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# Diamond milling of an Alvarez lens in germanium

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ABSTRACT

Single crystal diamond milling of optical materials opens up new design degrees-of-freedom for optical engineers. However, parameters for milling of many optical materials have not been investigated, understood, or documented. This paper focuses on the milling of germanium to fabricate a freeform “Alvarez lens” in the mid-wave infrared (MWIR). While the design concepts for such optical systems have been known for decades, implementation has been limited due to difficulty in manufacturing the freeform surfaces. Ultra-precision, multi-axis machining centers can manufacture these surfaces through single crystal diamond milling. A battery of high speed diamond milling tests was performed in germanium to develop the parameters for machining the Alvarez components. Near-surface crystal quality and residual stress measurements using confocal Raman spectroscopy are reported, along with representative test results of the functioning optical system.



## 1. Introduction

The generation of high quality freeform surfaces in optically transmissive materials opens up possibilities for entirely new optical designs. Unlike traditional axisymmetric surfaces, these surfaces have complex forms that must be described by general polynomial equations with significant height variation, or sag. Such surfaces allow the designer to introduce a near arbitrary phase variation in the incoming light that can be exploited in optical designs. However, manufacturing and measurements of the freeforms present significant challenges. This paper focuses on a freeform optical system in germanium that was manufactured using single crystal diamond milling.

The motivation for this work dates back to Kitajima [1] who showed that it was possible to vary the optical power of a lens system by translating two refractive freeform components perpendicular to the optical axis. This approach was developed further by Birchall and Lewis [2–4] and formalized by Alvarez [5,6]. Alvarez showed that two cubic surfaces translated relative to one another form a composite converging or diverging lens. While design innovations have continued [7,8], fabrication methods have limited the implementation and practical use of an “Alvarez lens” [9,10].

With the introduction of new multi-axis ultra-precision machining centers and small scale single crystal diamond end-mills, it is now possible to fabricate these novel designs by milling [11,12]. Previous research in diamond turning has shown that non-refractory metals and plastics can be machined to produce optical quality surfaces with surface roughnesses below 5 nm Ra without significant chemically induced or abrasive tool wear [13]. Further, research in nominally brittle semi-conductor materials has demonstrated that by introducing a negative rake angle on a turning tool, hydrostatic pressure inhibits brittle fracture and produces an optical finish. Single-crystal and polycrystalline germanium [14–19], zinc selenide [20], zinc telluride, zinc sulfide [20], and silicon [21–24] can all be turned this way. Indeed, complex optic arrays can be turned in germanium for use in infrared multi-imaging systems [25]. Research in diamond milling of brittle materials is accelerating. Takeuchi showed that BK-7 glass could be milled to produce a complex shape with a high quality surface roughness [26]. Matsumura et al. [27] have demonstrated milling of crown glass with polycrystalline diamond milling cutters and have correlated fluctuations in cutting force with brittle crack domination of the material removal mechanism. Rusnaldi et al. [28] have demonstrated milling of silicon with diamond coated cutting tools and Arif et al. [29] have demonstrated the milling of silicon carbide using polycrystalline diamond end mills.

While research is accelerating and components are being successfully machined in the private sector, quantitative and comprehensive understanding of the milling and micro-milling of materials in the so-called ductile mode is still lacking. Equally

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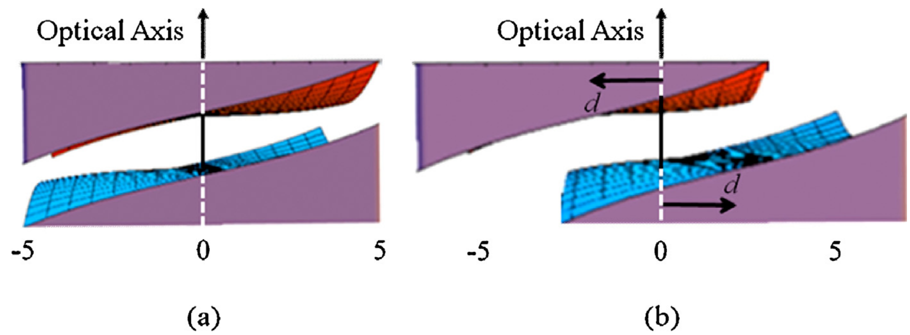


**Fig. 1.** Alvarez lens schematic consisting of two polynomial cubic surfaces (a) aligned such that the optical path length is constant for all rays entering parallel to the optical axis and (b) laterally shifted by *d* to produce a focusing of the rays with a focal length depending on the shift (dimensions in mm).

important, single crystal diamond endmills, particularly those with negative rake angles that are suitably balanced (or balanceable) for high-speed milling spindles with greater than 100,000 rpm capability, have only become commercially available in the past several years. The designs for these cutting tools are still evolving and, compared to conventional high-speed steel and silicon carbide milling tools, the geometry of these tools is still quite limited. With this confluence of different technologies, it is necessary to continue to research the cutting mechanisms/mechanics active in the milling of brittle materials.

