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Investigation of injection moulded UHMWPE liner manufacturability

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***Abstract*— In our study, the difficulties of the injection moulding of pure ultrahigh molecular weight polyethylene (UHMWPE) are collected and presented. We focused on the manufacturability and the dimensional accuracy of an injection moulded UHMWPE liner.**

Keywords—UHMWPE, injection moulding, prototype tooling, shrinkage, prosthesis

I. Introduction

Ultrahigh molecular weight polyethylene (UHMWPE) is a linear homopolymer of ethylene with outstanding physical and mechanical properties, therefore it is used in a wide range of industrial applications (e.g. runners for the bottling industry, bumpers and sliding for harbours, cluding pickers for the textile industry, and lining for dump trucks and coal chutes). UHMWPE is widely used in the medical field as well due to its chemical inertness, impact resistance, lubricity, and excellent wear resistance. Typically, it is used for joint replacements but coiled UHMWPE fibres can also be used in artificial muscle reproductions [1-2].

Typical manufacturing techniques of UHMWPE prostheses are compression moulding, ram extrusion, hot isostatic pressing, and direct compression moulding. They all use the powder resin form of the material produced from ethylene gas by polymerization, with the use of the Ziegler process. The very high melt viscosity of UHMWPE, and its extremely low melt flow rate can be associated with its high molecular weight; it is hard to manufacture it with conventional processing techniques such as injection moulding. Injection mouldable UHMWPE granules open the door for further experiments and technology research [1].

As no or limited usage of processing aids or additives is allowed in medical-grade materials, it is harder to find a material which improves processability but at the same time does not impair the mechanical or tribological properties of the material and keeps its medical grade as well. Based on a literature review, we can say that processability can be improved with PP [3] and HDPE [4-5], and especially Hydroxyapatite [6-8], which has great importance in the case of prostheses. Another way of improving manufacturability is to optimize manufacturing conditions and parameters [9-11]. In the case of medium to high volumes and standardized sizes, injection moulding could be a viable technology for the production of prostheses. However, in case of customized prostheses or standardized prostheses with small-series production, prototype tooling could be the best solution. With additive technologies, waste could also be minimized during processing. In injection moulding, reusing the runner or the sprue is still an important factor of waste reduction. In the longer term, not only re-granulation could be a solution but there is also a strong emphasis on the reusability of the above-mentioned parts in other applications. For example, reused UHMWPE can be used in asphalt mixtures [12].

We investigated the manufacturability of injection mouldable UHMWPE and the dimensional accuracy of the final product, and also checked current prosthesis designs to see if it is possible to injection mould their geometries in good quality. In our experiment, an UHMWPE liner was used as part of hip prostheses because of its nearly constant and relatively thick wall thickness. Shrinkage properties of the material were measured. For experiments on hip prosthesis liners a prototype mould was fabricated by the PolyJet technology. First of all, the dimensional accuracy of the prototype mould was examined, because it affects the quality of the final product. The research is supported with simulations; we determined the expected change in geometry and monitored the resulting pressure values. After the mould was manufactured, the part was injection moulded and the accuracy of the final product was measured by 3D scanning. The results were compared with the appropriate CAD model of the prosthesis. We wanted to check if it is possible to manufacture good quality UHMWPE parts with a prototype injection mould.

II. Methods and Experiments

A. Raw material

For injection moulding, Lubmer (L4000) commercial grade UHMWPE was used. The injection mould was created with an ABS-like material with the PolyJet technology (Objet 500 Connex 3). It is a photopolymer resin and it is recommended for injection moulds due to its high temperature resistance and toughness.

B. Simulations

As the liner was made by injection moulding, it was important to optimize the product and the processing technology by simulations. For this purpose, Autodesk Moldflow 2019 was used. During the simulations, the exact material, machine, and tool properties for the prototype mould were set manually.

C. Measuring shrinkage

As a preliminary experiment, moulded plates of the material were fabricated and its shrinkage properties were measured with a Keyence VHX-5000 optical microscope and a Mitutoyo ID-C112B digital indicator.

D. Design and fabrication of the mould

As a first step, an injection mould was produced for the liner with an Objet 500 Connex machine. With the prototype mould, high-quality parts can be injection moulded even at high pressures and temperatures.

