed on highly polished mandrels.

Ultra precision turning machines capable of diamond turning 3 meter optical mirror optics can be built. The glass slumping mandrels required for IXO would be segments mounted on a large fixture so that multiple mandrels of a particular radius and contour can be produced at one time. Figure 1 is a Dallas Optical Systems, Inc./ Moore Tool concept for a 3 meter capacity diamond turning machine shown with 16 electroless nickel plated super alloy slumping mandrels on the machine.

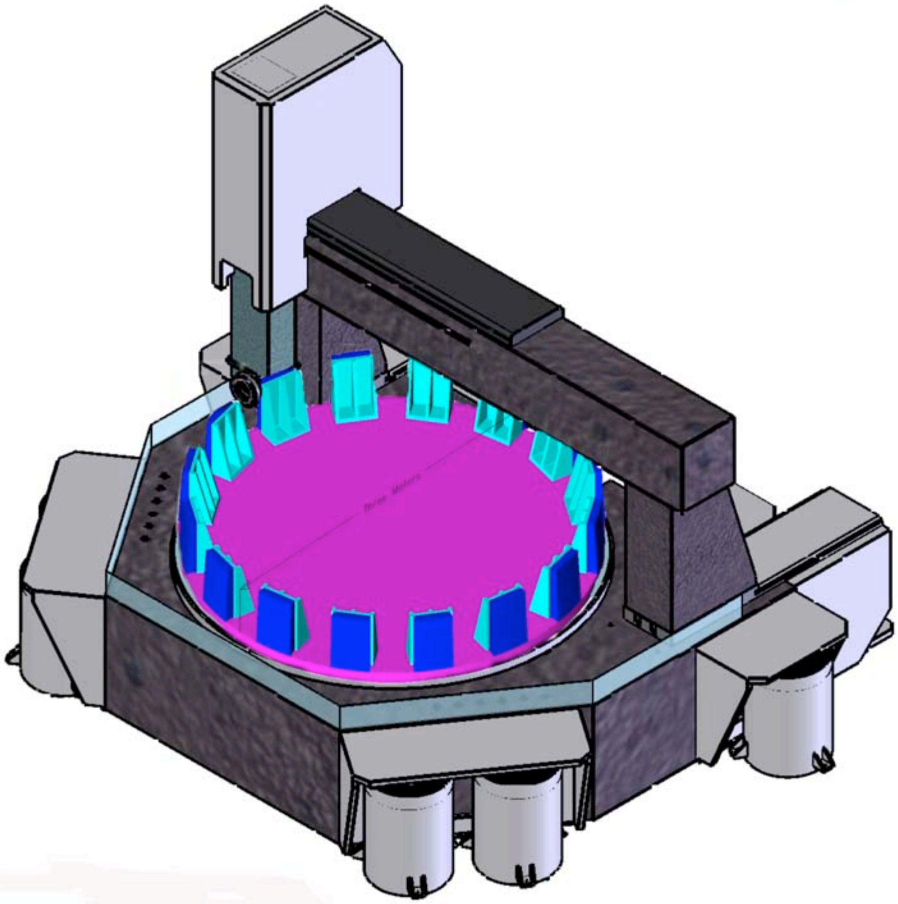

Figure 1. Concept drawing of DOS/Moore Tool Co. 3 meter capacity diamond turning machine with 16 super alloy slumping mandrels utilizing the 20,000 lb. load capacity air bearing spindle.

The use of ultra precision turning to produce glass slumping mandrels meeting the 5 arc second requirement of the IXO means that the mandrel material must meet a number of property requirements as follows:

- **very high dimensional stability under repeated cycle of heating to 600 C.**
- **acceptable thermal expansion match with borosilicate glass.**
- **suitably machineable with diamond or other cutting tools to high dimensional accuracy.**
- **suitable for polishing to extreme smoothness.**

Electroless Nickel plated Super Alloys Meet These Essential Material Requirements

Super alloys designed for exceptional dimensional stability and strength under continuous cycling to high temperatures have been under continuous development for use in turbine engines for many years. Some of the super alloys are tailored to exhibit significantly lower thermal expansion compared to common stainless steel. The thermal expansion can be in the range of the expansion of the borosilicate glasses used for X-Ray mirrors. These super alloys have a thermal expansion which is very close to the expansion of high phosphorus electroless nickel plating (12μm/m/C).

