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Measurement of in-mould shear rates by x-ray particle image velocimetry

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Abstract
The manufacturing of large quantities of polymeric optical and micro-optical components becomes more and more important regarding industrial applications as MEMS devices, customer electronics or micro imaging systems. The relevant parameters for the qualification of polymeric micro optics as surface roughness, shape and positional tolerances, refractive index, molecular orientation, injection moulding process induced deviations and their connection to injection moulding parameters are largely known. The manufacturing of micro optics by micro injection moulding and associated with that, micro injection moulding machine tools with highly complex plastification and injection systems is far less understood. In particular, the influence of shear loads and temperature deviation on replication quality has not been fully investigated. The occurring shear rates during injection moulding lead to mechanical damage of the polymer on a molecular level and reduced optical functionality. This work presents an approach for in mould shear rate measurement by the use of a metrological computed tomography system. Using metal powder with a particle size 3 µm ≤ dp ≤ 5 µm as tracer particles, Polyetheretherketon (PEEK) as mould material, a Zeiss Metrotom 800 computer tomography system and a Babyplast injection unit, streamlines of polymer flow could be visualized. In accordance to optical particle image velocimetry (PIV), for each frame a matrix including particle position was calculated. The temporal shift of these positions lead to velocity gradients that allow the calculation of shear-rates . By reproducing relevant elements of injection units and mould structures, this works enables the profound investigation of fluid dynamics regarding micro injection moulding and the correlation between shear loads and polymer characteristics.

Keywords: micro injection moulding, micro optics, PIV, computed tomography, shear rates

1. Introduction

Mould filling mechanisms and fluid mechanics of polymer melt were frequently investigated [1, 2, 3, 4]. With regard to micro injection moulding of highly complex components, an assumption of mould filling mechanism and occurring velocity and shear rate distribution is essential for mould and process design. By default, the prediction of these parameters is based on injection moulding simulation or empirical values. The measurement is made by indirect measurement methods, for example by cavity pressure or temperature sensors. The direct investigation of in mould polymer flow under real conditions has not been performed yet.

2. Fluid dynamics of polymer melt

Polymer melts are non-newtonian fluids with a shear rate and temperature dependent viscosity. The viscosity of technical relevant polymers tends to drop nonlinearly with increasing temperature and shear rate. Due to intermolecular chain relationship, shear force load causes an overcome of the binding forces and a liquefaction of the polymer melt. Furthermore, frictional heating due to shear loads lead to an inhomogenity of the specific volume of the polymer and also an inhomogenity of the shrinkage. As an effect of the shear rate dependent viscosity of a polymer melt, the velocity distribution over cavity cross-section exposes its maximum in the centre flow and a significant reduction at the side flow. Due to polymer adhesion and resolidification at the cavity walls, flow velocity reduces to $v_{pflow} = 0$ m/s. In a row with the velocity gradients, shear rate increases in close to wall areas. The shear rate maximum during cavity filling process occurs in the transfer region between solidified layer and polymer melt. This shear rate maximum leads to a significant influence on the polymer solidification process and to increased molecular orientation. Due to the deviation from random molecular orientation, an anisotropic expression of part properties and residual stresses occurs. Consequently, shearing loads of polymer melt during injection moulding have a considerable impact on the dimensional accuracy of injection moulded components [5]. Monitoring of injection moulding processes is currently limited to machine tool based monitoring systems and injection moulding tool integrated pressure and temperature sensors. With special regard on axis velocities, plasticizing and injection pressures as well as temperatures, the monitoring of industrial production processes is possible with adequate significance. For the direct observation of technologically demanding replication processes and the determination of injection velocity profiles and local shear rates no methods are available.

3. X-ray particle image velocimetry (PIV)

PIV is a proven method for the investigation of complex flow phaenomena. Because of the necessity of an optical accessibility, PIV has not been used for the investigation of injection moulding tools until now.

3.1. Experimental setup

By the use of an x-ray tomography system Metrotom 800, Zeiss IMT GmbH, Oberkochen, Germany, a mould manufactured from PEEK polymer, and a Babyplast injection unit, Christmann Kunststofftechnik GmbH, Kierspe, Germany, the injection cycle was recorded and analysed.

As presented in figure 1, the injection system consists of the Babyplast micro injection moulding unit and a mould. By a rigid connection of injection unit and mould, the sealing of the nozzle is ensured. Using a rigid support structure, the mould and the region of interest are positioned into the beam path with a distance between x-ray source and mould s_{work} = 100 mm. As a result of this, a focal spot with a diameter d_{Spot} = 18 µm was used for the experimental study.

