Are miniaturised high-precision optics reaching the limits of classical machining?

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Today's optical lenses are produced either through conventional surface machining, or through various replication procedures. Below we compare these manufacturing methods and detail the benefits of classic miniature optics manufacturing, including the realisation of stable production series.

When high-precision optics with difficult geometries and tightest tolerances are miniaturised, classic production techniques remain the manufacturer's method of choice, except for very large quantity applications (>10^5 units) and despite great efforts in the further development of replication procedures.

"Small is Beautiful"

This mega-trend's motto is often cited by modern technology developers. However, in contrast to conventional dimensions (cm, >10^{-2} m) on the one hand, and the operational sizes in nanotechnology on the other hand (nm, 10^{-9} m), the functional optics structures involved with micro-technologies have dimensions in the micrometer range (10^{-3} mm, or 10^{-6} m).

There are strong design tendencies toward optics miniaturisation, especially with weight reduction benefits to be gained. Micro-optical components, with their dimensions of a few micrometers, are chiefly produced by micro-scale based technologies themselves. We refer to micro-optical components as having dimensions between approximately 200 microns and several millimeters. To avoid any confusion with dimensions, this latter type of micro-optics will instead be referred to as "miniaturised optics". One of the leading applications for high-precision miniaturised optics is in endoscopy, where the miniaturisation trends have advanced consistently for more than 40 years (**figure 1**).

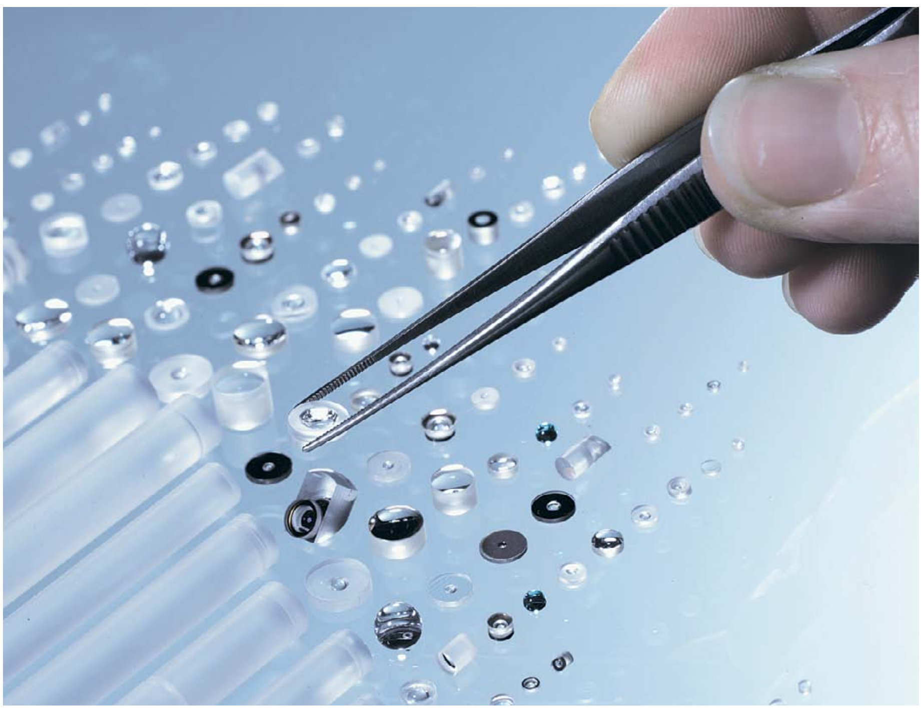

Figure 1: Examples of miniaturised high-precision optics in endoscopy

Round optical components, for example, can be produced with several different materials and methods:

- classical methods with glass (grinding, lapping, polishing)
- glass pressing (moulding)
- polymer moulding
- Hybrid procedures, where conventional, spherical glass doublets are aspherised by a polymer-based top layer.

With high-precision miniaturised optics applications, particularly in special cameras or in medical devices, the image quality requirements have to meet the highest standards, despite the small operational dimensions.