Because diamond turning can produce mandrels with extremely repeatable contour accuracy, the process allows manufacture of mandrels which can be adjusted in dimension to compensate for the thermal expansion of the borosilicate glass and the mandrel so that the curvature of the slumped glass can be adjusted. Any number of slumping mandrels can be produced with exactly the same contour with repeatability of approximately 1/100 wave visible light. This uniformity and rapidity of production of a relatively low cost mandrel will be enabling technology for IXO mirror fabrication.

A partial list of available super alloys is shown in Figure 2 below. In Figure 3 a comparison of thermal expansion of selected super alloy steels is shown with the properties of two types of borosilicate glass material that are supplied as high technology glass sheets.

Alloy group	Material	Hardness HV		Approximate contents in %											
		Ann.	Aged	Ni	Cr	Co	Fe	Mo	W	Nb	C	Mn	Si	Al	Ti
Nickel CMC 20.2	**Inconel 718**		425	52,5	19,0	1,0	19,0	3,0			0,04	0,4	0,9	0,9	0,9
	Inconel 706		285	42,0	16,0		40,0				0,03	0,2	0,3	0,4	1,8
	Inconel 625	200		62,0	21,5		5,0	9,0			0,04	0,5	0,5	0,4	0,4
	Hastelloy S			67,0	16,0		3,0	15,0			0,02	0,5	0,4		
	Hastelloy X	160		47,0	22,0	1,5	18,0	9,0	0,6		0,10	1,0	0,5		
	Nimonic PK33		350	55,9	18,0	14,0	0,5	7,0			0,05	0,3	0,3	2,1	2,2
	Udimet 720			56,0	16,0	14,7		3,0	1,3					2,5	5,0
	Waspaloy			58,0	19,0	13,5	0,8	4,5			0,07	0,1	0,1	1,4	3,0
Iron CMC 20.1	**Greek Ascoloy**		300	2,0	13,0		80,0	0,2			0,15	0,4	0,3		
	A286		300	25,5	15,0		56,5	1,3						0,2	2,0
	Incoloy 909			38,0		13,0	42,0			4,7			0,4		1,5
Cobalt CMC 20.3	**Haynes 25**			10,0	20,0	51,0	3,0		15,0		0,10	1,5	0,4		
	Stellite 31	280	340	10,5	25,5	56,0			7,5		0,50				

