Fabrication of infrared optics

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Abstract. Methods for grinding and polishing IR transmitting materials are described and contrasted with better known methods for making glass optics. Because many IR optical systems use aspheric surfaces, single-point diamond turning (SPDT) is suggested as the most prudent method of making both reflective and refractive aspheric surfaces. For cases in which sufficiently good surface finish cannot be achieved with SPDT, either for system use or for testing with visible-light test equipment, a *postpolishing* technique that uses fine diamond paste and synthetic polishing pads is given as an alternative method. Finally, some practical aspects of good mechanical and optical engineering relating to SPDT are reviewed. By taking a few simple precautions and by building in appropriate optical alignment and mechanical mating surfaces, a difficult test and assembly situation can be reduced to something that is trivial.

Subject terms: infrared technology; optical fabrication; polishing; infrared materials; single-point diamond turning; postpolishing; diamond polishing.

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1 Introduction

The field of IR optics is one of the fastest growing branches of traditional optics. New laser sources, fiber optic communications, night vision devices, and a host of new detector technologies make the field of IR optics ripe for further growth. To support that growth, lenses and mirrors are needed for IR optical systems. This paper discusses the similarities and differences between the fabrication of the more familiar glass optics used in the visible and the fabrication of optics used in the IR.

The major differences between glass and IR optics revolve around the limited number of materials that transmit in the IR and their very different mechanical, chemical, and thermal properties from those of glass. These material differences make some great differences in how IR optics are fabricated. On the other hand, the actual mechanics of making spherical surfaces lead to many similarities with the making of glass optics. Without going into the details of making glass optics, we will point out aspects of making IR optics that require special attention.

The relatively limited number of materials that transmit in the IR along with the rather broad spectral bands over which some IR systems are expected to operate create problems with the achromatization of IR systems. This leads to the use of aspherics on lenses and the much greater reliance on mirrors in IR systems than in the visible. To keep the number of surfaces to a minimum, virtually every mirror surface in an IR system is aspheric, and, as is commonly

known, aspherics are much more difficult to fabricate than spherical surfaces.

The difficulty of making aspheric surfaces can be somewhat overcome by single-point diamond turning (SPDT) the surfaces directly to the required aspheric shape and specularity. Even in cases where SPDT would not be a satisfactory fabrication technique for use in the visible, it is quite useful in the IR because the residual errors left on the surfaces are still small compared with the wavelength of IR radiation in question.

In those cases where the finish left by SPDT is still too rough for the intended application, the surfaces may be *postpolished*. Recent experiments indicate that an improvement in finish of a factor of 10 is not difficult to achieve. This leads to a reduction in scattered light of about a factor of 100.

We finish our discussion of the fabrication of IR optics with some practical comments on SPDT and postpolishing.

2 Similarities and Differences Between Visible and IR Optics

To begin the discussion of the differences between IR and visible optics, we have produced a glass chart in Fig. 1 that includes the traditional glass table but also shows a variety of typical IR materials. The vertical axis is a pseudo-Abbe v number of the material or the reciprocal change of the index of refraction with a change of wavelength. We have defined the v number the same as in the visible except we have used the 3- to 5- and 8- to 12-μm IR bands to come up with the extreme values of the index in each region.[1] We use this notation so that the glass portion of this table looks somewhat familiar to the visible light optical designers. The horizontal axis is the index of refraction of the materials listed.[2]

The first thing that is obvious is that the traditional glasses occupy a very small region near the center of this chart. Because of the very wide range of v number in the IR, we have used a log scale to compress the figure. Inverse dispersion is never displayed this way in the visible because of the limited range of dispersion in the visible.

The values in this chart are not intended for use in design nor is the chart exhaustive in the IR materials listed. Rather, the purpose is to illustrate how very different the optical properties are of the materials that transmit in the IR from those materials used in the visible. With these great optical differences it is not difficult to imagine that the chemical, mechanical, and thermal properties of these materials differ greatly from the traditional glasses as well.

