Application of Single Point Diamond Turning in Infrared Optics

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Abstract: Non-ferrous metal, crystal material, infrared glass and so on are widely used in the infrared optical system, they can be cut directly by single point diamond turning, so single point diamond turning technology was soon applied to infrared optical elements processing, which can be understood that infrared optics are main application areas of single point diamond turning. This paper introduced the application of the infrared optical elements which are processed by single point diamond turning in weapon system, including the processing methods and processing equipments of typical infrared optical elements. Finally, the development status of single point diamond turning at home and abroad was compared.

Introduction

Infrared technology is not only widely used in space field, such as infrared detectors which are installed on the space station or space shuttle, but also has a very important position in national defense security and civil field. Infrared optical elements include infrared crystal soft brittle material optical elements and hard brittle materials optical components such as glass, SiC, etc [1]. Processing these materials is difficult, so traditional machining methods are difficult to meet the requirements.

Single Point Diamond Turning (SPDT) is the most important part of the ultra-precision machining. Processing crystal-based optical element can ensure high precision by SPDT, improve the laser damage threshold and avoid embedding in polishing abrasive, so as to effectively reduce subsurface damage on the crystal surface. Based on the processing characteristics of infrared optical components, the paper introduced the application of SPDT in infrared optics.

Infrared Optical System

As a new generation of observation instrument, passive infrared thermal imagers work by collecting infrared radiation energy of targets, and transform it into visual images. Thermal imagers can work on day and night, and have strong penetrating power to smoke, good concealment, so thermal imagers are expensive, but they have been widely used in the military field [2]. The infrared optical systems have the functions of absorbing and transfering the infrared thermal radiation, and they are the most important part of the infrared thermal imagers.

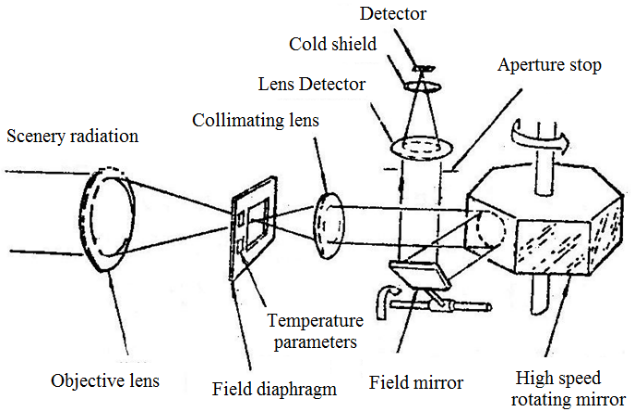


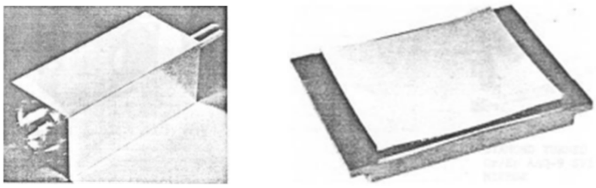
Fig.1. Typical optical system diagram of the first generation of thermal imager

Fig.1 is typical optical system diagram of the first generation of thermal imager. Infrared optical system consists of infrared lens, flat or curved surface of reflector and scanning drum. Infrared lens only can be made by infrared light materials, such as germanium, silicon, zinc sulfide, zinc selenide, arsenic, selenium and germanium, etc. Single point diamond turning technology can not only process non-ferrous metals, glass and other crystal materials, but also high-precision plane, spherical, aspherical, polyhedra and other optical elements[3].

Application of Infrared Optical Elements of Single Point Diamond Turning Processing in Weapon System

Foreign military weapon systems[4] almost use all kinds of photoelectric sensors. These photoelectric sensors consist of all kinds of infrared optical elements which are processed by SPDT, such as the US military laser and infrared thermal imaging products all have a large demand on infrared optical elements, one AN/AVS - 6 pilot night vision glasses includes 9 aspherical optical components and 2 spherical optical components.

Fig.2 is the rotating mirrors and parabolic mirrors of the infrared thermal imaging reconnaissance AAD–5 which are all processed by SPDT.



(a) rotating mirror (b) parabolic mirror

Fig.2. Rotating mirror and parabolic mirror of ADD-5

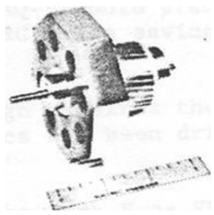


Fig.3. The high speed rotating mirror AAQ–9

Fig.3 is the high speed rotating mirror of the US military infrared detectors AAQ-9 which is processed by SPDT.