Figure 2. Chemistry of various heat resistant super alloys

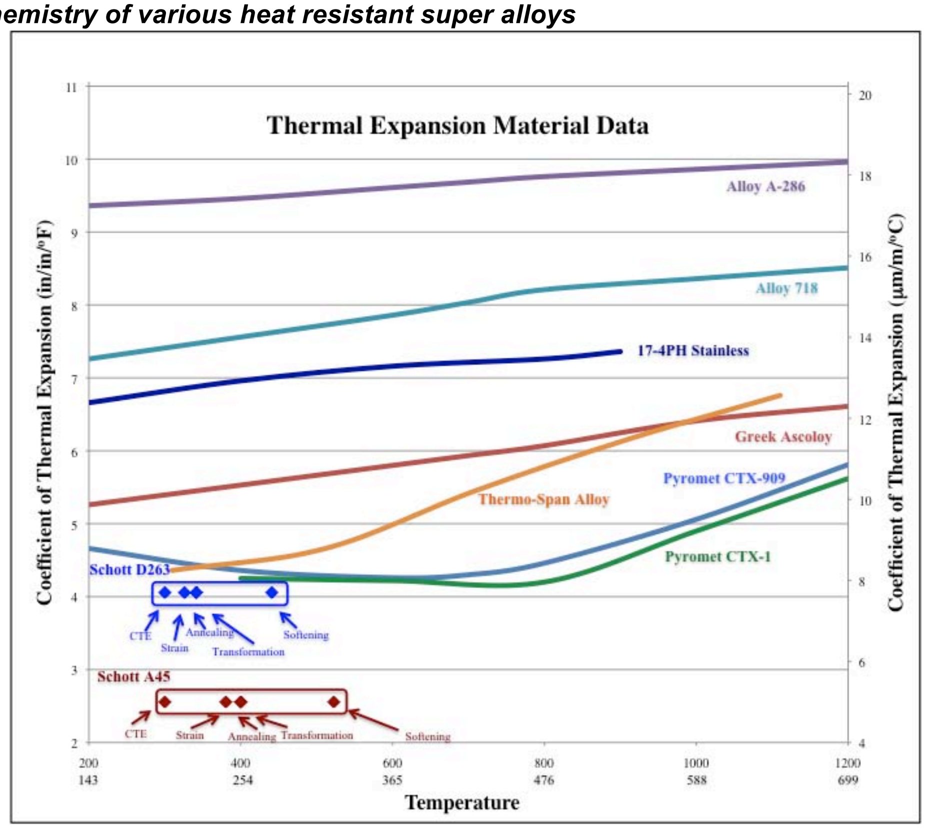

Figure 3. Thermal expansion comparison of various high temperature super alloys and Schott D263 and A45 borosilicate glasses

Large Scale Diamond Turning

Diamond turning has been proven to be capable of producing highly aspheric optical contours to visible wavelength tolerances with extremely smooth surfaces. The major shortcoming of this highly efficient manufacturing technology is that very high quality diamond turning is generally restricted to apertures of less than 0.5 meter. The very large aperture optical systems such as IXO are impossible to produce using diamond turning technology that exists today for the simple reason that large diamond turning machines capable of machining large optics do not exist. This is because there is no air bearing spindle available with the load capacity to carry the combined weight of the optical component and the much heavier part holding fixture required for successful optical quality machining. Although conventional vertical lathes exist that can turn parts as large as 6 meters in diameter, ultra precision turning machines capable of diamond turning 3 meter optical mirror optics do not exist. The large diamond turning machines that have been built all have oil hydrostatic work spindles. Lathe turning of very large diameter parts of any kind is best done on machine tools with a vertical axis of work piece rotation. The very large spindle load capacity required is only practical with large bearing surfaces of large diameter turn tables.

Oil Hydrostatic Spindles: Because viscous shear frictional heating increases with the 4th power of the bearing radius, oil hydrostatic machining spindles are kept small in diameter for high speed applications. Large oil hydrostatic spindles must turn very slowly to avoid unacceptable heat generation even with water cooling of the bearing. Examples of this type of unsuccessful diamond turning machine are the recently scrapped Large Optics Diamond Turning Machine (LODTM) built by Lawrence Livermore National Laboratory which is limited to a maximum rotational speed of only 52 rpm and a large diamond turning machine built by Toshiba Company in Japan which is limited to about 80 rpm. The capacities of these machines were about 1.5M and 2M respectively.

Air Bearing Spindles: A solution to this spindle problem is to use air bearing spindles. The viscosity of air is more than three orders of magnitude less than the thinnest oil, therefore the frictional heating of large diameter air bearings is very small and very manageable. A formidable manufacturing problem with large air bearings is that the extremely low viscosity of air requires that the thickness of the bearing film is also very small. Bearing clearance of about 5 micrometers means that the required accuracy of form and dimensions of air bearing components is extremely difficult to achieve. While the manufacturing precision required for oil hydrostatic bearings is within the capability of a very good conventional machine shop, the extreme precision required for air bearings is in the realm of optical tolerances.

Classical air bearings utilizing two metal surfaces fail in large sizes because of the tendency of metals to friction weld together in the event of the slightest touch or electrical arcing. The required air film thickness of 5-8 microns makes this fatal touching inevitable in large bearings. The solution to this problem is to make large vertical air bearings with hard metal journals running against porous graphite bearing surfaces. Porous graphite air bearings do not friction weld in the event of the spindle bearing surface contacting the bearing journal surface, the result is only slight polishing of the graphite surface. The porous graphite flow structure provides extremely uniform flow of the air film and the tortuous flow path acts to damp the flow induced dynamic instability that is a serious concern in both oil and air hydrostatic bearings.

Porous Graphite Air Bearings

The Dept. of Energy Oak Ridge Y-12 Plant in Oak Ridge, Tenn. developed porous graphite air bearing technology to meet their needs for super precision bearings over a period of 30 years. Figure 4 is a photo of a 2 meter capacity diamond turning machine at the Y-12 Plant with eight 16” diameter off-axis parabolas on the air bearing spindle.