The materials on the left of the chart are crystalline alkali halides, most of which are quite water soluble. All are available in single-crystal forms, but any of these are now also made in a polycrystalline form that is much stronger and more resistant to cracking than the single-crystal varieties.[3] In the same area on the chart are the alkaline earth fluorides, generally hard, brittle materials that are almost insoluble in water. Many of these are also available in polycrystalline forms as well as the usual single-crystal variety.

Toward the right of the chart are chalcogenide and semiconductor materials that exhibit much higher indices of refraction than visible light glasses. These materials are generally much easier to grind and polish than the lower index materials. A very useful description of the behavior of the widely used IR materials during grinding and polishing is given by Karow.[4] In addition to treating the material properties from an optician's perspective, he gives a thorough treatment of how each of the materials is manufactured so that it is suitable for use as an optical quality material.

To give some idea of what the optician is up against when working with some of these materials, we give a few examples. The very dielectric alkali halides and alkaline earth fluorides all have high coefficients of thermal expansion and low thermal conductivities. This means it is very easy to introduce thermal gradients in these materials. This coupled with the high thermal expansion can easily produce stresses beyond the modulus of rupture, particularly if there are any flaws in the material such as cracks introduced in the early stages of generating (machining or shaping) or loose abrasive grinding prior to polishing.

Because the alkali halides are so water soluble, their initial shaping is done largely by water-aided processes. Before diamond wheels and saws were common, the alkali halides were cut from the raw crystal boule using a saw made of a damp string. Now diamond saws running in oil are used in this operation. To remove the saw marks and reduce the salt window or lens blanks to dimensions suitable for polishing, the surfaces are rubbed on water-dampened felt laps. Depending on the wetness of the lap, up to 1 mm/min of material can be removed from the surface by dissolution.

Cesium iodide (CsI), a material that is very useful because it is transparent out to 80 μm, has the consistency of butter just removed from the refrigerator. It is so soft that impressions of the spacer shims used in mounting CsI windows in cells are clearly visible in the surface when the windows are removed for repolishing. In spite of its usefulness, CsI is not easy to polish and is avoided if at all possible because of its softness.

On the other hand, all these materials can generally be treated very similarly to glasses during the initial steps of manufacture, the cutting of the blank from a boule, generating to a flat or specific radius, and loose abrasive grinding to a
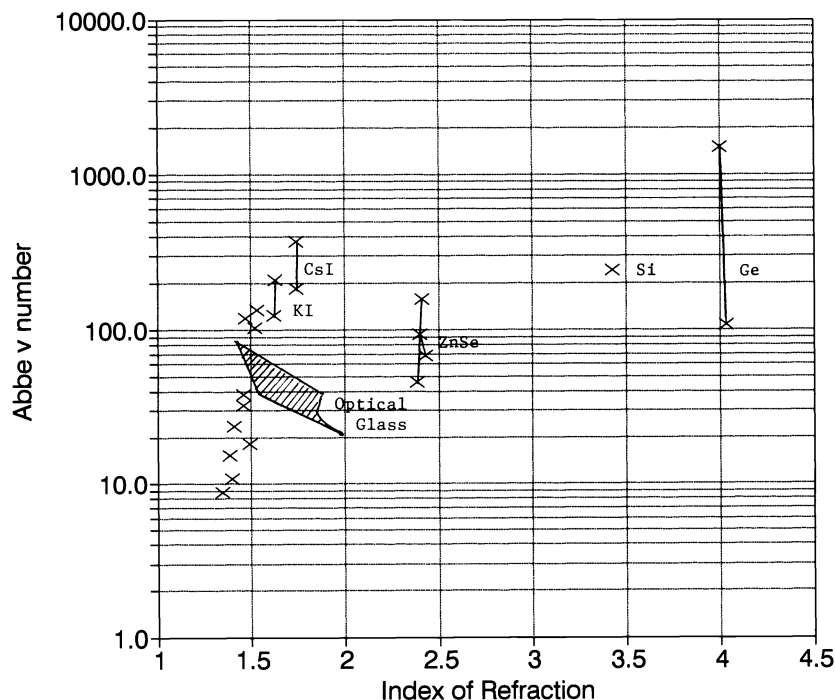

Fig. 1 Abbe v number as a function of index of refraction for various IR transmitting materials and optical glasses.

dimension and finish suitable for polishing. Even in polishing, the same types of tooling are used as for glass and the same sorts of strokes are used during polishing to control the radius.