The US Dark Eyes Navy FLIR includes two aspherical lenses and a rotating mirror, which are processed by SPDT.

Fig.4 is the RPV FLIR of the US Army Night Vision Laboratory which also uses aspherical lens and metal reflectors.

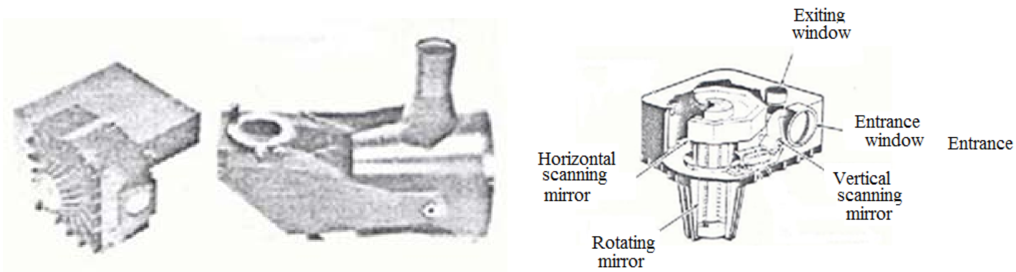
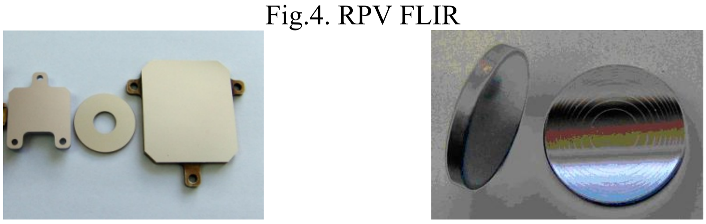
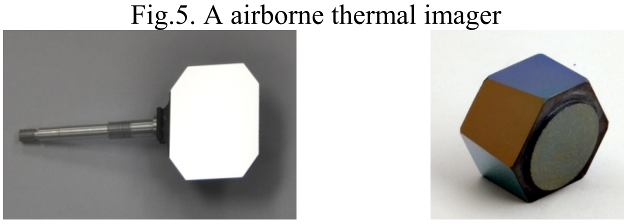


Fig.4. RPV FLIR



(a) plane mirror and aperture stop (b) aspherical binary Diffrative lens

Fig.5. A airborne thermal imager



(a) row sweep swing mirror (b) Six germanium refraction drum

Fig.6. A tank thermal sight

During the Gulf War, the US-British-led multinational force generally equipped with a thermal imager, which makes tanks and other weaponry in Iraq to the targets of the multinational force. So China has also stepped up investment in thermal imager. China has achieved the first generation of thermal imager prototype engineering in 1989. For example, a airborne thermal imager includes two flat mirrors, two aperture stop and three aspherical lenses as shown in Fig.5. A tank thermal sight has two aspherical lenses, one row sweep oscillating mirror and a six germanium refractive drum as shown in Fig.6. They are all cut by SPDT.

Applications of Single-point Diamond Cutting in Infrared Optics

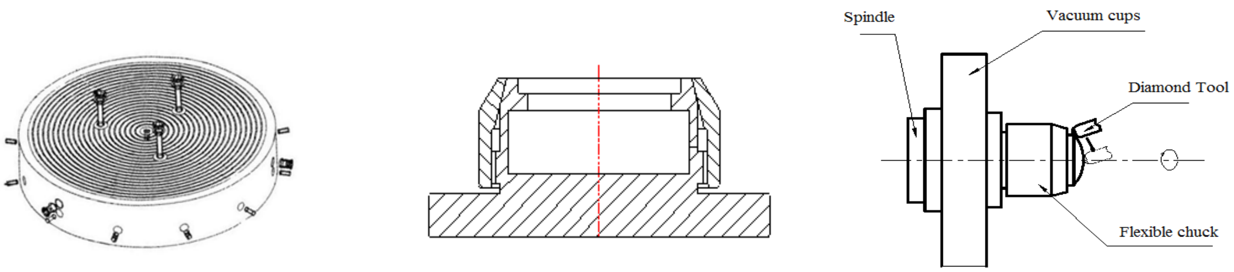
Turning Aspherical Lenses

Aspherical can improve the image quality of the system, reduce the number of lenses, and reduce costs. Here aspherical specifically refers higher axial symmetry aspherical by equation (1) [5].

$$Z=\frac{Cr^2}{1+\sqrt{1-(1+K)C^2r^2}}+A_1r+A_2r^2+A_3r^3+A_4r^4+\ldots+A_{20}r^{20} \quad (1)$$

K: aspherical coefficients, A_1 to A_{20}: High order aspherical systems, C=1/R (R: aspherical vertex radius).