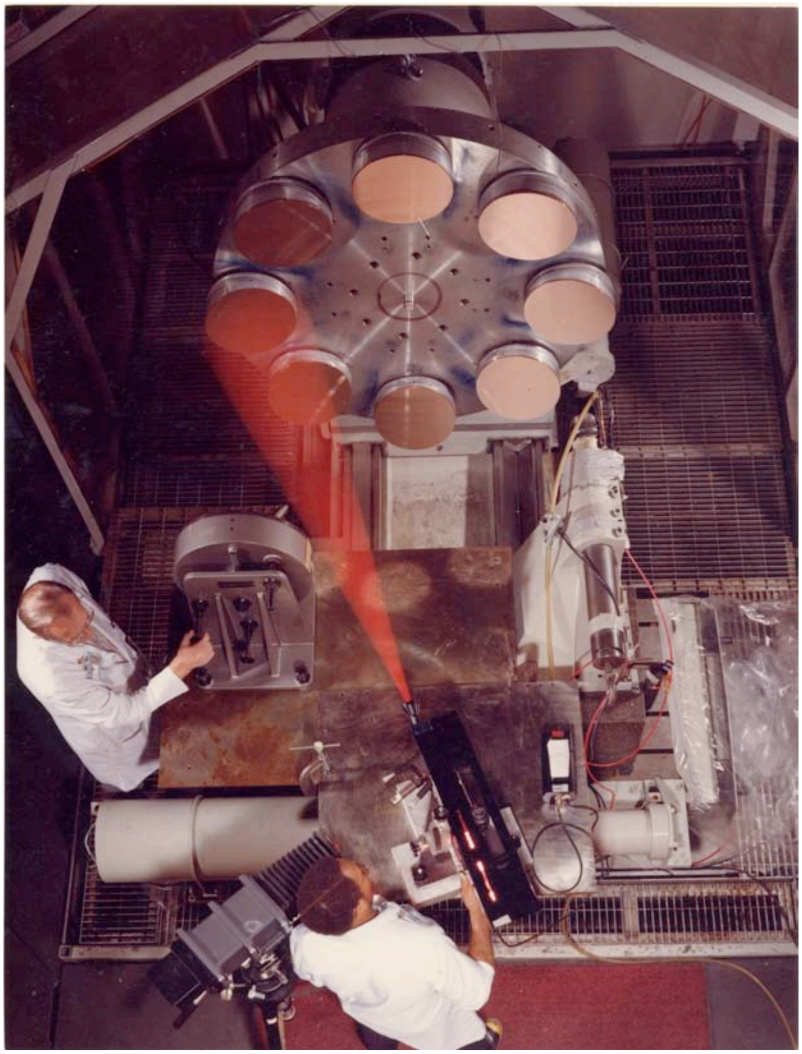

Figure 4. A large diamond turning machine at the Oak Ridge Y-12 Plant equipped with a large capacity porous graphite air bearing was used to diamond turn 16" (0.4M) diameter off-axis parabolic mirrors for laser fusion research. Peak to valley contour accuracy achieved was 1/8 wave at 633nm.

John Casstevens worked seven years as a development engineer at the Oak Ridge Y-12 Plant during which time he engineered and built a number of porous graphite air bearings for diamond turning machines and extended the air bearing technology resident in Y-12 at that time. When Casstevens left the Y-12 Plant and joined Optic-Electronic Corporation in Dallas, Texas he brought his years of experience at diamond turning highly aspheric optical components and experience at building diamond turning machines to that company. At OEC he directed the design and construction of a large diamond turning machine by Moore Tool Company of Bridgeport. Conn. That 2 meter capacity machine was installed in a state of the art temperature and vibration controlled room. The M-40 Moore diamond is shown in Figure 5 with a 1.5 meter diameter diamond turned aluminum spherical mirror on the oil hydrostatic spindle.