Our goal in this work was to manufacture a single crystal germanium refractive Alvarez lens for use in the 3–5 μm wavelength band: the mid wavelength infrared (MWIR). This required basic experimentation with the milling of single crystal germanium, resulting in quantitative data on surface roughness and residual stresses as a function of milling parameters and tool design. This work provides a baseline set of parameters for milling germanium optics.

The paper is arranged as follows. The second section gives a brief overview of the design of an Alvarez lens. Section 3 discusses the high-speed milling tests completed on this material with single crystal diamond endmills. Surface roughness was measured with scanning white light interferometry (SWLI) (discussed in Section 4) and subsurface damage measured with confocal Raman spectroscopy (discussed in Section 5). Systematic changes as a function of milling parameters suggest that a more thorough scientific study of the brittle-ductile cutting mechanics in milling is needed. The sixth section describes the surface roughness and form of the fabricated Alvarez lens component. The seventh section overviews functional optical testing of the lens and gives a comparison of analytical and numerical results. We have reported previously on the design and testing of the MWIR Alvarez lens [10], but to our knowledge this paper is the first to report on freeform ultra-precision diamond milling of germanium for this class of optical systems. Such lenses have numerous applications for infrared imaging and night vision systems.

## 2. Optical design

The design of the lens followed the first-order analytical approach described by Alvarez [7,8]. Alvarez showed that two cubic lenses with surface heights described by Eq. (1) will form a composite spherical lens of variable power.

$$z_i(x,y) = A\left(\frac{x^3}{3} + xy^2\right) + C \qquad (1)$$

As shown in Fig. 1, the two surfaces are odd in $x$ and can be oriented and nested to form a composite plate of constant thickness. However when lateral shift $\pm d$ perpendicular to the optical axis is introduced, the composite optical component is a lens with variable curvature that depends on the lateral shift. Details of the optical design used herein are given in Smilie et al. [9]. The key result is that the focal length $f$ of the composite lens is inversely proportional to the lateral shift $d$.

$$f = \frac{1}{4Ad(n-1)} \qquad (2)$$

In Eq. (2), $A$ scales the overall surface sag and $n$ is the index of refraction of the lens material. The index of refraction of single crystal germanium at the center of the design wavelength range (4 μm) is 4.025. Fig. 2 shows the change in focal length as a function of $d$ for three different values of $A$. For a given active lens area, larger values of $A$ result in more rapid changes in focal length with lateral shift.

As described by Smilie et al. [9,10], the overall design balanced testing and manufacturing constraints. Accordingly, each optic was specified to be 14.14 mm in diameter with an amplitude coefficient $A$ of 0.0012 mm$^{-2}$ (solid curve in Fig. 2). A lateral shift of 1.8 mm results in a minimum focal length of 38 mm for a maximum testable aperture of 10 mm. Total height modulation of the surface for these parameters was 400 μm, allowing easy reach and access for a 1 mm diameter single crystal ball endmill with a single cutting edge (flute).

Six spherical fiducials were designed into each lens component to enable optical or mechanical alignment of the two surfaces and to set the lens spacing during initial assembly.

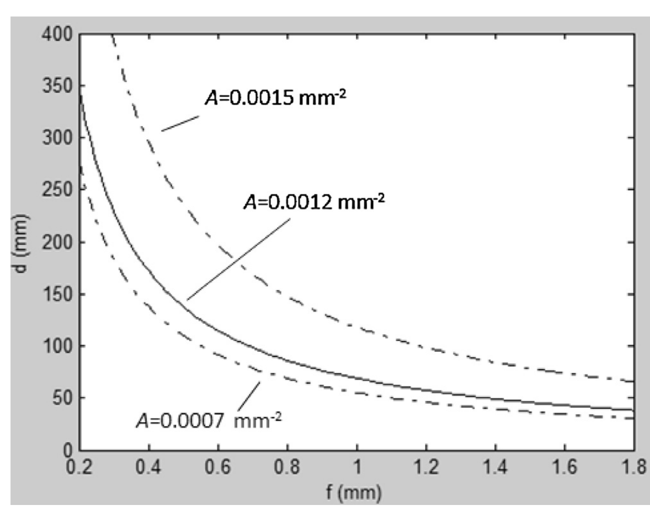


**Fig. 2.** Variation in focal length as a function of lateral shift for a germanium lens ($n$ = 4.025) and various values of $A$.