E. Injection moulding

An Arburg 420 C injection moulding machine was used to produce plates for the measurement of shrinkage. The zone temperatures during the injection moulding of the UHMWPE plates were set to 225, 230, 235, 240 and 240 °C, and the temperature of the mould was 40 °C. The volume was 80 cm^3, the switch-over point was 25 cm^3/s and the injection rate was 40 cm^3/s. Holding pressure was set to $7 \cdot 10^7$ Pa and holding time was 20 s. The decompression volume was 5 cm^3 and its rate was set to 5 cm^3/s. Cooling time was 30 s.

An Arburg Allrounder 370 S injection moulding machine was used to produce the liner. The zone temperatures for the UHMWPE liner were 195, 200, 205 and 210 °C. The injection rate was 10 cm^3/s, holding pressure was $2{,}5 \cdot 10^7$ Pa, holding time was 25 s, and cooling time was 400 s. The decompression volume was 5 cm^3 and the decompression rate was 5 cm^3/s.

F. Checking dimensional accuracy

Finally, the dimensional accuracy of the mould itself and the final product were measured with a GOM Atos Cor 5M 3D scanner.

III. RESULTS AND DISCUSSION

First data from simulations were used, such as the predicted size of the final product and the measured shrinkage values of the material. After the injection mould was fabricated and its accuracy was measured, all data were fed back in the design phase, so that an injection moulded UHMWPE liner with accurate dimensions was produced.

A. Simulations

Hip liners have a geometry that makes them easy to injection mould in good quality due to their relatively thick and constant wall thickness. The simulation results show that the gate must be located on the top of the surface so that material flow can be consistent (Fig.1).

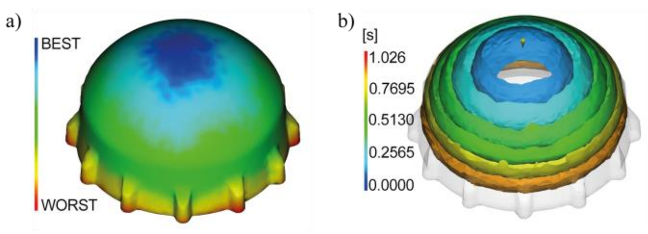

Fig. 1. Gate location (a) and expected flow direction during the filling process (b)

In the case of injection moulded parts, one of the biggest challenge is to ensure accurate final dimensions and to follow the exact shape of the product, which can be influenced not only by the geometry but also by the mould, the processing equipment used, the characteristics of the raw material and the manufacturing parameters.

In terms of shrinkage, the two most important material characteristics are the viscosity curve (Fig. 2) and the pressure-volume-temperature curve (pvT) (Fig. 3) UHMWPE does not show a Newtonian character even in a very low shear rate range; the temperature dependence of the viscosity is less than usual. The pvT curve of UHMWPE, as expected, shows similarities to the general pvT curve of semi-crystalline raw materials.

