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Additive manufactured injection moulds with optical quality surfaces

Max Schneckenburger[1,2], Markus Hofele[1,3], Jonas Raab[1], Simon Ruck[1,3], David Harrison[3], Harald Riegel[1], Rainer Börret[1]

[1]*Hochschule Aalen, Centre for Optical Technologies, Aalen, BW 73430, Germany*
[2]*Technische Universität Ilmenau, Ilmenau, TH 98693, Germany*
[3]*Glasgow Caledonian University, Glasgow, Scotland*

Email: max.schneckenburger@hs-aalen.de

Abstract

Miniature size optics are the key components in most electronic devices. They are becoming increasingly important for example in intelligent systems, mobile robots or driving assistance devices. The image quality depends, among others, from the surface roughness and the shape of the optical lenses. Alvarez-Humphrey-lenses is one type of these lenses, which are focused by laterally shifting two lenses against each other. Such a lateral focussing can minimize the size of optical systems. The aim of this work is to manufacture miniaturized additive Alvarez-Humphrey-steel-moulds. The manufacturing methods of the injection mould for this complex lens are disclosed. The main advantage of using additive manufactured moulds for injection moulding are the possibility of using conformal cooling channels, that will shorten the manufacturing cycle of the plastic lenses. Furthermore, specific moulding materials can be efficiently used. Due to the holes and pores, from the additive manufacturing process, it is impossible to polish additive manufactured surfaces in optical quality without a further process step in between. In that case, the injection mould surface is manufactured in a process chain: after selective laser melting (SLM) the surface is milled, generating the main shape and removing irregularities. In a second step, the surface is laser polished to close small holes and pores by re-melting of a thin surface layer. Afterwards, the surface is milled a second time to generate the final shape of the mould, this time without holes and pores. In the final step, the surface is polished by conventional pad polishing process and/or fluid jet polishing. With this process chain, additive manufactured injection moulds with optical surface quality can be manufactured.

Keywords: additive manufactured injection moulds, laser polishing, pad polishing, fluid jet polishing, selective laser melting

1. Introduction

Miniature size cameras becoming increasingly important in mobile electronic devices like smartphones or as vision sensors in intelligent systems. Today, image sensors a few millimetres in size incorporate more than ten million pixels. However, image quality does not only depend on the resolution of the image chip, but also on quality and functionality of the optics. The most critical factor for active optics in miniature size cameras is the available space. Due to their great potential for miniaturization, Shape Memory Alloys (SMA) appear particularly well suited for this task. SMA wires change their electrical resistance with their shape, so they can be employed as actuators and sensors at the same time. SMA can used as adjustment systems for lenses systems [1]. For example anamorphic lenses, which generates variable cylinders lens power and variable cylindrical lens rotational alignment over incremental viewpoints chosen through its surface, by moving two identical lenses planar in x-y-direction. A type of anamorphic lenses are Humphrey lenses, which are round instead of the square Alvarez lenses. This adjustment of the optical axis results in a space-saving design. The optical surface of such a lens can be defined in terms of thickness equation:

$$t(x,y)=0.0583175389x^3+0.1749526169xy^2+0.2$$

A figure of the 3D-model of the lenses is shown in Figure 1.
The presented lenses have a diameter of 16 mm and a high of the lowest to the highest point of the optical surface from 5 mm.

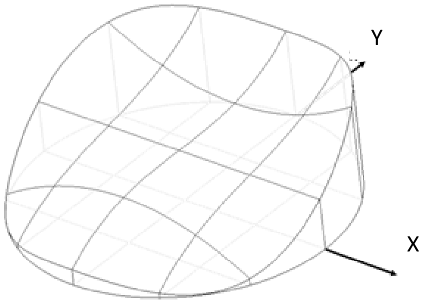

Figure 1: 3D-model of the optical surface of a lens

Lenses are usually injection moulded in large quantities and a steel mould is manufactured. The polishing of such moulds is usually the final processing step and is still mainly carried out manually by experienced specialists [2]. Therefore a great interest in automation of the polishing process for complex surfaces exist. The advantages of additive injection moulds are close contour cooling, fast production of mould inserts and the possibility of repairing moulds [3]. In preliminary tests, the pores created by additive manufacturing were flushed out. Therefore, additional process steps in the production chain are necessary. Between the two lenses there is a transparent liquid with a high refractive index [4]. The aim of that publication is to show the additive manufacturing of optical surfaces from such Humphrey lenses. With the introduced process chain, injection moulds with compelx geometries and / or contour-closed cooling can be produced in all sizes with optical surface quality.