Aspherical lens is clamped by elastic jig, and then jig is adsorbed onto the vacuum chuck of machine for turning. Fig.7 is schematic of single point diamond turning Aspherical.



(a) vacuum chuck (b) resilient chuck (c) processing schematic

Fig.7. Schematic of single point diamond turning Aspherical

Diamond machine only do fine finishing for workpieces, so at first, workpieces should be rough shaped by traditional grinding methods, and reserve processing capacity of blank does not exceed 0.15mm. And the radius of curvature of the blank is equal to the optimum radius of the aspherical surface.

Turning Infrared Mirrors

Mirrors are the earliest infrared optical elements cut by SPDT [6] and mainly refer to non-spherical mirrors and plane mirrors. These mirrors only can be made of aluminum, copper and other types of non-ferrous metals [7].

Fig.8. Φ237 aluminum alloy aspherical mirror

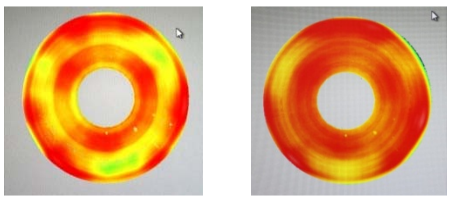


Fig.9. Interferometer test results in uses the compensation mirror

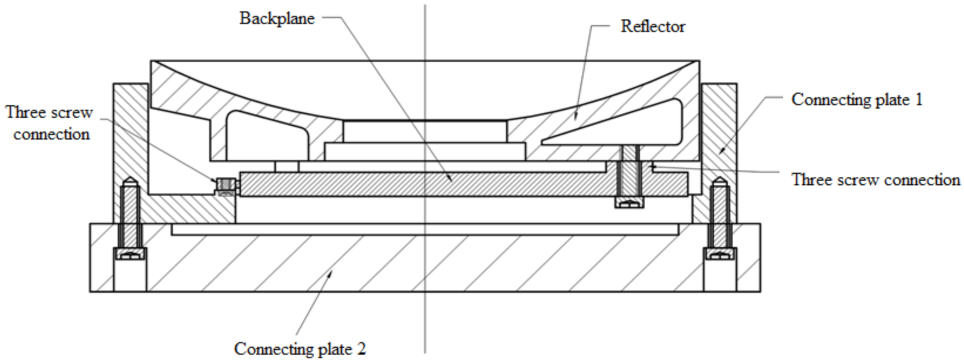


Fig.10. SPDT tooling schematic

Schematic of single point diamond turning Aspherical mirrors as shown in Fig.7, which are non-spherical cutting, so the process of aspherical mirrors is substantially same with aspherical germanium lenses [8]. Fig.8 is Φ237 aluminum alloy aspherical mirror, the entire mirror body except the surface are groove structure, and can not be clamped by elastic jig or adhesive bonding mode. So for the reflector structure, Fig.10 is a designed and processed dedicated jig. Fig.9 is the test results of mirror interferometer using compensating mirror. RMS, surface accuracy, reaches 0.13λ (λ = 632.8nm). The reflectance of middle-wave infrared band is greater than 99%, which meet the requirements of the thermal imagers.

Because of rectangular view field of infrared optical system, the shape of mirror is rectangular or oval. So there is a balance problem in turning, processing plane mirrors is normalized to fly-cutting. Fig.11 is processing schematic of fly-cutting plane mirror. The position of workpieces and tools are mounted on the knife disc [9] and whirl with the spindle rotation, while the workpieces are on location where the tools are installed in turning. When the spindle feed along straight line, the cutting track that the tip rotates is a plane.