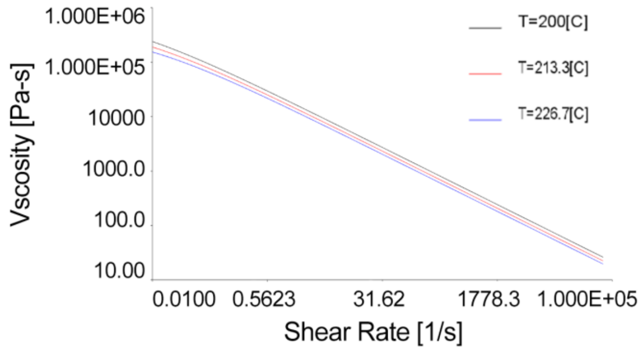

Fig. 2. Viscosity curve of UHMWPE

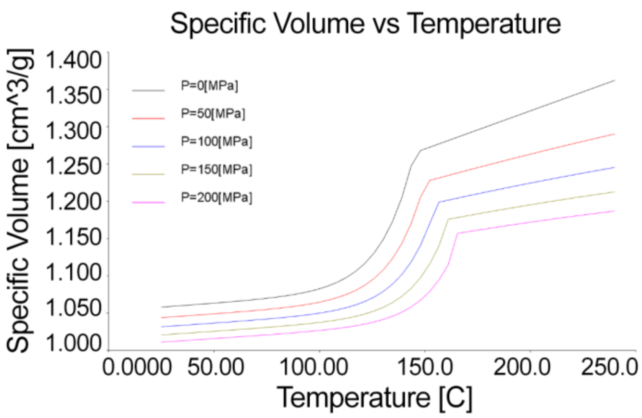

Fig. 3. Pressure-volume-temperature curve of UHMWPE

With our prototype mould it is important to ensure good flowability and lower-than-usual pressures in the mould cavity. Accordingly, moderate speeds and pressures and the maximum allowable temperature were set. Melt temperature was set to 250 °C, the injection rate was 10 cm^3/s, holding pressure was $2{,}5 \cdot 10^7$ Pa, holding time was 25 s, and cooling time was 400 s.

In terms of shrinkage, it is important to examine how much the pressure differs at certain points of the flow path. Large deviations often mean uneven shrinkage, which causes the product to deviate from the intended shape, which is difficult to compensate in some cases. In the case of the liner, pressure as a function of time shows a good agreement in different parts of the product (Fig. 4).

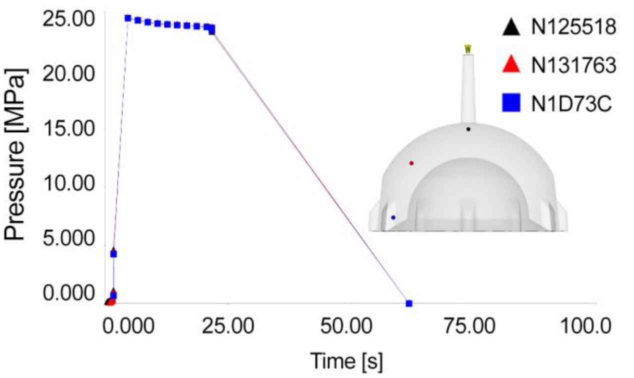

Fig. 4. Mould cavity pressure as a function of time at different distances from the gate

From the thermal history and the pressure as a function of time, warpage and shrinkage can be predicted; orientation effects also need to be taken into account. The sprue was not considered in the calculations as it is expected to be removed immediately after the manufacturing phase. Due to the geometry of the part, a mesh of four-node tetrahedral elements were used. The dimensional changes of the part after production and the nature of the deformation are illustrated in Fig. 5. As the figure shows, the size change of the part can be considered fundamentally proportional, the shape deviations from the design are negligible; however, the part suffers significant shrinkage. The characteristic diameter change of the part exceeds 1.5 mm, which means a size change of more than 3%. This significant shrinkage is due to the relatively high thickness and prototype tooling.

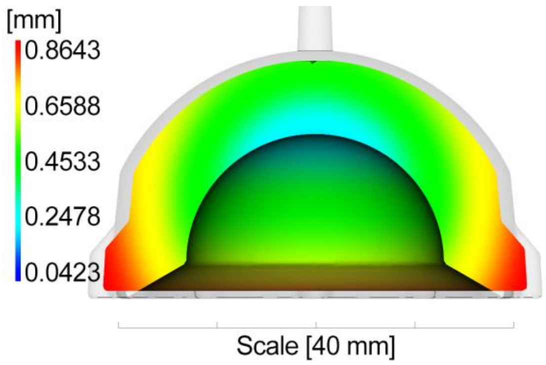

Fig. 5. Expected size change of the liner after injection moulding

B. Measuring shrinkage

Equation (1) was used to calculate shrinkage [13].

$$S_t = \frac{L_{sz}-L_t}{L_{sz}} \cdot 100 \qquad (1)$$

where S_t [%] is the shrinkage at (t=24 hours) a specific section, L_{sz} is the size of the same section of the mould measured at room temperature and compensated for the thermal expansion of the steel (the plates were injection moulded in a steel mould) according to mould temperature, and L_t is the real size of the injection moulded part on the same section t hours after production. In the calculation, ideal injection mould dimensions were used as L_{sz}. For more precise calculation, measuring the dimensional accuracy of the mould is necessary [13].

First of all, 6 plates were produced with a film gate with a two-cavity mould and their dimensions were measured to calculate shrinkage. For the calculation of the shrinkage of the nominal thickness, 9 points on each plate were measured with a digital indicator (Fig.6). Shrinkage was 3.05 ± 1.18 %. Fig. 6 shows the measurement of shrinkage along the x and y-axis. 3+3 measurements were performed on each plate with an optical microscope.