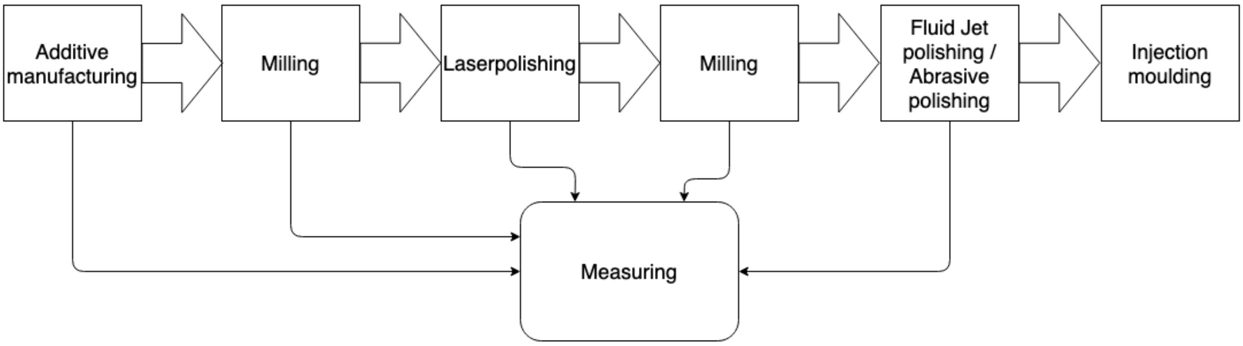

Figure 2: Process chain to generate optical surfaces on additive manufacturing tool inserts

2. Methodology

A process chain was set up for the production of additive mould inserts with optical quality: additive production of the basic contour by SLM, production of the contour by milling, laser polishing to close the pores, milling again to eliminate the waviness. In a final step, the surface is polished to optical quality by fluid jet polishing and abrasive pad polishing (see Figure 2). Due to the complex geometry of Alvarez-lenses, the shape of the injection mould and the injection-moulded lens are both identical. After each production step, the surface is qualitatively measured in order to evaluate the change. The quality of the surface is determined by the roughness and shape accuracy. The roughness is measured by a white light interferometer (WLI) and the shape is measured tactilely. The shape accuracies are measured with the tactile machine ZEISS Prismo. *Sa* is the average roughness and is evaluated over a 3D surface. As already mentioned additional process, steps are necessary. Due to the conventional process chain, laser polishing and fluid jet polishing are combined to create high precise optical surfaces. Milling is done by a conventional high speed milling cutting machine with a cartesian movement system. All polishing steps are done by using industrial six axis robots. The surface quality of the moulds is an essential requirement due to its direct appearance of the plastic injected parts [4]. The contour of the tool insert is enlarge by a factor of four, so the diameter of the lens will be 16 mm. Because of the novel process chain, the focus was on the manufacturing and not on the miniaturizing or minimizing of the tool insert.

2.1. Selective laser melting

Selective laser melting (SLM) is a powder-based additive manufacturing technique with the opportunity to produce highly complex shapes. In comparison to conventional produced parts without a remarkable wastage of material and a long production time. Stainless steel 316L was used to manufacture the tool insert for the injection mould. The 3D printing was done at a TruPrint 1000 Multilaser with a focal diameter of 50 µm. The samples were build up with a layer high of 30 µm at a laser power of 175 W and a scan velocity of 350 mm/s. The lens is tilted slightly to obtain a surface that is as horizontal as possible for laser polishing. However, the surface of the manufactured SLM parts has a high roughness which can affect integrity and the SLM process can affect geometric tolerances [5]. So afterwards different types of manufacturing steps are necessary to generate an optical quality surface. The tool insert is also lightly larger and the outer contour is produced in a final milling step.