3 Selection and Testing of IR Materials Before Polishing

In a sense we have become spoiled because of the good job the optical glass manufacturers have done in inspecting and certifying the glass they supply. Although on occasion a story is heard of a slipup somewhere in the inspection of optical glass, most opticians rely exclusively on the suppliers of optical glass to do all the inspection. They simply use the glass to make lenses with every expectation that if there is a problem with an optical system it will be due to imperfectly polished glass surfaces rather than a problem with the glass itself.

The same is not true for IR materials for several reasons. Many IR materials do not transmit in the visible. Therefore, it is difficult for either the vendor or the optician to measure the quality of the raw material until it has been installed as part of a finished optical system. Another problem is that almost all optical glass companies are part of larger commercial glass companies where the emphasis is on producing all kinds of quality glass products. On the other hand, most suppliers of IR materials are subsidiaries of companies whose main business has nothing to do with IR materials for optical applications. For example, silicon is made primarily for the electronics industry, a business that is hundreds of times larger than the optics market for silicon. Germanium is a byproduct of refining lead and most lead goes into car batteries. Is it any wonder then that optical grade germanium is selected on the basis of its resistivity rather than on anything to do with actual optical inhomogeneity?

These problems are not necessarily unique to materials that are opaque in the visible. Even the alkali halides and alkaline earth fluorides can have homogeneity problems that can render finished optics unusable for their intended purpose. The suppliers of the crystalline materials know that the way they grow the crystal boules largely takes care of any impurities that are likely to cause inhomogeneity, but problems can still occur. It is unlikely that the manufacturers of raw crystal materials ever check the homogeneity interferometrically. Therefore, the polisher is not likely to find out that there is a problem until they check the finished part in transmission.

While most vendors of IR materials will replace the defective material when presented with evidence that there is an inhomogeneity problem, this does not pay for the cost of polishing the original piece(s) or the cost of the schedule delay. All we can say, until standards are written for the quality of IR materials, is *caveat emptor*. If there is a requirement on transmitted wavefront quality, let the supplier of the IR materials know and work out ahead of time who is responsible for what if there is a problem.[5]

4 Fabrication of Spheres and Flats in IR Materials

In this section we discuss the use of traditional optical techniques to polish spherical and flat surfaces in IR materials. The difference between polishing IR materials and glass optics is entirely in the chemistry of the polishing process. Other

than this, the techniques are the same as for glass. Now some IR materials are much softer and/or more brittle than glass so more care must be used, but the techniques for what size tools and what strokes to use are identical to those used in making glass optics. The reader is referred to the excellent and very thorough new book by Karow on optical fabrication in general.[6] Another excellent reference by Fynn and Powell that is more specifically about crystalline optics is also suggested.[7]

On the chemistry front, glass is almost always polished with a polishing compound of high cerium oxide content. The cerium oxide is thought to soften and perhaps even dissolve the outer layers of glass as the polishing lap moves over the surface. After the lap has passed, the silica-rich polishing slurry tends to redeposit a silica layer on the glass almost like putting a coat of varnish on wood. This silica layer provides the fine surface on well-polished glass but can also cover up small defects left from previous manufacturing steps that cause so-called *subsurface damage*. Not only does the cerium play an extremely important role in polishing glass,[8] but there is some evidence that the pitch lap also may contribute to the chemical action.

This advantageous cerium oxide chemistry does not work for most IR materials, so other polishing media must be used. The compound of choice for most materials was, and to a large degree still is, a fine-grade aluminum oxide. Once the crystal is fine ground (usually on a glass rather than cast iron tool), polishing starts with Linde C, an alpha aluminum oxide with a roughly 3-μm particle size, on a pitch lap. Just as the last of the grinding pits disappears, a change is made to Linde A, a 1-μm alumina. If polishing with Linde C is continued beyond where the surface is polished out (the point where the grinding marks are gone), the surface of some IR materials will tend to pit, i.e., 10-μm or so sized pieces of the surface will pull out. Since the reason for this is not well understood, it is best to make the change to Linde A, a 1-μm alumina. The balance of the polishing and figuring are typically finished up with the Linde A.