Production procedure assessments:

Materials – glasses or plastics

The plastic transmission materials regularly used in the polymer moulding process differ significantly in their optical properties from glass, which is used in the other two procedures. Plastic optics can weigh up to five times lighter than those made of glass. Another advantage plastic materials enjoy over glass is the possibility of producing a high-unit volume series at a very reasonable price per unit. In addition, there are alternative design freedoms for plastic optics that cannot be achieved with glass for economic reasons. Therefore, aspheric lenses, Fresnel

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optics, diffractive surfaces and integrated assemblies are easier to manufacture with polymer-based technologies and processes. However, unlike plastics, glass is harder and thus more scratch resistant. Glasses are also more damage resistant and stable over wider temperature and humidity ranges than plastics. With plastics, the working temperature range is typically between -40° and 130° C. Outside of this temperature range, a lens form can change significantly. Excessive humidity is another nemesis of polymer-based components because moisture can alter both the form and the refractive index of most plastic lenses. Glasses readily deliver a higher refractive index (e.g. LASF-Glass >1.8) than plastics (up to 1.7) [1], which provides designers with more useful design parameter choices. Therefore, plastic lenses are most suitable for lower image-quality requirements, as well as for high-unit volume, mass market applications. A comparative overview of materials suitable for miniaturised optics is summarised in **table 1**.

	Plastic	Glass
Manufacturing costs for large quantity series (>10^6)	+	-
Manufacturing costs for small quantity series (<10^4)	-	+
Material hardness (scratch resistance)	-	+
Stability over wide temperature range	-	+
Stability over wide humidity range	-	+
Refractive index range	-	+
Weight	+	-
Design freedoms	+	-

Table 1: Main advantages and disadvantages [1]

Moulding

Glass moulding is mainly employed for thick-walled optics and other moulded parts. The greatest advantage of moulding, once a precise master mould is available, is the one-step manufacturing process. Disadvantages stem from the high costs of entry because of tool development requirements. With most glasses shrinking upon cooling, the production of a ceramic master mould is both costly and time consuming, because typically several iterations are required. The glass blank must also be proportioned very precisely. Size and weight must not be changed. Once the mould with desired qualities is created, repeatable batches of lenses can be made for little more

	Glass pressing	Polymer moulding	Traditional machining
Procedure	moulding or hot embossing	injection moulding, compression moulding, hot stamping	tuning, grinding, lapping, polishing
Material	glass	plastic	glass
Operating temperature	up to 250°C (for cold-pressing)	usually up to 800°C (for fused silica at about 1400°C)	room temperature
Typical diameter	<30 mm	several mm to 100 mm	several mm to 100 mm
Typical form deviation of the surface	a few µm	a few µm	a few µm
Low refractive index variations in the material	well	medium (streaks)	very well
Typical unit quantities	>10^5	>10^5	<10^4
Manufacturing in quantities >10^5	++	+++	+
Material resistance	+++	+	+++
Material diversity	++	+	+++
Short initial delivery time by short lead time	+	+	+++
Miniaturisation for high precision requirements	+	+	+++
Typical applications	Consumer optics, for example in CD & DVD drives, digital cameras, car headlights, bar code readers, optical sensors for machines		Optical precision instruments, camera lenses, master forms for glass pressing and polymer moulding

Table 2: Characteristics of the three main manufacturing processes for high-precision optics

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than the low maintenance costs of the moulding tool.
Precision lenses are usually cooled within the moulding tool to prevent distortion or shrinkage. Therefore, economical moulding can be achieved only from high unit volumes, usually in the 10^5 to 10^6 piece range. And in contrast to the classical manufacturing methods, glass miniaturised optics pressing is viable only for a few types of glasses, because of the requirements for the lowest possible transformation temperatures (Low-Tg-glasses) [2-4].

Polymer moulding
In contrast to the lengthy development times needed for ceramic master moulds, the metallic master moulds for plastics are faster to produce and corrected more easily. However, plastic injection moulding, or plastic moulding into a closed form, can be achieved only with limited image quality due to refractive index fluctuations (streaks) in the material. These negative effects can be reduced in the plastic hot stamping steps by slowing material transport into the mould, but it cannot be completely avoided. Therefore, polymer moulding is applicable preferably with lower quality requirements and valuable only for high-unit volume quantities of 10^5 or more. And because the mandrel preparation process of still very expensive, a typical unit volume threshold for polymer moulding is in the million unit range [1,2,4].

