COST-EFFECTIVE FREEFORMS
THE ADVENT OF OPTICS WITHOUT BOUNDARIES

Optical designers have traditionally steered clear of freeform components, often telling their lens design software specifically to disallow their use. Otherwise, design programs will automatically seek a 'best form' solution that achieves the highest performance using the minimum number of surfaces. This is frequently accomplished most easily by incorporating freeform optics.

Designers have mostly avoided freeform optics for a simple reason. They have been too expensive and until recently, difficult to source for use in most commercial products. But MKS has developed new fabrication technology that makes high-quality freeform reflectors a cost-effective solution that can be readily obtained in volume. The old boundaries on symmetrical optical design have disappeared.

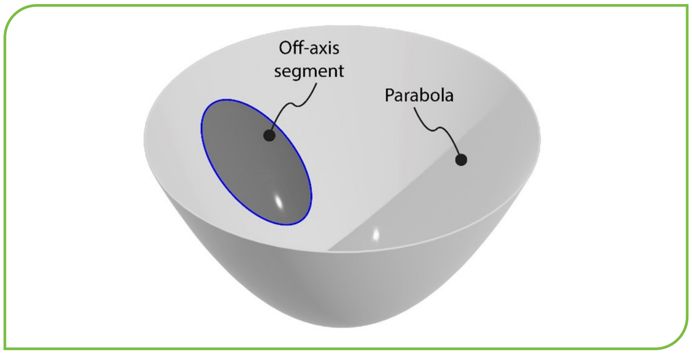

Figure 1. A freeform is a surface without symmetry. One of the simplest and most widely used freeforms is an off-axis segment of a parabola or other conic section.

The Benefits of Freeforms

What exactly is a freeform, and what makes it so useful? A freeform is a surface that lacks rotational and translational symmetry, as shown in Figure 1. This puts them in sharp contrast to most traditional optics which employ spherical surfaces – which are rotationally symmetric in all axes (a sphere has no vertex) – and aspheres which typically have a single axis of rotational symmetry.

This lack of symmetry in a freeform enables more sophisticated control over ray paths than otherwise achievable. This allows freeform surfaces to correct aberrations more effectively than traditional optics, and in particular off-axis aberrations, which are common in wide-field and high-resolution imaging systems. This capability translates into higher throughput and superior image quality, with increased sharpness and contrast across a wider field of view. This benefits several applications from microscopy and spectrography to photography and advanced surveillance.

Freeform optics can also yield designs that are more compact and lightweight without sacrificing performance. Their complex shape allows one surface to do the same work that usually takes many. This often reduces the component count, leading to smaller, more efficient designs. It's ideal for applications where space and weight are critical factors, which range from aerospace to portable consumer electronics. Plus, freeform surfaces can reduce an optical system's sensitivity to real-world mechanical tolerances, making it easier to assemble, and permitting it to consistently perform better in actual use.

The increased design freedom with freeforms opens up entirely new possibilities in optical design. It can allow optical engineers to tackle challenges previously deemed insurmountable, supporting the development of more innovative, novel solutions.

The Freeform Fabrication Challenge

To understand why freeforms have been problematic to source, it’s worthwhile to review the various fabrication methods that have been used in the past. There are a few, and the particular one chosen for a given application depends on several factors. These factors include the component surface shape (especially how far it departs from a simple sphere), the required precision, the part size, the substrate material, the required quantity, and, of course, the target cost.

Most freeform fabrication methods can be broadly classified into a few different groups. The first are various CNC machining methods, including diamond turning. The most advanced of these can deliver optical surfaces that approach the quality achieved with conventional polishing methods. Additional post-machining steps are sometimes employed to further enhance shape or surface quality.

Various sub-aperture polishing techniques can also deliver very high precision freeform surfaces. These include techniques like magnetorheological finishing (MRF) or computer-controlled versions of traditional lap polishing. Again, these might utilize additional processing steps, like Ion Beam Figuring (IBF), to make final adjustments in the required surface shape.

There are also various replication methods, ranging from plastic injection molding and glass molding to more sophisticated techniques. Today, even various additive manufacturing methods (3D printing) are coming into use.