In a few cases, attempts are made to obtain even smoother surfaces by switching to Linde B or a mixture of A and B. Linde B is a gamma-type aluminum oxide with a particle size of about 0.3 μm. Some opticians have good luck with Linde B and others just find their work going backward. The use of Linde B seems to be technique dependent to a high degree. For further recommendations for polishing various IR materials, see Ref. 9.

One of the problems with the use of aluminum oxide polishing materials is that they do not tend to "charge," or imbed in, the pitch lap the way cerium oxide does. Thus, the Linde materials tend to roll around on the lap instead of cutting. To help secure the polishing compound to the lap, beeswax is often applied to the pitch surface by first rubbing the wax on kraft paper and then rubbing the lap over the paper, or by using a shoe brush to first rub on a block of beeswax to transfer the wax to the brush and then to brush the pitch lap to produce the desired thin layer of wax on the pitch. This fine layer of wax will hold the aluminum oxide so that it will cut the material being polished. Another trick is to add a little detergent or glycerine to the water slurry of alumina if the contact or friction between work and lap is too great and might lead to pitting. The detergent or glycerine reduces the friction and helps wet both surfaces.

One is often bothered by sleeks or scratches when polishing IR materials, particularly the crystalline ones. These scratches are often caused by bits of the material breaking off right at the edge of the material where the bevel and face being polished meet. This problem can be largely cured by polishing the bevels (everything being polished should have bevels) before polishing the face in question. There may be a tendency here to hurry the work along because the bevels are nonoptical surfaces. However, remember that most of these materials have a high coefficient of expansion and low thermal conductivity. Since the bevels are narrow, anything but moderate pressure will build up heat and the optician may well end up with two or more crystals instead of one. It is not worth trying to save a few minutes of time on a simple but necessary task if the result is breaking an expensive IR crystal.

Obviously the technique of polishing with water and alumina will not work well on the water-soluble crystals. The first thing that is different from working with insoluble materials is that latex surgical gloves must be worn at all times so that moisture from the skin does not ruin the surfaces. Also, the workplace humidity should be controlled to around 30%.

Instead of loose abrasive grinding water-soluble crystals to the correct dimensions for polishing, they are usually "watered" to size. Watering makes use of a piece of dampened hard felt stretched over a flat surface. The crystal is gently rubbed over this felt surface until sufficient material has been dissolved to bring the part to the proper thickness and parallelism. Once the salt is within perhaps 0.2 mm of the upper thickness limit, it is time to polish to get the final figure and thickness.

Polishing is done on pitch laps covered with beeswax honeycomb starter sheets. This material is available from bee supply shops and is what beekeepers put in the hives for bees to start making their combs on. The material is first rolled with a smooth steel rod to flatten the honeycomb pattern to about half its original height. The pitch lap is prepared in the usual way including channels every inch or so both ways. After pressing the pitch lap flat, the surface is quickly wiped with acetone on a rag and then pressed onto the beeswax sheet. The beeswax will stick well to the dissolved pitch surface. Then a broad-tipped low-temperature soldering iron is used to form the beeswax down into the channels and down around the beveled edge of the lap. Once finished, the lap is pressed under weight so the beeswax takes on an overall flat, but textured, surface. Several identical laps should be prepared that are two to five times the diameter of the parts to be polished. This holds for spherical as well as flat parts unless the part size gets quite large (150 mm or greater), and then the lap can be more nearly the size of the work.

Polishing is done with Linde A in ethylene glycol. A couple drops of the mixture rubbed into the lap surface with the gloved hand is usually sufficient. Newly made laps are used to do the initial rough polishing. As the laps are used, they will produce a better and better final surface finish and figure up to a point. When the laps get too full of salt, they must be washed and reconditioned. Thus, the laps are rotated depending on how close the work is to being finished. When a lap is not being used it is left to press, and when a part is not being polished it is stored in a desiccator.