Traditional glass machining
For applications that demand miniaturised optics with the very high-precision surface qualities associated with spherical surfaces, and for most manufacturing batch quantities below 10^5 units, the classical machining processes of optical components remains the most appropriate choice.
One quality advantage for miniaturised optics, which can be made from a wide variety of glass types, is the full exploitation of glass benefits as a transmission medium. In addition, there are attractive price and performance ratios associated with glass machining. In the final proofing of high-precision optics over 5-10 mm diameters, local polishing processes such as CCP (computer controlled polishing), MRF (magnetorheological finishing), water-polishing, and ion-beam shaping can be used; these deliver final precisions below 10 nm residual deviations from the intended area. Sophisticated aspheric lenses can also be produced from a diameter of about 5 mm [2-5].
The disadvantages on the technical sides of all three processes are increasingly outweighed with progressive miniaturisation. Despite all the progress in the replication processes, classical surface machining remains the method of choice when miniaturised, high-precision optics are produced in small and medium quantities. **Table 2** shows a comparison of the classical and replication procedures used in the manufacture of miniaturised optics.

Figure 2: Typical production jobs using the classic procedures (from left to right): lens manufacturing, centering, assembly and control

Human advantages in the special challenges of traditional machining

In the production of high-precision miniaturised optics, those between 0.2–5 mm diameters, technicians are still much more precise compared to machines (**figure 2**). One reason humans are more precise than machines is because the machines available for optics production often experience problems both in handling these miniature pieces and in working to the required precision. Negative

Figure 3: Individual lenses and lens groups with diameters from 0.9–5 mm

influences from machines also are more evident in the processing of the smallest dimensions. For example, the smallest changes in pH, temperature, or density of polish suspension, as well as the condition of the tool wear during the production process, will likely have significant influences on the final product quality.
In contrast to machines, skilled technicians can use their powers of observation, experience and reason to quickly respond with flexibility to such changes and thus ensure a high process stability. Innovative and experienced staff, who gained high-process expertise and precision measurement technology competence during the manufacture of miniaturised optics, often employ self-developed tools for use in specialty cases; some of these tools involve special bearings used to achieve high-centering requirements.
The close integration of optical design with the manufacturing, assembly, and testing of the miniaturised lenses has a significant influence on the process yield stability, and hence on the resulting product quality and price. There is also proprietary knowledge and special equipment, such as that used for conical shape processing or coating. Self-made tools, with small dimensions and radii accuracies in the range of 1 µm, as well as unique holders and other special equipment, round out the typical skills of a manufacturer of high-precision miniature lenses.
Feasibility limits have changed due to the continuous development towards ever smaller, more accurate optical components. The accuracies achieved with conventional methods in a stable series production, even with diameters below 1 mm, meet today's highest quality standards. For example, component diameters and center thickness tolerances of ±5 µm, irregularities of λ/4 and a surface quality of 5/1x0,006 (ISO 10110) can regularly be achieved in a stable and reproducible way, under normal production conditions.
Even higher requirements may be achieved with some extra efforts, especially from additional control steps and corrective steps. Depending on the types of glass and geometric requirements, doublets with diameters from 0.3 mm and high-precision compact lenses with a diameter from 0.9 mm, consisting of several individual lenses and a prism group can be manufactured in series (**figure 3**).

Summary and outlook

When moulding is the choice, compounded difficulties arise in the forming process, in the production of moulding tools, in the coordination of each material, and in the process steps. The EU-Project "Production 4µ – Empowering Europe for the µ-Century" [7] is organised in part to not only optimise the entire replication process chain, but also allow future manufacturers of small series optics to produce cost-effective high-precision miniaturised optics. The EU-Project's aim is to achieve a reliable and economical production of high-precision optical components [8].
Meanwhile, today's classical manufacturers of miniaturised optics continue to develop their technologies, achieve even smaller dimensions and even higher accuracies, while reducing costs. The demand for cheaper precision optics continues in growth markets, such as information technology, telecommunications, health care, biotechnology, lighting equipment, aerospace and space exploration. Moreover, some of these applications simultaneously require smaller and smaller optical components with diameters below 5 mm with the highest precision and optical quality requirements. Today's replication methods do not offer profitable and satisfactory solutions, neither for very high quality requirements nor in quantities under 10^5 units. Cost effectiveness and minimum lot sizes are determined by the processing and costs of the complex manufacturing of the forming tools. A limited range of Low-Tg-glasses used in mouldings further restricts application developers.Therefore, classic optics machining remains the most accurate, most reliable, and cost-effective method for the production of high-precision miniaturised optics in small and medium number application fields.

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