2.2. Milling

As an initial test, the shape of the lenses are milled in a larger scale and different material (S235JRC+C and Böhler W400). W400 is a vacuum remelted hot work tool steel with a good macro- and microstructure. That kind of steel has a good polishability, because of the lowest levels of unwanted trace elements and an excellent homogeneity and isotropy. In a second step, the moulds are manufactured additively and pre-processed by milling. All milling steps are done on a RÖDERS RXP500 DS with jig grind technology. The grind technology enables the usage of precisely temperature-controlled, flushing grinding oil. That increases the optical surface quality of the milled work pieces. To increase the accuracy of the manufacturing a zero point clamping system is used. A HITACHI EPBTS2060 TH with a short cantilever extension is used. In a first step, the edge and bottom of the base plate of all additive manufactured tool inserts were milled. Therefore, in further steps there was a clear orientation and an easy calibration of the tool inserts. The optical surface of the tool insert is milled with a meander toolpath and a path distance of 0,005 mm. The idealized prediction of surface roughness (Sa-value) done by PowerMILL was 2 nm, which differ from the reality by vibrations of the machine and process fluctuation.

2.3. Laser polishing

Laser polishing is a contact-free and volume-remain surface treatment technique. It offers the opportunity to work on complex 3D-freefrom surfaces with acheavable high roughness reduction rates in combination with high area rates and fully automatic [6]. Laser polishing is done by remelting of a thin surface layer of the material. For a areal treatment the laser beam is guided highly dynamically over the surface of the workpiece by means of multidimensional scanner optics. Several investigations on additive manufactured metall parts, e.g. Steel alloys, Titanium, Inconel or Aluminum have shown a huge surface improvement. In order to prevent oxidation on the polished surface by reaction with the oxygen content of the air, the process is done inside a process chamber, which is flooded by a controlled Argon atmosphere. The laser polishing was done with a 4 KW disc laser TruDisk4002 (Trumpf). The beam was guided by means of a 3D-Scanner optics I-PFO (Trumpf) with a focal diameter of 760 µm. The samples were polished by a linear hatching with a hatch distance of 50 µm at a laser power of 300 W in combination with a scan velocity of 200 mm/s, comparison to complex 3D-surfaces laser polishing of flat samples was already investigated [7].

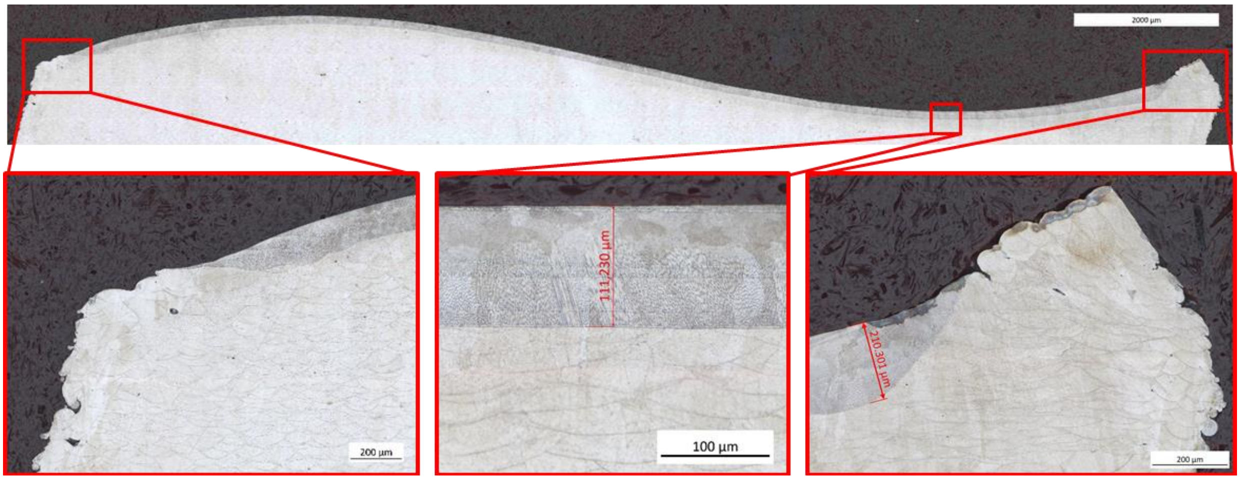

Figure 6: Cross section of laser polished sample, homogenious remelting zone without porosity

2.4. Abrasive polishing

In preliminary tests, fluid jet polishing (FJP) [8] (an alternative polishing process) was carried out on injection moulded components manufactured with additives. The processing pressure creates pores in the surface (see Figure 3), which are created by the additive manufacturing basic form. If the surface is frequently run over by FJ polishing, the pores deepen due to washing out effects. For this reason, laser polishing was combined with abrasive polishing in this paper.