Polishing water soluble optics is an ideal job for an impatient optician because things happen very quickly. One or two hand strokes over the lap can change the figure by a Newton's fringe of power or two, if that is what is wanted. The downside is that getting the work off the lap at just the right degree of flatness and finish can be tricky and requires experience.

To the best of my knowledge, all precision salt optics of an easily held size are hand polished, one piece at a time, on stationary or very slowly revolving laps. After a couple of strokes around the lap, the part is removed, the bevel is wiped with a facial tissue, and the surface is "buffed" with the tissue to remove the polishing compound. The polished surface is then set on a test plate to check the figure. Since the part will have picked up some heat from the optician's fingers and perhaps some from the polishing itself, the part is left on the test plate for 5 to 10 min before reading the power and figure. Just as the laps are rotated, depending on the stage of polishing, so is the work. While two or three parts are coming to equilibrium on the test plate, another is being figured. This procedure is continued until the figure is good and the finish is satisfactory. The finish is never as good as for most glasses but can be nearly as good with great care and skill.

5 Working Larger Quantities of Flats

The first part of this paper has been about working one or two pieces at a time such as might be done with prototype or relatively large IR optics. There is also a large market for small windows for spectrometer cells, for example. Here the work is blocked down to tools and finished *en masse*. Since the coefficient of thermal expansion of most IR materials is higher than glass, the preferred blocking tool is made of aluminum rather than cast iron as in the case of glass. It will pay to match the blocking body and material carefully. Along the same lines, the work is often set on a prewaxed blocking tool and the weighted combination placed in an oven to warm and melt the blocking wax, and then allowed to cool gradually.

The block is then generated using a 320 or so grit, resin bond diamond wheel and ethylene glycol as a coolant. The finish obtained this way is good enough to go directly to polishing with Linde C. When polishing is finished on the first side, another tool is waxed to the finished side in an oven. After thoroughly cooling, the original tool is heated quickly from the back on a hot plate. Just as the wax starts to melt, this original tool can be pushed off the work exposing the unworked second side. Black tissue paper is used between the work and the tool to keep the parts from being scratched. The black tissue is used so that inspection of the polish is easier than against a lighter background.

We finish this section by saying that with the exception of the water-soluble crystals, it has been our personal observation that almost everything except glass (and there may be some exceptions here) polishes best with diamond and synthetic polishing pads rather than alumina and pitch. One reason is that crystalline materials have varying hardnesses depending on orientation. Since diamond is so much harder than the crystal in any orientation, it polishes all crystal facets with equal speed and produces a surface free of "orange peel" and microsteps at crystal boundaries.

While this approach with diamond may not yield the very best surface on a particular IR material, diamond compound has always seemed to yield the most uniformly predictable

and quickest polish on IR materials, both refracting and reflecting. There is no question that in most cases the surface will have very fine sleeks left from the diamond when the polishing is finished, but this is an aesthetic rather than functional objection in the IR in most cases. Surface smoothnesses of 1 to 2 nm rms are easily obtained with 1-μm diamond and synthetic pads on the harder IR materials.

Typically, diamond polishing is started, after generating with a fine resin bond diamond wheel or loose abrasive grinding, with 3- to 6-μm diamond on a Pellon self-adhesive pad. For flat work, the Pellon can be attached directly to a flat tool. For curved surfaces, it may be desirable to have a pitch underlayer so the lap may be pressed. If pitch is used, petroleum-based diamond compounds must be avoided but ethylene glycol can be used as an extender. The extender supplied with some diamond pastes slowly attacks pitch, but for making just a few of any one lens type, the job will be done before the pitch starts to dissolve.

One beneficial aspect of the diamond is that once the Pellon faced lap is charged with a little diamond paste, polishing can continue for several hours with only the addition of a few drops of extender every 15 min. The polishing is almost a dry process in that the lap is just barely damp with extender. After the grinding pits are gone, the part is thoroughly cleaned and finished on another Pellon lap with 1-μm, or possibly 0.5-μm, diamond paste. The polishing approach with diamond is virtually the same as that used to polish out diamond-turning marks, a technique described next.