The problem with these approaches is simple. The methods that deliver high surface accuracy and low surface roughness are time consuming and only generate one part at a time. There’s no way to easily scale them up to process multiple parts simultaneously. So, they’re not a practical alternative for making cost-competitive components in any significant volume.

On the other hand, the methods that naturally lend themselves to volume production don’t yield high quality optical surfaces. This inability to deliver high surface accuracy negates the benefits of freeforms in most imaging tasks and mostly limits their use to illumination applications. Plus, some of these volume production methods incur substantial tooling costs at startup.

New Freeform Technology from MKS

MKS Newport has now developed freeform reflector fabrication technology that transcends the limitations of these legacy manufacturing approaches. The result is economical, high precision freeform reflectors that can be supplied in volume.

The process is conceptually straightforward and similar to other existing replication techniques (in which we already possesses a high degree of knowledge and experience). The primary steps are shown in Figure 2 and described below.

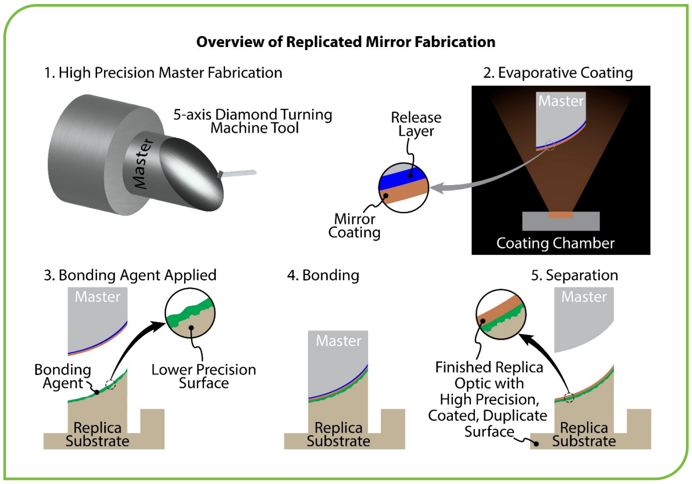

Figure 2. Overview of replicated mirror fabrication.

Key steps in the production of high precision replicated reflectors

1. The process begins with the creation of a high-quality master part. This is usually produced through 5-axis diamond turning of a metal part. Great care is taken at this step since the final replicated parts will closely reproduce the surface of the master. The shape on

this master is the inverse of the final desired surface shape (e.g. a convex master is made to yield concave replicated reflectors).

Various post-processing steps may be performed, along with the use of interferometric and other metrology tools, to reach the desired level of precision. Typically, the goal is to achieve a surface accuracy in the λ/10 –λ/20 range, and a surface roughness that rivals that of traditionally fabricated optics (for the intended operating wavelength).

2. A "release layer" is placed on the optical surface of the master and then a mirror coating is applied over this using standard evaporative methods. Metallic reflective coatings compatible with the Newport replication process are aluminum, UV enhanced aluminum, bare gold, and protected silver.
3. The substrates for the replica optics are fabricated. These parts can take nearly any shape or form and can include various support structures in addition to the optical surface. It's also quite possible to place multiple replicated reflectors on a single, monolithic substrate.

   Most importantly, the optical surfaces on the replica parts do not have to be fabricated to anywhere near the same level of precision as on the master. In fact, they can often be in the range of 20X – 50X worse in terms of surface accuracy and surface roughness. This means that the substrates for the replicas can be made much more quickly and at a substantially lower cost than the master.

   A very diverse range of substrate materials are compatible with the Newport replication process. These include various metals (like aluminum, steel, beryllium, and titanium), glass, ceramics, Silicon carbide and other composite materials, and even carbon fiber reinforced polymers (CFRPs).

   With the substrates in hand, the first step in the actual replication cycle is to place a bonding agent on what will become the optical surface of the replica.
4. Next, the master and replica are brought into contact and the bonding agent is allowed to cure.
5. Finally, the master is removed. The metallic coating stays attached to the bonding agent and thus transfers from the master to the replica. The viscosity of the bonding agent allows it to fill in any "gaps" between the pristine master surface and the much lower tolerance replica substrate.