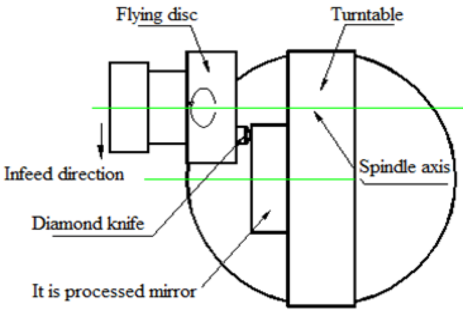
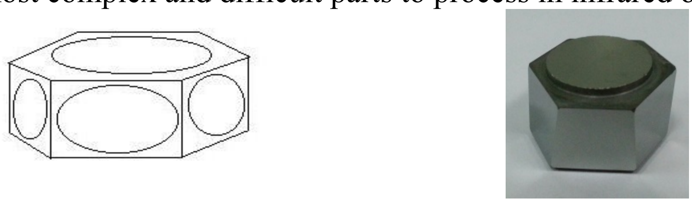


Fig.11. Processing schematic of fly-cutting plane mirror

Fly-cutting Polyhedrons

Polyhedrons (also known as scanning drums) are core optical elements of the first generation thermal imagers and also are the most complex and difficult parts to process in infrared optical components.



(a) Six sides line scanning drum of CNTICM-Ⅱ (b) Ge six scanning drum of CNCM-I

Fig.12. Scanning drums of Chinese

Fig.12 (a) is Six sides line scanning drum of CNTICM-Ⅱ which is reflective aluminum drum, and processed with single point diamond fly-cutting by the Changchun Institute of Optics, Fine Mechanics and Physics; Fig.12 (b) is Ge six scanning drum of CNCM-I which is single crystal germanium trans-missive two-dimensional scanning drum. The drums have been processed with a hand-grinding mode by the Kunming Institute of Physics before 2001, and the drums were fly-cutting worked successfully on the machine tool Nanoform250 in 2001 early[10 -12].

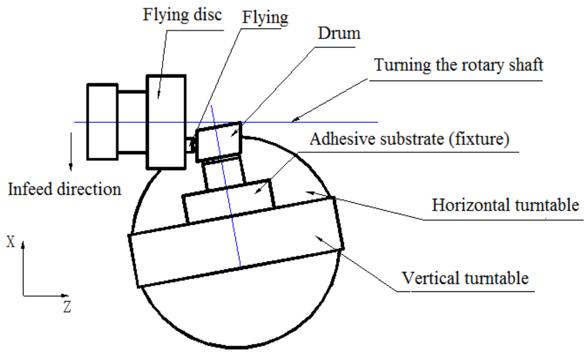


Fig.13. Schematic of two-dimensional scanning drum

Fig.13 is schematic of two-dimensional scanning drum. The drum is two-dimensional, so each one faces to be cut according to each center and inclination angle of the requirements [13]. First, set up a central angle of rotating perpendicular turntable, rotate the level turntable to the required integer degree, and then set up the fractional part of inclination with private block.

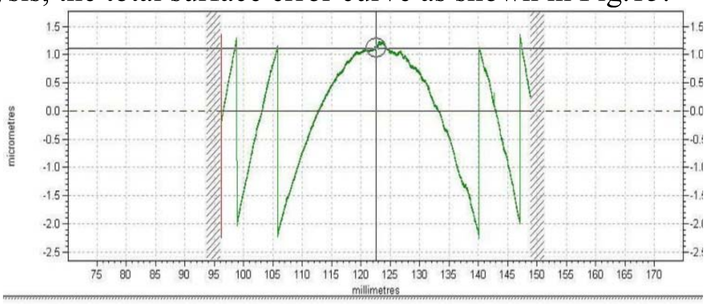
Turning Binary Optical Elements

Binary optical elements are diffractive optical elements of phase type. In order to obtain high diffraction efficiency, relief structure will be made to more phase orders (2N). Using the N blocks template can obtain L=2N phase orders. When L=2, 4, 8 and 16, the diffraction efficiency was respectively 40.5%, 81%, 94.9% and 98.6%. When adopting sub-wavelength microstructure and continuous distribution phase surface shape, efficiency is close to 100% [14-15]. Fig.14 is ZnSe diffractive surface.

Fig.14. ZnSe diffraction surface

When the error of binary optical elements are analyzed by profiler, the curves can not only include the error of diffraction surface , but also the step height of the diffractive surface, and height of the step is micron order, so the error of diffraction surface can not be accurately reflected. Thus, dedicated software to detect the diffraction surface is developed by Northern Yunnan Kiro-CH Photonics Co., Ltd., which fills Chinese gaps in the field.

Binary optical element contour curve is measured with profiler, and based on the base surface parameters for error analysis, the total surface error curve as shown in Fig.15.