6 Fabrication of Aspheres in IR Materials

Because of the limited number of materials that transmit in the IR, particularly in the 8- to 12-μm region, each optical surface must work harder in a successful design. This means that aspheres are used to a larger extent in IR systems than in visible ones. In addition, because detectors are not as efficient and sources are often weak, IR systems tend to be faster than visible ones and thus the aspheres are generally more severe than those encountered on visible systems.

Mild aspheres can be made in IR materials using traditional techniques just as aspheres are made in glass. The only difference is that alumina polishing compounds and wax-covered laps would be used in place of cerium oxide and pitch laps. However, aspheres are difficult to make in any material by traditional methods, and the additional difficulties imposed by the IR materials themselves and the somewhat different laps and compounds make the task difficult. Fast aspherics, because of their large departure from a sphere, are virtually impossible to do by classical methods.

This being said, we turn to the only really practical method of making aspheres in IR materials and metals, single-point diamond turning (SPDT). SPDT is a method of producing an optically finished surface in suitable materials on a very precise, numerically controlled lathe with a cutting tool made of a single-crystal diamond polished to a fine cutting edge. The diamond tool produces a specular surface that appears almost flawless until examined critically. Then the fine feed marks of the tool are apparent as shallow grooves, typically 10 to 20 μm apart. If necessary, these can be removed by postpolishing.

First we deal with transmitting optics and then we treat mirror systems. Luckily, a number of IR materials can be

diamond turned quite successfully. Germanium objective lenses have been diamond turned from almost the first days of SPDT. Zinc selenide and sulfide also turn very well, and silicon turns but is somewhat more difficult to do well. Not surprisingly, the very soft IR materials like cesium iodide, for example, turn well. Although it is much less obvious why, many of the harder crystalline materials such as magnesium and calcium fluoride are also readily SPDTed.[10,11] Although not an IR material, the water-soluble crystal KDP is SPDTed in production quantities for use as a frequency doubler in laser fusion work.[12] This would indicate that other water-soluble crystals could be diamond turned if there were an economic incentive to do so.

SPDT is more widely used to make mirror surfaces for IR systems. Just as aspheres are needed for transmitting optics in the IR, it is even more necessary to make each surface pull its weight in a reflecting system because each element has only one surface. Thus, in most reflecting systems, every surface is an asphere, and, for the same reasons as earlier, these tend to be fast aspheres with substantial departure from the nearest sphere. Again, the only practical method of making these surfaces is by SPDT.

Almost all the nonferrous metals are readily SPDTed.[11] For high-power industrial laser use, copper or silicon are the materials of choice because of their high thermal conductivity. For most imaging applications however, an aluminum substrate is used and the rough-cut SPDTed surface is then chemically plated with a high phosphorous (12 to 14%) electroless nickel. This plated surface is then SPDTed into the actual mirror surface. Since the e-nickel is fairly thin (40 to 150 μm), the part being turned must be remounted on the diamond-turning lathe with a high degree of precision so that in the process of making the final cut, the operator does not inadvertently cut through the plating.

Since all diamond turning necessarily leaves residual tool marks whose depth and spacing are a function of the feed rate and nose radius of the tool, it is sometimes necessary to postpolish the surface to reduce the effect of these marks.[13] Because scattering is proportional to the square of the rms roughness of a surface, even removing about half the height of the turning marks can reduce the scattered light by a factor of 4. Of course, since the diamond-turning marks are very shallow to begin with, 0.1 μm being quite crude, it is seen that postpolishing that does not remove the diamond-turning marks completely cannot possibly change the figure of the part in any significant way.