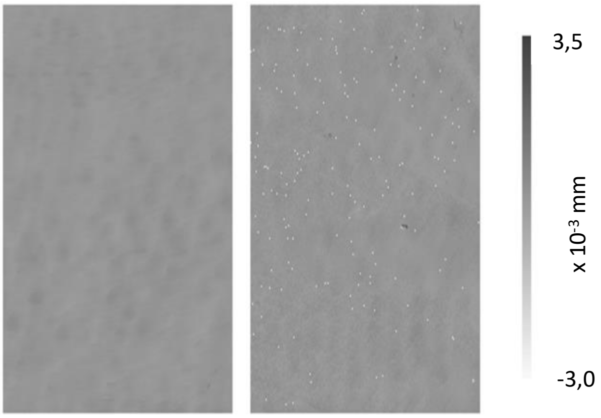

Figure 3: FJ polished surface of laser polished surface (left) and FJ polished surface of additve manufactured surface (right); the white spots on the surface are the pores

Like FJP, abrasive pad polishing is a cutting technique with geometrically undetermined cutting edges. Aluminiumoxid is used as loose abrasive, which is added to water to generate the polishing slurry. It is a continuation of fine grinding with even finer grains and more accuracy to ensure a high surface quality and less shape deviation. The objective of polishing is the levelling of the surface and removing of spikes from previous process steps. The suspension acts between the workpiece and metals.

There are various theories in the literature regarding the mechanisms of the mechanical polishing carrier removing glass, silicon and metal [9].

3. Results

All different processing steps of the tool inserts process chain are shown in Figure . As can be seen in the pictures and the WLI images (Figure 4 and Figure 5), the roughness was considerably reduced by the milling steps and polishing.

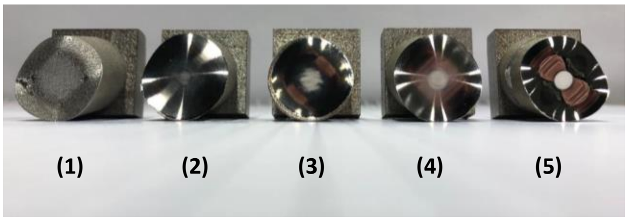

Figure 5: Additive manufactured tool inserts in different manufacturing steps; (1) Additive manufactured; (2) Milled surface; (3) Laser polished surface; (4) milled again; (5) Abrasive pad polished surface

Laser polishing achieves a homogeneously remelted surface layer, shown in Figure 6. Thereby the melting depth varies between 102 µm and 147 µm. The remelted surface layer is absolutely free of porosity. The mean hardness of the remelted layer decreases to 195 HV 0.5, compared to the SLM initial structure hardness of 240 HV 0.5. Table 1 shows that the roughness was reduced about 98,5 %. These Sa-values are the average from five measuring points, all almost the same position on the surface. Laser polishing as the third process step increased the roughness slightly. Considering the form deviation between the desired form and the required surface, there was a maximum deviation of 1 µm (see Figure 7). The coordinate system of the figure is identical with the coordinate system of Figure 1.

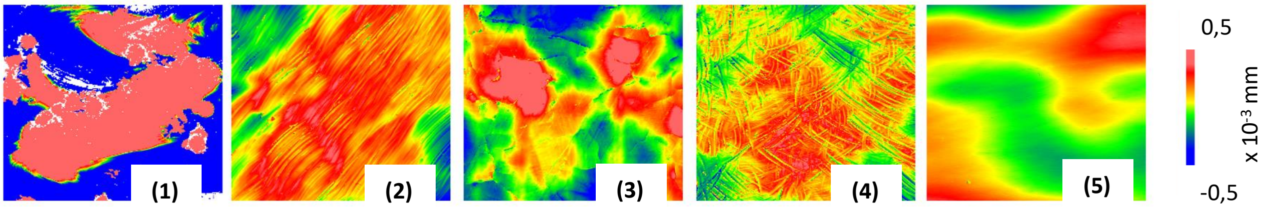

Figure 4: WLI measurements of each process step; (1) Additive manufactured; (2) Milled surface; (3) Laser polished surface; (4) milled surface after laser polishing; (5) Abrasive pad polished surface
Measuring field size: 1,66 x 1,66 mm (additive) and 0,22 x 0,22 mm (all others); Filter: 4th Order