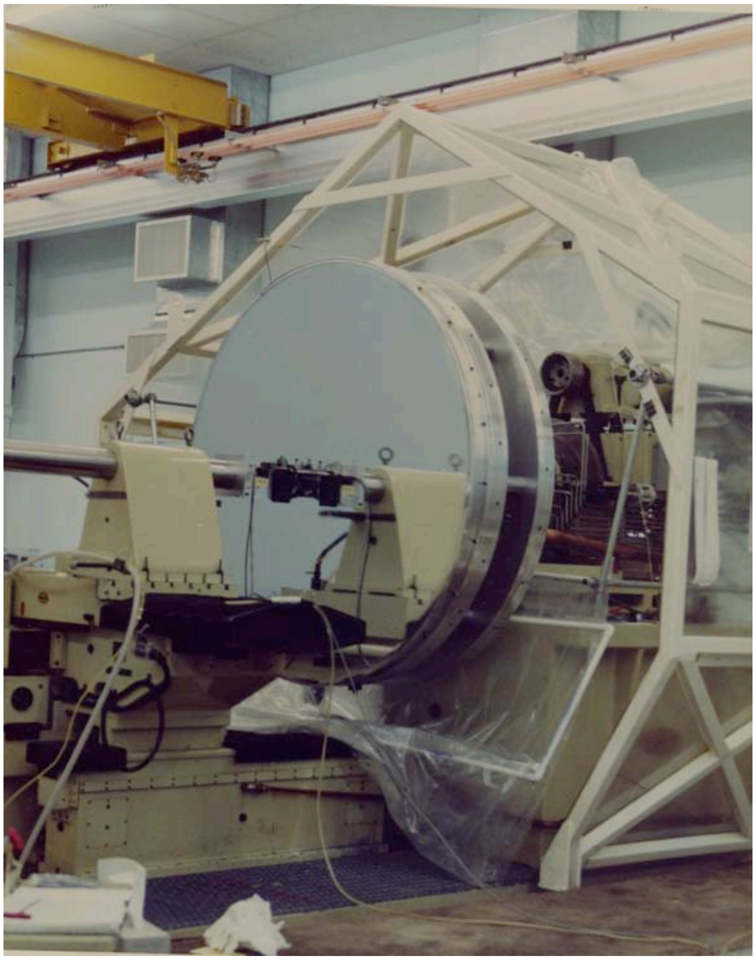

Figure 5. Moore Tool Co. M-40 2 meter capacity diamond turning machine built for John Casstevens at Optic-Electronic Corp. Shown here with a1.5 meter diamond turned aluminum spherical mirror.

Moore Tool Co.

The PMT Group, symbol for Producto and Moore Tool, is comprised of three primary operating companies – Producto Corporation, Moore Tool Company and Moore Nanotechnology Systems. Moore Tool Co. will work with DOS to build large diamond turning machines based on the Moore/DOS concept a diamond turning machine that would incorporate the large air bearing spindle to be built by DOS. The new design Moore 3 meter capacity diamond turning machine will have a working load capacity of approximately 10,000 Kg (22,000 lb.). By utilizing an air bearing spindle, the diamond turning machine will have a rotational speed capability of 1000 rpm for machining of small diameter parts.

The combination of years of DOS experience with the fabrication of porous graphite air bearings, a DOS in-house capability to do large size diamond turning as well as massive part lapping gives DOS a unique capability to develop this type of large air bearing.

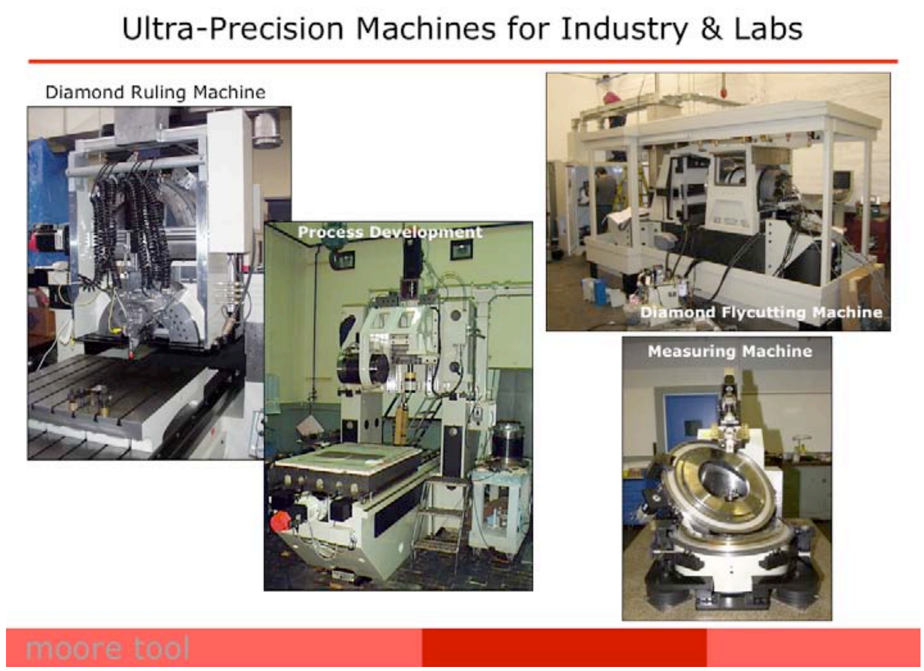

Figure 6. Photos of the many special purpose ultra-precision machines built by Moore Tool Co.