The notion that careful postpolishing does not change the figure of the part and the costs associated with applying a thick e-nickel coating and diamond turning the coated surface have led us to suggest a more economical process.[14] In this modified process, the aluminum substrate is diamond turned to figure using a rather fast feed rate because it is accepted that the part will be postpolished. After e-nickel plating to 20 to 25 μm, the surface is postpolished both to brighten the e-nickel and to remove the diamond-turning marks that print through the coating. The surface roughness that can be achieved with this method is as good or better than that of the process using a thick coating and performing a second diamond-turning step. Figure 2 shows microinterferograms of a SPDTed electroless nickel surface before and after postpolishing. The example before polishing is typical of the finish on the substrate material after a fast finish cut.

(a)

(b)
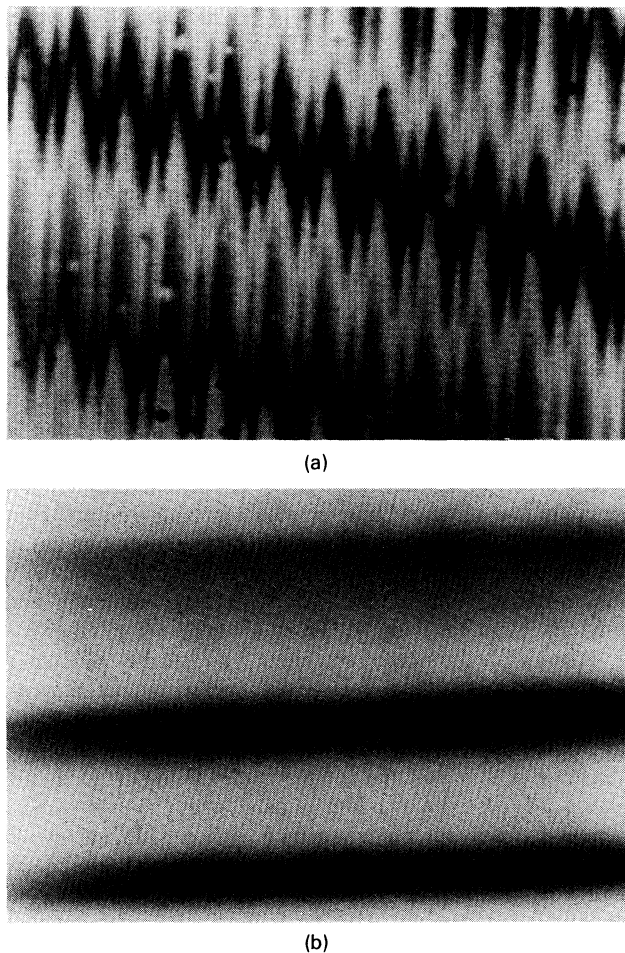
Fig. 2 Microinterferograms of a fast feed finish SPDT aluminum substrate that was subsequently electroless nickel plated: (a) as plated and (b) after 3 min of postpolishing with 1-μm diamond. The scale is about 200 μm across the width of each figure.

We finish this discussion on diamond turning with a few practical comments on the process. First, the current generation of diamond-turning machines can move the diamond tool within hundredths of a micron of the desired curve. On the other hand, this is no guarantee that parts of acceptable figure quality will be produced because there are many possible setup errors. A common error is to not have the cutting point of the tool exactly on the center of the part when the computer controller thinks it is on the axis of symmetry. This leads to a cone or ogive error that is quite damaging to optical performance because it cannot be corrected by any type of realignment.[15] It also leads to a three-corner-hat-type figure error in off-axis parts. Thus, it is imperative to optically test the diamond-turned parts and take corrective action. Most testing is done interferometrically and much of this is in a double-pass null-test configuration. If the finish on the part is not sufficiently good, it will be difficult to obtain data over the entire aperture of the part and/or the regularly spaced tool marks will alias with the pixel spacing and give erroneous figure data. Here, too, postpolishing can greatly aid in obtaining reliable interferometric test data.