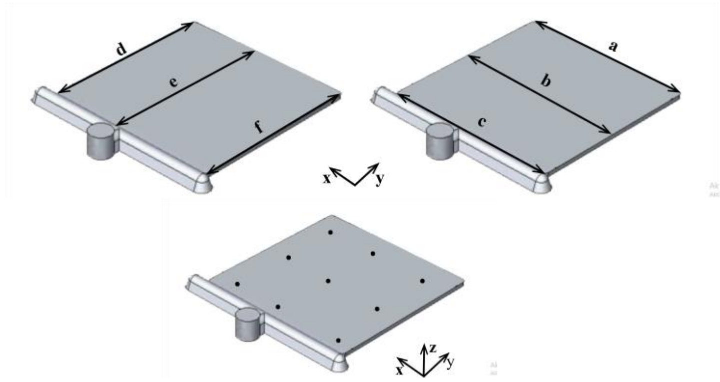

Fig. 6. Average linear shrinkage from distance and thickness measurements

Table 1 shows average linear shrinkage 24 hours after production. It shows the effect of distance from the gate perpendicular to the flow and parallel to the film gate. Closer to the gate, average linear shrinkage is the lowest, and away from the gate it is the highest. The result is logical, as shrinkage was compensated for longer near the gate. With thin walls and a relatively massive sprue/gate design, shrinkage is more pronounced.

TABLE 1.

Linear Shrinkage properties, %					
a	**b**	**c**	**d**	**e**	**f**
1.55± 0.20	**1.48±** 0.19	**1.40±** 0.18	**2.10±** 0.50	**2.21±** 0.55	**2.44±** 0.72

C. Design and fabrication of the injection mould

The results of the simulations and estimated shrinkage data were used in the design of the prototype mould. It has one cavity, due to the small number of parts produced and also because our main goal was to test the manufacturing technology, so we tried to make it as compact as possible. Fig.7 shows the main parts of the tool.

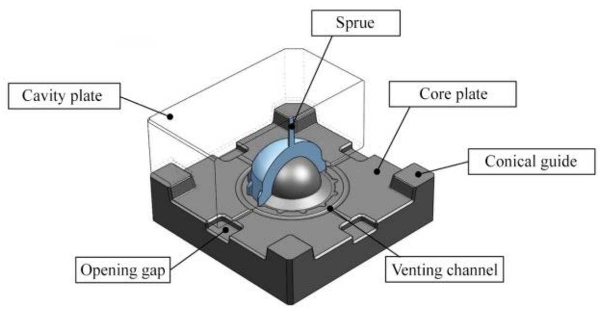

Fig. 7. Injection mould design

Venting channels were created to allow the mould to be properly vented. Opening gaps were provided to open the mould halves. Conical guides at the corners ensure the position and the centring of the mould. Due to the design of the mould, the injection moulded liner remains on the moving (core) side, and makes it easier to remove it. Ejectors were not used; the product was removed manually in all cases. Fig. 8 shows the section view of the mould and the main dimensions.

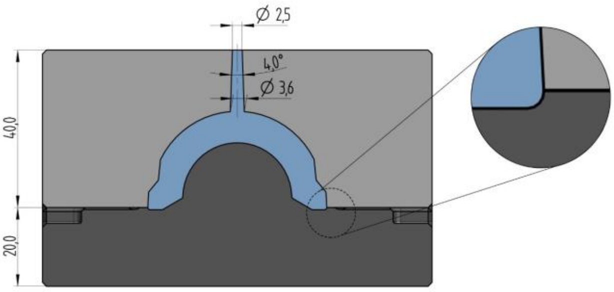

Fig. 8. Section view of the mould with main dimensions

D. Checking dimensional accuracy

Before it was used, the dimensions of the mould were measured. Fig. 9 shows the comparison of the original CAD models and the produced injection mould halves. There were no big differences or inaccuracies.