Moore Tool Co. builds large diamond turning machines using small diameter oil hydrostatic spindles in both vertical and horizontal orientations. These large granite based diamond turning machines are used for turning cylindrical drums for the printing and screen products industries. Moore Tool Co.'s Moore Nanotechnology Inc. located in Keene, NH. Is a world famous leader in state of the art diamond turning machinery.

Figure 7. Large Moore granite base horizontal spindle diamond turning machine with oil hydrostatic spindle.

Figure 8. Large Moore vertical diamond turning machine using a vertical oil hydrostatic spindle.

Spindle Requirements Defined:

A study of optical mirror component projected needs was done with consideration of the size and weight of part fixturing and inspection required to fabricate various metal and ceramic mirror components as large as 3 meters in diameter. The weight requirement for the spindle to be used in a large diamond turning machine capable of diamond turning 3 meter diameter mirrors was set a maximum load capacity of 18,000 kg (40,000 lb.) with a working load of 10,000 Kg (22,000 lb.). The spindle must be capable of speeds of at least 1000 rpm to enable turning of smaller diameter components. Figure 9 is a CAD model of the prototype porous graphite air bearing spindle designed and 90 percent completed under a NASA Phase I SBIR. This prototype air bearing spindle should have a working load capacity of around 8000 lb.

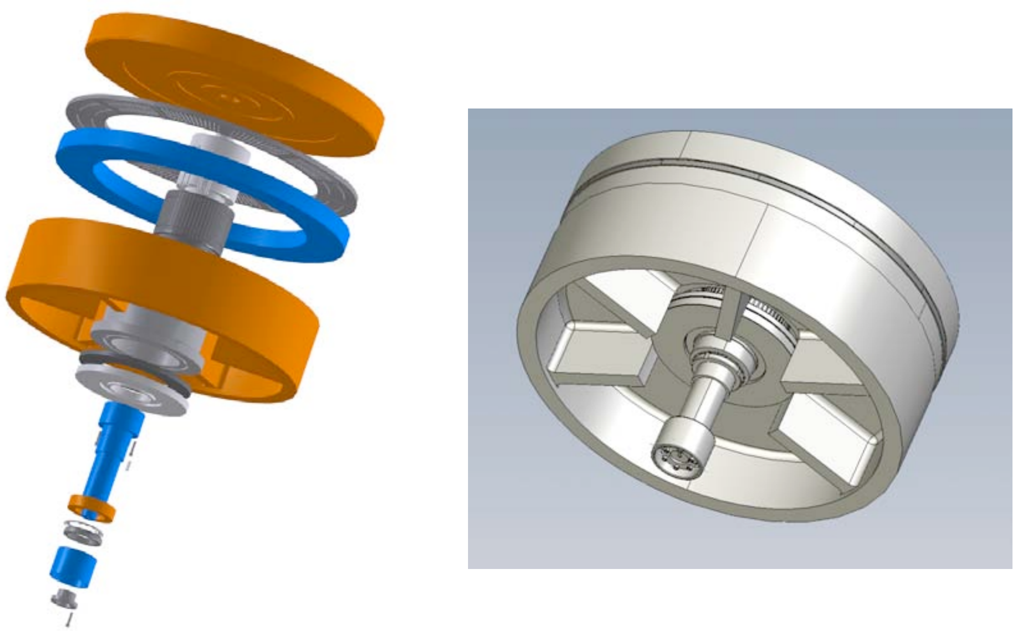

Figure 9. CAD model of prototype air bearing spindle.

Figure 10 is a view of deflection FEA calculations for a concept of the Ten Ton Capacity Air Bearing Spindle (TTCABS) faceplate.

