Abstract
(Chemo-) mechanical polishing, abrasive flow machining and laser polishing are applied to finish structured molds for injection molding of optical elements. The paper focusses on the development of a (chemo-) mechanical polishing process for structured surfaces that requires specially shaped tools and process strategies which differ from conventional polishing of not structured surfaces. Machining results, i.e. surface roughness and form accuracy of the polished structures, are compared to that achieved by abrasive flow machining and laser polishing.

Introduction
Precision molds for the replication of structured optical elements are generated by precision machining processes like diamond machining or precision grinding. To achieve highest surface quality the application of polishing processes to improve surfaces roughness of the structured surfaces can be necessary [1]. Within this work, possible polishing processes as subsequent finishing operations are evaluated and (chemo-) mechanical polishing, abrasive flow machining as well as laser polishing are applied to structured surfaces.

Structured steel (X40 Cr13) and electroless nickel plated steel samples as shown in fig. 1 were used for all polishing experiments. The workpieces exhibit linear V-grooves with depths d and widths w between 0.1 mm and 1.5 mm and included angles α of 60°, 90° and 150°. The samples were premachined by grinding and diamond fly-cutting, resp. White-light interferometry (WLI) was used for measuring surface roughness and form accuracy of the structures.

(Chemo-) mechanical polishing of structured surfaces
(Chemo-) mechanical polishing of structured surfaces requires dedicated tools and process strategies which are different from conventional polishing of continuous, i.e. not structured surfaces. At the Laboratory for Precision Machining LFM a (chemo-) mechanical polishing process for finishing of rectangular and V-grooves using pin type and wheel type polishing tools is in development [2]. The polishing tools are made of the polyamid PA6 that incorporates relatively high hardness to guarantee form stability and sufficient toughness so that the abrasives can be impressed into the tool. Furthermore, PA6 can be machined very precisely by means of diamond turning. For performing the polishing experiments a Precitech Microfinish 300 aspheric polishing machine was
modified, now consisting of three linear axes as well as polishing and a workpiece spindle. For the application of both pin type tools and polishing wheels the polishing spindle can be tilted by +/-90°.

Conical pin type tools with an included angle \(2\cdot\kappa\) of 140° and conical wheel type tools with an conic angle \(2\cdot\kappa\) of 30° were used for polishing of one side of 0.2 mm deep 150°-grooves (fig. 2). To achieve full contact with the one side of the structure the conical pins have to be tilted by 5°. 2 mm long groove sections were polished with varying process parameters. The polishing time was varied between 1 min and 15 min, polishing forces \(F\) between 0.02 N and 0.3 N and the rotational speeds \(n_p\) of the polishing spindle between 100 rpm and 1000 rpm (in case of conical pin type tools) or 25 rpm and 100 rpm (in case of polishing wheels), i.e. relative velocities \(v_r\) between 0.01 m/s and 0.1 m/s for polishing both the steel and electroless nickel plated substrates. A water based diamond suspension with a grain size of 0.1 µm was used.

Fig. 2: Polishing tools for structured surfaces.

Fig. 3: (Chemo-) mechanical polished side of a V-groove in electroless nickel.

Fig. 3 shows a diamond fly-cut V-groove in electroless nickel after polishing using a conical pin type tool (polishing time 5 min, polishing force 0.2 N, rotational speed of the polishing spindle 300 rpm, relative velocity 0.02 m/s). The roughness Ra of the fly-cut groove of about 14 nm was improved by a factor of two. Furthermore, one can see the high form accuracy at the bottom of the V-groove. Roughness values Ra of the polished steel substrates are in the same order using both pin type and wheel type tools.

Abrasive flow machining of structured surfaces
Abrasive flow machining is a process actually used for improving the surface quality of inner profiles as well as for deburring and rounding of edges [3]. An abrasive medium consisting of a polymer fluid, abrasives with a defined grain size and additives is
pressed along the contours at a certain pressure and temperature. For these purposes the workpiece is positioned in a special workpiece holder and clamped between the upper and the lower cylinder of the abrasive flow machine tool. Then, the heated abrasive medium is cyclically pressed from one cylinder into the other passing the surface of the workpiece at a defined speed. In abrasive flow machining the material removal rate is in direct proportion to the speed of the abrasive medium [3].

For polishing of the structured steel and electroless nickel plated workpieces by abrasive flow machining the tool holder defining the pass of the fluid was made of polyamid (fig. 4). For machining the abrasive medium (50% SiC, 200 mesh) was heated up to 35°C. Machining time was 15 min for 5 cycles and the machining pressure was 1.5 MPa. Fig. 5 shows WLI-images of an abrasive flow machined V-groove in steel. As can be seen the edges at the bottom and top of the groove are rounded. Surface roughness Ra at the sides amounts to about 100 nm. Roughness Ra of the sides of the electroless nickel grooves is about 150 nm.

**Laser polishing**

Laser polishing of structured surfaces is performed by focussing a laser beam perpendicularly on the workpiece. In dependence of the power of the laser beam the surface of the workpiece is evaporated, i.e. material is removed, or slightly melted. In this case material is no longer removed and due to surface tensions of the melted material a smoothing effect can be achieved.

In first experiments a Nd:YAG-laser (\(\lambda = 1064\) nm) was used for laser polishing of a steel substrate with linear V-grooves (fig. 1). The feed velocity of the laser beam was varied in the range of 80 mm/min to 500 mm/min and the power of the laser beam between 50 W and 100 W. The diameter of the laser beam was 200 µm. Laser polishing was performed in three steps from "rough" polishing to finishing by reducing the laser power. Fig. 6 shows the laser polished steel sample (left) and a WLI-image of one side.
of a 150° V-groove (right). The roughness Ra of the grooves is in the range of 300 nm to 450 nm. The melted and solidified surface can clearly be seen.

Fig. 6: Laser polished structured steel sample.

**Conclusion and outlook**
The new developed (chemo-) mechanical polishing process is well suited to improve surface roughness and to guarantee high form accuracy of the structured electroless nickel plated and steel substrates. The reduction of the structures' dimensions as well as polishing of circular, e. g. Fresnel structures are main objectives for future work. Due to its process technology abrasive flow machining is limited to more or less linear structures. Furthermore, the rounding of edges can not be avoided. Nevertheless, abrasive flow machining of structures will be continued using finer abrasives and optimized process parameters. Also, laser polishing experiments will be continued using optimized process parameters and to improve surface roughness and form accuracy. First results show the potential of laser polishing for finishing of structures but optical surface quality could not be achieved.

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**References**