   The result is that the shape of the master is reproduced with a very high degree of fidelity, both in terms of overall surface accuracy and even as regards to surface roughness. Any tooling marks and mid-spatial frequency surface errors originally present on the replica substrate surface are erased by this process, as shown in Figure 3. Typical specifications for these replica parts are λ/8 surface figure and a scratch-dig of 60-40.

   The master is unchanged at the end of this cycle, and can then be used to make many, many more replicas. Thus, it's possible to turn out a large number of high precision parts on relatively low-cost substrates in a short time. And only one or a few of the higher cost, high precision masters need to be fabricated to accomplish this.

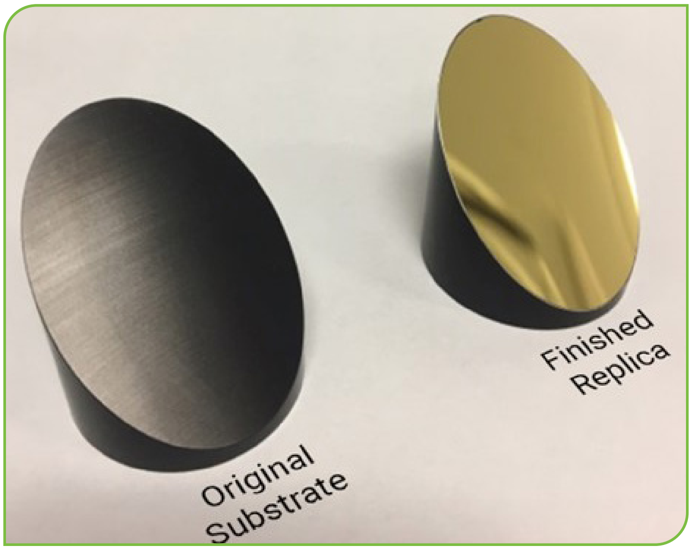

Figure 3. The optical surface of a substrate before the transfer process (left) shows obvious tool marks and surface roughness. After transfer of the gold metallic coating (right), it is smooth and accurate to tolerances typical for high-precision optics.

Freeforms for All

The MKS Newport replication process enables volume production of high-performance freeform reflectors at a fraction of the cost traditionally associated with these types of components. It truly democratizes freeform reflective optics, bringing a technology that has long been associated mostly with high-end military and aerospace optics into the hands of commercial product designers.

Our replication process really delivers much more than just cost-effective freeform optics. Specifically, there are two key benefits beyond just freeform surfaces themselves.

The first is the ability to integrate any type of optic and mount on a monolithic substrate. This capability has been used by defense and aerospace designers for some time to make metal mirror assemblies which are lighter, more compact, and more robust than systems composed of separate optical and mechanical components.

Figure 4 shows a single metal part that contains four flat mirrors – not freeforms. One of the mirrors has a perforation. Having such a monolithic structure eliminates what could be a complicated and time-consuming alignment process during assembly. Furthermore, this system will never go out of alignment. It's robust and rugged.

The four-mirror assembly also highlights the second benefit of our replication process. Namely, having the mirrors and mount composed of the same material eliminates any coefficient of thermal expansion (CTE) mismatch between optics and mount. Thus, this assembly is inherently more stable when exposed to environmental changes.

Figure 4. Four-mirror monolithic design with a through-hole in a mirror for beam entry into system.

Also, the variety of substrate materials available allow the system designer to optimize for a particular use case or a specific set of performance criteria more highly. For example, if light weight is key, aluminum, ceramics or even CFRP can be employed as the substrate. If high stiffness and high thermal conductivity are needed, then silicon carbide can be used.

The ability to replicate high-quality aspheres, as well as other complex components like corner cube retroreflectors, coupled with their seamless integration into mechanical structures, greatly expands the design landscape for system developers. Previously reserved for high-cost, single-use systems in military and aerospace, these capabilities powered by our process can now benefit a wide range of commercial applications. From medical instrumentation and environmental monitoring to LIDAR and ADAS systems, this technology opens doors to a wave of innovative solutions at accessible cost and lead times.

Newport has the expertise and years of experience to help leverage the many advantages of replicated freeform mirrors in optical systems. Contact Newport to find out how freeform mirrors can eliminate unwanted optical constraints, setting optical system design free.

For more information go to:
https://www.newport.com/s/freeform-replication-mirrors

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