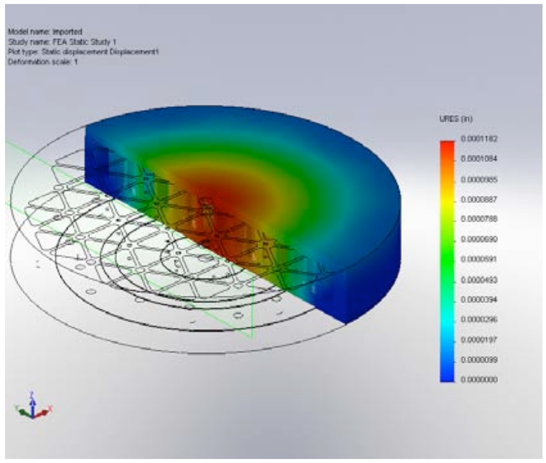

Figure 10. Finite element stress analysis of a TTCABS face plate concept.

Part 5: Diamond Turning of IXO Slumping Mandrel at DOS

In 2009 DOS fabricated a test mandrel for the IXO project at Goddard Space Flight Center which was made from electroless nickel plated 17-4PH stainless steel. Figures 11 and 12 are photos of this test mandrel on a DOS diamond turning machine.

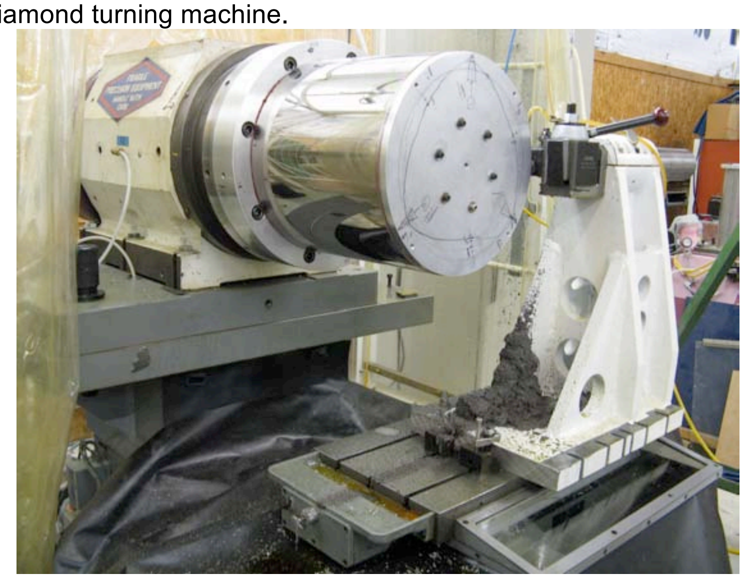

Figure 11. Single point diamond turning electroless Ni plated stainless steel slumping mandrel.

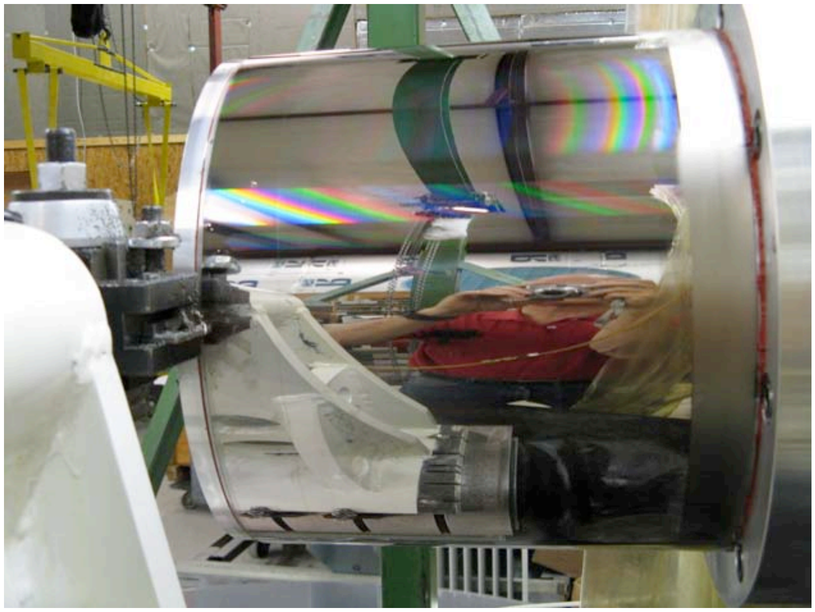

Figure 12. Electroless nickel plated 17-4PH stainless steel IXO test mandrel on a DOS diamond turning machine.

Figure 13 is a photo of this mandrel after removal from the diamond turning machine.

Figure 13. Diamond turned IXO test mandrel. 298mm long x 337.4mm diameter tapered cone.