Table 1: Roughness of each manufactured surface

Manufacturing step	Sa [µm]
Additive manufactured	5,82
Milling step 1	0,16
Laserpolishing	0,325
Milling step 2	0,1
Abrasive polishing	0,09

The form deviation is symmetrical, which indicates systematic errors: With a 6 mm milling cutter, the kompleye contour cannot be machined to the desired shape everywhere. Small milling cutters could be a remedy, but they are less rigid than the selected milling cutter. Oversizing could also be a remedy.

4. Summary and conclusion

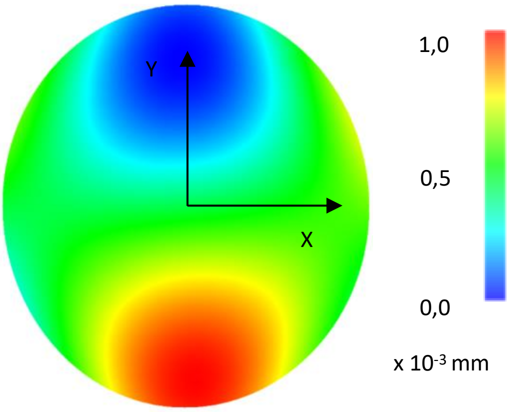

Figure 7: Shape deviation of the manufactured surface and the desired surface

The rapid additive production of injection moulds with optical surfaces was successfully demonstrated. Optical quality (Sa < 10 nm) was not reached yet, but the surface quality of additive manufactured tool inserts was improved. Pores from the additive manufacturing step were closed. To have an exact orientation and exact position of the tool insert, the additive part should be printed on a milled base plate. This makes it much easier to calibrate the tool insert in further steps for milling or post-milling after laser polishing. Furthermore, the repeatability of the manufacturing will be increased. Due to the high radius of curvature, the surface could only be measured in the centre of the surface. With this process chain, the pores from the additive manufactured surfaces can be closed. With this step, polishing processes can be improved to generate in futher optical surfaces on additive manufactured parts. It was possible to produce practically reproducible additive surfaces for tool making. These are comparable with conventionally manufactured steel components. In a further step, the behaviour during injection moulding (e.g. heat and pressure) must be considered over a longer period.

5. Discussion

Due to the complex process chain, an economic production of workpieces is not possible. The effort is only worthwhile for injection moulds with conformal cooling channels or for complex geometries. Manufacturing of moulds by die-sinking EDM or milling is just cheaper, time saving and much more simple.

The targeting with the laser beam and the fluid jet beam during manufacturing will be a challenge. One possibility could be the using of conventional manufactured and milled base plates. The manufacturing of such small objects with optical surface quality challenges the optic manufacturing as well as the conventional manufacturer.

6. Further work

The real scaled shape of the optical lens was milled and polished on an ejector with a diameter of 4 mm. The ejector has a hardness of about 45 HRC. With this ejector as a tool insert first real scale lenses are manufactured by injection moulding. As a further step the ejector should be replaced by an additive manufactured ejector. At the moment, the surface is just polished by abrasive polishing. This is just possible due to the enlarge contour of the tool insert. Another next step is the development of a demonstrator in original size, with a diameter of the lens of 4 mm. In this scale pad polishing is no longer possible and the steel must be polished by FJP. The complexity of the additive manufacturing of such scaled parts and the calibration of the work piece for polishing are challenges for the future. In a further step material, which is simple to polish should be used. Such material has is very homogeneous and has a fine macro- and microstructure.The shape of the surface is not measured yet. In a further step, the shape should be measured and corrected by polishing.

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