While on the subject of optical testing, it should be pointed out that aspheric surfaces are difficult to align with optical test devices, particularly if the component is an off-axis sec-

tion. All SPTD aspheric surfaces should contain some sort of alignment reference surface turned at the same time as the asphere itself. On off-axis parabolas, for example, a narrow SPDT lip perpendicular to the optical axis and a mark or surface parallel to the optical axis as an indication of the distance off-axis will more than pay for themselves in reduced labor in setting up the optical test and analyzing the test data after raw data is obtained. Knowing that an aspheric part is aligned to the optical axis within a fringe or so can turn a difficult test and/or assembly situation into something as routine as testing a sphere.

Finally, we would like to suggest that the accuracy SPDT can achieve should not let designers stray from good kinematic design principles. For example, while it is possible to diamond turn a surface flat to better than 0.1 μm, do not assume that two such surfaces can be bolted together and retain this sort of flatness on the exterior surfaces. First, there is a good chance that the SPTDed surfaces will not retain their original flatness after they are removed from the diamond-turning fixture. Second, it is very difficult to clean two surfaces well enough to avoid having particles between them bigger than 0.1 μm. Even if these particles are not foreign to the parts themselves, many parts will gall and create their own foreign matter that prevents a perfect match.

One thing that will definitely help the galling problem is to bevel parts before the final diamond-turning pass. SPTDed metal parts need bevels for the same reasons that all optical parts require bevels. For one thing, it is almost impossible to preserve good surface finish when postpolishing unless there is a bevel. However, it is difficult and time consuming to put a bevel on after diamond turning and not damage the surface the bevel was intended to protect. Therefore, always indicate bevels on the substrate parts that are wide enough to be preserved through all the plating and finishing steps.

Another thing that must be done when two diamond-turned surfaces are to mate is to relieve the material slightly over the entire surface except in the immediate vicinity of the bolt holes. This leaves slight bosses around the bolt holes that become the actual mating surfaces. By relieving the material in between, any contamination trapped in the relieved part will not distort the surfaces. If the contamination ends up on the mating surfaces, the force exerted by the bolt is confined to a small enough area that the contamination will be squeezed into the mating surfaces without distorting the whole assembly. Last, if bosses are incorporated around the bolt holes, there is a last chance to take out any residual warp of the mating surfaces by one or two passes across a lapping plate that has been cleaned of all but residual abrasive. If the parts have warped in any way, it will be immediately obvious from how the bosses pick up (or gray out) on the lapping plate. If the pickup is not complete in one or two strokes, it is indicative of more serious problems and the parts ought not be assembled anyway.

The point of this last bit of discussion is that while SPDT is an extremely powerful fabrication technique, it is not a solution to all problems. It still requires that good engineering principles be adhered to. It also shows that many classical or traditional optical techniques have an important place directly alongside the newer techniques.

7 Conclusions

We have tried to show why the fabrication of IR optical

components differs in several material-related ways from the fabrication of most visible-light optical elements. The mechanical and/or geometrical aspects of producing both types of elements are the same, but the polishing step itself differs because of the unique chemical properties of glass and cerium oxide that are not present when polishing IR materials.

While alumina polishing compounds and pitch laps have traditionally been used for the polishing of IR materials, diamond compounds and synthetic lap materials are increasingly being used. The diamond compounds and synthetic laps appear to be less technique dependent and give more consistent results, optician to optician. Although it may be possible to achieve better ultimate surface smoothnesses with the alumina, surface roughnesses of 1 nm rms are easily produced with diamond and Pellon on most IR materials.

Since many IR components require aspheric surfaces, diamond turning is the method of choice in most instances for the fabrication of these surfaces that are so difficult by traditional methods. Residual surface roughness from diamond turning can quickly be improved with a little postpolishing without affecting the figure accuracy produced by the diamond turning. Postpolishing is also a useful technique for improving surface roughness if difficulties are encountered during optical testing.

Finally, it is suggested that good engineering practices are still needed even though diamond turning removes much of the burden of making aspheric surfaces. Attention to detail and the use of a few traditional techniques in conjunction with diamond turning are the most cost-effective method of making IR components.

Acknowledgments

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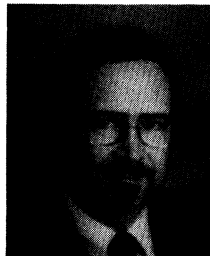
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