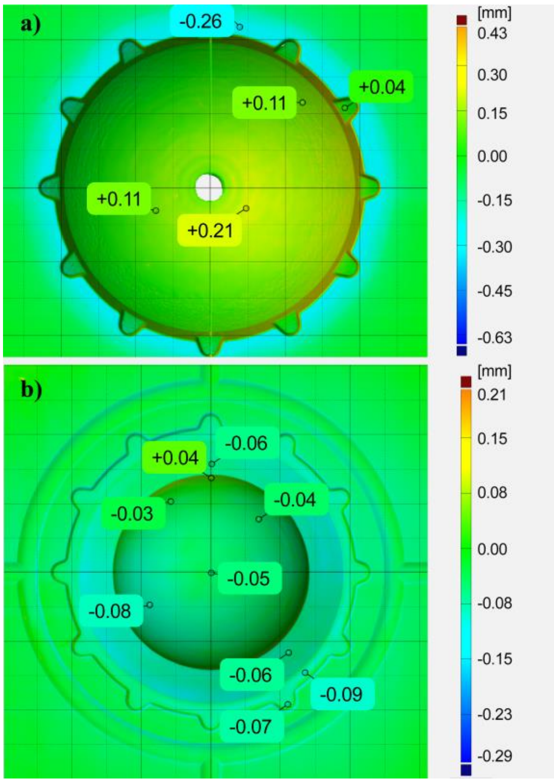

Fig. 9. Comparison of the CAD models and the 3D scanned mould halves

After assessing the accuracy of the mould, the test liner was injection moulded and its accuracy was checked too. Fig. 10 shows that there is considerable shrinkage on the outer surface of the product, while a slight increase in size is observed on the inner surface. A comparison of the results of digitization with the Moldflow results shows that they are similar.

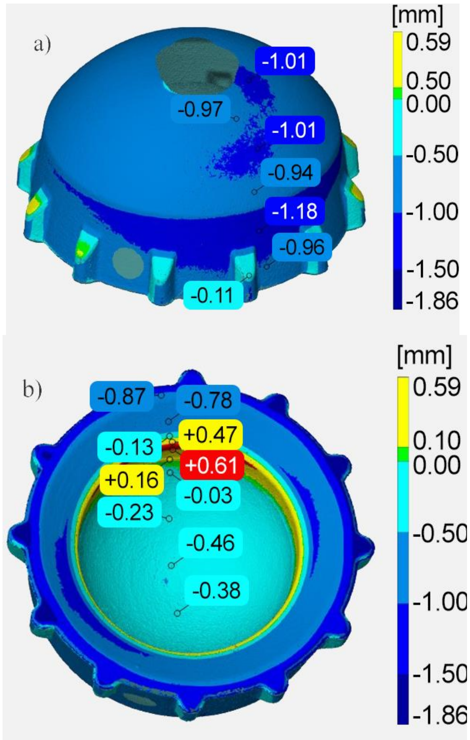

Fig. 10. Comparison of the original CAD models and the injection moulded parts: (a) outer and (b) inner geometry

Using the results of simulations and experiments, we redesigned the injection mould to produce an UHMWPE liner with accurate dimensions. Finally, Fig. 11 shows the assembly and the fitting test of the UHMWPE liner with the acetabular component produced by DMLS. The mating surface of the DMLS acetabular component was finalized by milling and the liner was injection moulded with the prototype injection mould. The liner fits properly in the acetabular component.

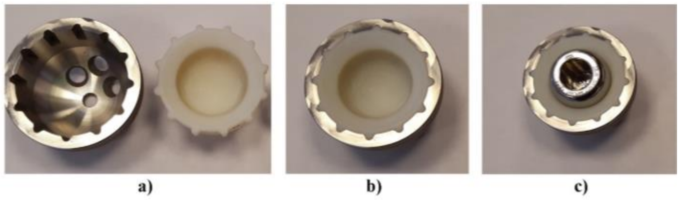

Fig. 11. The injection moulded UHMWPE liner in the acetabular component

IV. CONCLUSION

In this paper, we examined the injection mouldability of pure UHMWPE using a prototype mould. The experiments proved that an injection moulded UHMWPE liner can be created with a prototype mould. The UHMWPE product had considerable shrinkage. This was partly caused by the inaccuracy and deformation of the prototype mould and also by the high shrinkage of the UHMWPE, which was difficult to manage. With good design, the high shrinkage of the material can be minimized and parts with appropriate dimensional accuracy can be produced. In the future, our aim is to measure important mechanical, tribological, and morphological properties of the product, compare the data, and explore if there is potential in injection moulded medical-grade UHMWPE prostheses in the long run.

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