Rt	3.6266	µm		
Ra	0.8360	µm		

Fig.15. Analysis of surface error curve of binary optical element with profiler

The MOD file is exported and imported the dedicated software to obtain surface error curve as shown in Fig.16.

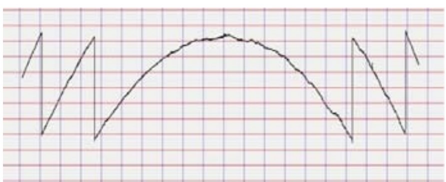


Fig.16. Surface error curve after importing the dedicated software

Input interface of diffracting ring-parameters of binary optical element as shown in Fig.17.

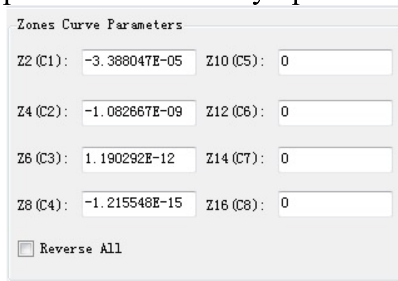


Fig.17. Input interface of diffracting ring-parameters of binary optical element

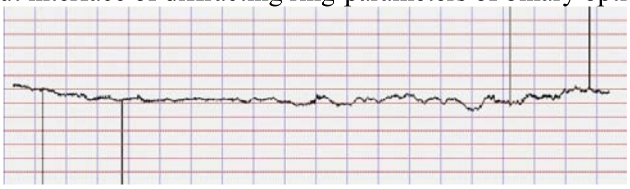


Fig.18. Error curve of surface shape of base surface

Removing influence of the ring step to obtain error curve of surface shape of base surface as shown in Fig.18.

Removing glitches caused by measurement fluctuation on the diffracting ring to obtain surface error curve of the final diffraction surface as shown in Fig.19.

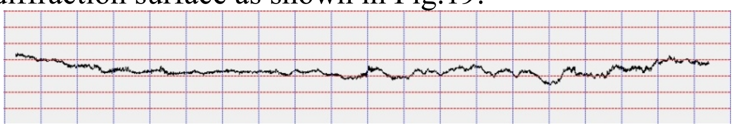


Fig.19. Final surface error curve of the final diffraction surface

Development Status of Single Point Diamond Turning at Home and Abroad

Table 1 shows early development of foreign SPDT technology [16-20]. In addition, the developed countries continues to initiate new research programs, such as the US national nanotechnology promotion program in 2001, the British multidisciplinary nanotechnology research cooperation program in 2002, Japanese nanotechnology support programs in 2002[21].

Table 1 Early development of foreign single point diamond turning technology

Time	Development Unit	Machine Model	Machining parts parameters			
			Size (mm)	Weight (kg)	Precision (μm)	Surface roughness Ra (μm)
1983	US LLNL Laboratory	DTM-3	Φ2100	4500		
1984	US LLNL Laboratory	LODTM	Φ1625×500	1360	0.025	0.0045
1990	UK Pneumo Company	Nanoform 600	Φ600		0.1	0.01
1991	UK Cranfield Company	OAGM-2500	2500 ×2500			
1990s	Toyota Machine Works	AHN60-3D	Φ600		0.35	0.016

In China ultra-precision processing technology is constantly developing. The Changchun Institute of Optics, Fine Mechanics and Physics introduced a MSG-325 ultra-precision aspherical turning machine from the UK Pneumo Precision Company in 1987. In the mid-1990s, China North Industries Group Corporation, China State Shipbuilding Corporation and a few other units have introduced different single-point diamond tools from the UK Taylor Hobson Company, such as Nanoform 250, 300 and so on [22] . In 2003, domestic aspherical ultra-precision diamond turning machine arrived, so the processed shape accuracy was 0.228μm and Ra7.8 nm.

Conclusions

In summary, single point diamond turning technology is widely used in infrared optics, which made the infrared thermal imaging technology is developed rapidly. In recent years, the number of machining scanning device was decreasing, but the number of aspherical and binary optical element was ascendant. With the development of second-generation thermal imager and an inactivated cold imager technology, more high-performance optical element is applied in infrared optical system, and thus the single point diamond turning technology will be higher required. Although Chinese single point diamond turning technology has made some achievements, but there is a large gap when compared with foreign advanced level. Only to improve single point diamond turning technology as quickly as possible can enhance the level of processing of infrared optical components and further push development of infrared optical technology.

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