This mandrel was measured by NASA GSFC and found to have very small slope and roundness errors which would be better than the specifications for the 5 arc second requirement of IXO. Unfortunately the test mandrel substrate material heat treatment was not adequately considered since the purpose of the test mandrel was to evaluate accuracy that might be achieved by diamond turning. The heat treatment chosen for the test part was selected for maximum hardness to enhance the machineability of the substrate in preparation for electroless nickel plating. When the test mandrel was heat cycled in the 600 C slumping process the mandrel exhibited unacceptable distortion. In fact the 600 C slumping cycle is roughly the same heat treatment used to produce a more dimensionally stable condition but which also results in significant shrinkage in reaching the more stable condition. This effort has triggered an SBIR proposal to utilize the existing manufacturing learning curve to develop a reliable material and manufacturing process for glass slumping mandrels. This development process will involve the following technology investigations and development goals:

-developing electroless nickel plating processes compatible with various super alloys,
-ultra precision machining of super alloys and polishability of super alloys.
-diamond turning of electroless nickel plating before and after the mirror slumping heat cycle.
-heat treatment to obtain best long term dimensional stability under repeated thermal cycling.
-evaluation of oxidation effects on surface smoothness of directly polished super alloys.
-evaluation of oxidation effects on surface smoothness of polished electroless nickel.

The slumping process heating will cause changes in the hardness of the electroless nickel plating as a function of phosphorus content. The effort will evaluate the metallurgical heat treatment and plating processes by producing a number of flat test mirror samples which will be measured optically before and after the IXO glass slumping process cycle to evaluate the effects of the slumping process on the mandrel including contour distortion, oxidation resistance, increase in surface roughness, change in diamond machineability of the electroless nickel plating. The developed process will be used in designing a test slumping mandrel to be built with funding from a Phase II SBIR.

Key Personnel

John Casstevens, is president of Dallas Optical Systems, Inc. Before founding his company in 1991 he was vice president of the advanced products division of Optic-Electronic Corp., Dallas, TX. At OEC he managed the concept, engineering and delivery of a very large diamond turning machine built by Moore Tool Co. to go in a specially built facility for the purpose of manufacturing mirror optics for the Strategic Defense Initiative. That large diamond turning machine called the M-40 is now at Marshall Space Flight Center. Mr. Casstevens holds BSME and MSME degrees from the University of Texas at Austin. He holds two patents in the area of diamond turning. He is a member of SPIE, OSA, ASPE. He has published approximately 30 technical papers and reports dealing with diamond turning and optical finishing of optical components.

Newman M. Marsilius, President and Chairman of PMT Group, Moore Tool Co. and Moore Nanotechnology, Bridgeport, Conn. and Keene New Hampshire.

Uses and Benefits of Large Scale Diamond Turning

Support and Infrastructure

DOS has expertise and experience to build a state of the art environmentally isolated facility with infrastructure, material handling, support machine shop and security to house extremely large diamond turning machining operations. A very large and specially engineered facility was built to provide the extremely stable environment required for the large optics diamond turning operations at Optic-Electronic Corp. DOS intends to construct a similar facility when future space and military optical business opportunities merit the investment. This type of unique facility includes redundant extremely stable environmental control systems, redundant utilities of high pressure instrument air, vacuum systems, and robust uninterruptible power systems so that ultra precision machining operations lasting as long as several weeks are not accidentally interrupted.

Additional Uses of Very Large Precision Air Bearings -- Extremely smooth and accurate rotary motion is essential for many large metrology applications as well as utility in conventional lapping and polishing of giant optical components. Ultra precision grinding and polishing can be improved by orders of magnitude by replacing relatively noisy, heat producing lower accuracy rolling element bearings in other types of conventional machining and optical fabrication equipment.

Dallas Optical Systems, Inc. Information and Facilities

Diamond Turning and Large Optics Polishing Equipment

Dallas Optical Systems, Inc. has three diamond turning machines with the largest machine having a capacity to diamond turn optics up to 1.25 meter diameter. A second diamond turning machine shown in Figure 14 has the capability to diamond turn parts up to 0.9 meter. DOS has conventional optical polishing machines capable of polishing optics up to 3 meter diameter.

Figure 14. Two axis diamond turning machine 0.9 meter capacity and 2.5 meter aluminum spherical mirror on one of the two DOS large capacity polishing machines.