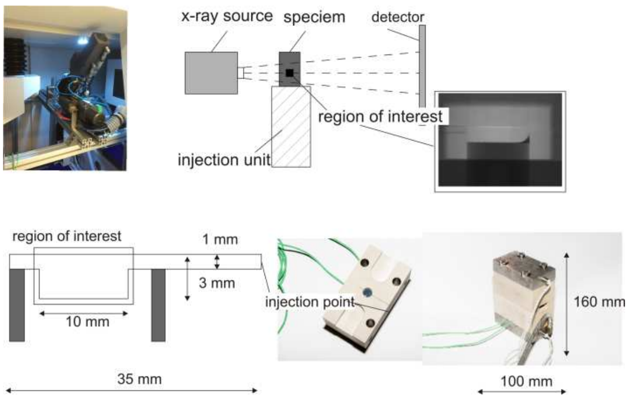

Figure 1. Experimental setup and schematic representation of the examined cavity

The used mould system (Figure 1) consists of two mould halves made of PEEK Polymer and two boundary tooling plates manufactured from tool steel. The boundary tooling plates include heating cartridges (Z110, Hasco Haseclever GmbH, Lüdenscheid, Germany) for the mould tempering. Furthermore, the mould locking force is applied across them. The microstructured mould insert is integrated into the lower mould half. For the injection moulding of the reference structure the Cyclo-Olefin-Copolymere (COP) Zeonex 300R, Zeon Corp., Japan was used. Additionally, carbide powder with a particle size 50 µm ≤ s_{part} ≤ 80 µm was added to the polymer granulate.

3.2. Design of experiments

The injection moulding processing data presented in Figure 2 were determined and optimized in a preliminary investigation to ensure a reliable replication process. The raw pictures were transferred into jpeg data format and inverted by the use of Photoshop CC, Adobe Systems, Mountain View, USA. Using the PIVLab plugin for MatLab 2016b, Mathworks Inc., Natick, USA the evaluation was performed.

4. Experimental results

As presented in Figure 2, the inflow of polymer melt could be visualized and transferred into a calculated velocity distribution. The resolution of the used setup was suitable for the distinction of single particles, the refreshment rate sufficient for the recording of several images during one single injection cycle.

As also shown in Figure 2, the formation of the flow front covers the expectation regarding the in-mould flow of a polymer melt. However, the peak values of the velocity are located in the close to wall areas of the flow, in particular near to the microstructured insert. These peaks are restricted locally. The formation of a velocity distribution as expected from literature is unverifiable [6].

Using the velocity distribution for the calculation of local shear rates, the exemplary results were calculated (Figure 2). In this respect again, the maximum values occur in the close to wall areas. Furthermore, the overlap of positive and negative shear rate maxima in adjacent areas leads to the conclusion of occurring backflow and stick-slip effects in close to structure areas.

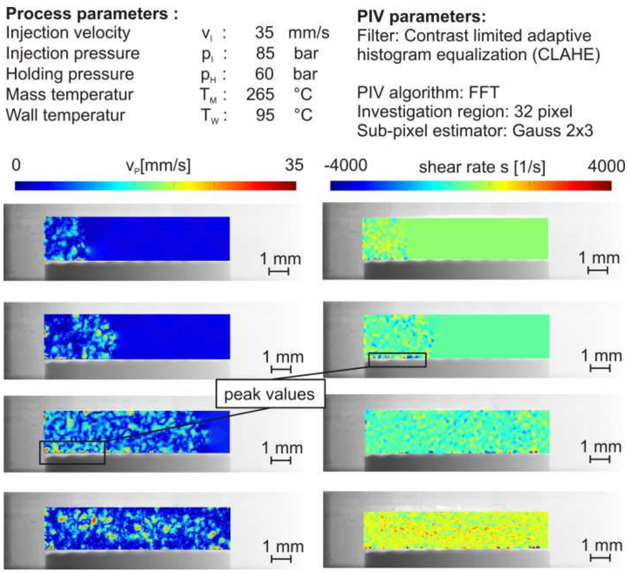

Figure 2. Velocity and shear rate distribution, determined by x-ray PIV

5. Summary and Outlook

The primary evaluation proves the functionality of the measurement principle. The visualization of flow and the calculation of local shear rates could be executed. Furthermore, the possibility for a velocity and shear rate calculation could be demonstrated. The reservation must be made, however, that x-ray PIV is not based on the visualisation of an intersection. The overall volume of the cavity is penetrated by the transmitted x-rays. Therefore, the investigation of cavities with a 2,5 dimensional shape is possible with high accuracy. The analysis of flow phenomena in cavities with highly complex geometries or greater wall thickness is limited. Nevertheless, for the further investigation of the relationship between shear rate and dimensional accuracy, the effects of polymer flow on shrinkage and distortion of parts as well as the correlation of the used mould-filling process and optical performance of polymeric micro optics x-ray PIV is a promising approach.

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