Titolo del programma: **Production and verification of high-precision injection moulded parts** (Produzione e verifica di parti di elevata precisione ottenute per stampaggio ad iniezione)

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Micro components and micro devices are strongly used in several fields: IT components, biomedical and medical products, automotive industry, telecommunication area and aerospace. The development of new micro parts is highly dependent on manufacturing systems that can reliably and economically produce micro components in large quantities and micro injection moulding is one of the most efficient processes for manufacturing micro parts because of its large scale production capability and relatively low production cost [1]. However, the optimized operation settings for different polymer materials is expected to be identified before real mass production to avoid the risk of re-engineering, reducing the manufacturing costs and guarantying products quality.

Micro injection moulding is referred to the production of parts that show:

1) weight in the range of milligrams and overall dimension, functional features and tolerance requirements in the range of micrometers;

2) overall dimension in the macro range and weight in the range of grams and parts with micro features.

On the base on these definitions, micro moulding can be called, as recently reported, "precision injection moulding" [2].

Currently the main research area of micro injection moulding include micro mould design and fabrication technologies and the studies of process parameters. Different studies have shown that the main process parameters that affect the part quality include: mould temperature, melt temperature, injection speed, injection pressure, holding time, holding pressure [3]. To achieve the optimization the following objectives have to be persecuted:

- to establish qualitative and quantitative measurement and assessment method for the quality of micro parts;
- to determine the optimized window of experimented polymer materials for the micro injection moulding;

- to understand the flow behavior and formation in the process of short shot, bar flash, dimension shrinkage and weld lines.

The aim of the short term mobility program realized at University of Nottingham is to investigate the effects of process parameters on the quality of micro moulded parts by using different polymers and verifying melt flow within micro cavities. In particular, a limitation exists regarding the achievable aspect ratio of columns, grooves and walls. These limits depend on the geometry, the polymer, and the process parameters and therefore, process optimization is of outstanding importance. The project have been developed in two stages: the experimentation and the characterization.

Experimentation

The experimentation have been carried out on micro moulding machine Battenfeld Microsystem 50, all electric moulding machine which is a three step micro system: plasticizing, dosing and injecting. In this machine, polymer is heated and molten by an extruder screw and a dosage barrel is used to control the amount of materials accurately, and then the material is injected into a micro mould by the injection plunger. The material is then cooled and the part is demoulded. The extruder screw with diameter of 14 mm is mounted at an angle of 45° to the injection axis. A 5 mm diameter dosage barrel is used to sort the polymer melt. In the dosage barrel there is an optical sensor to monitor the amount of melt. When it achieves the pre-set volume, a pressure piston delivers the shot volume to the injection barrel and then the plunger is used to allow shot weight ranging from 25 mg to 1 g to inject at high velocity into the mould cavities. This unit ensures a stable production process with minimum shot weights. The mould is a highly sophisticated device, which comprises many parts requiring high quality steel to make. There are different types of moulds and the used one have been a three plate mould including a fixed plate, middle plate and a moving plate [4].

The materials were selected after a comparison of the properties of different polymers, and they were: the Liquid Crystal Polymer (LCP Ticona Vectra C130D-2) and the PolyOxyMethilene (POM Ticona Hostaform C27021 TF). These two materials are excellent candidates for highly specialized applications and to injection mold parts requiring extremely precise replication of fine details in thin-walled structures and at the same time must be highly rigid. In particular, the characteristic feature of liquid crystal polymers is their molecular structure. These polymers consist of rigid, rod-like macromolecules, which align in the melt to produce liquid crystal structures. If a liquid crystal polymer melt is subjected to shear or stretching flow, as is the case in all thermoplastic processing operations, then the rigid macromolecules order themselves into fibers and fibrils along the direction of flow which are frozen-in when the melt cools. In this way the specific morphology of liquid crystal polymers in the solid state is formed [5]. POM has excellent toughness, high hardness and rigidity, good heat resistance and excellent resilience. Moreover POM basic polymer can be modified in various ways with suitable reinforcing materials and additives and optimized for specific end uses.

There are two types of components used in the research area of micro injection moulding. One is that the overall size of the component is less than 1 mm, the other is that the component has larger dimensions but micro features on it. The test part studied in this research belongs to the latter one. It is a tensile bar test part (Fig. 1), shaped as a thin plate (15x30x0.3 mm^3) and including three micro features having a trapezium section. The two wings are going to be studied presenting microstructure on each side: the circle with the microbars. The diameter of the circle is 2 mm and the 3 bars have the dimensions reported in Fig. 2. The weight of the whole part made by LCP and POM are respectively 0.23 g and 0.19 g.

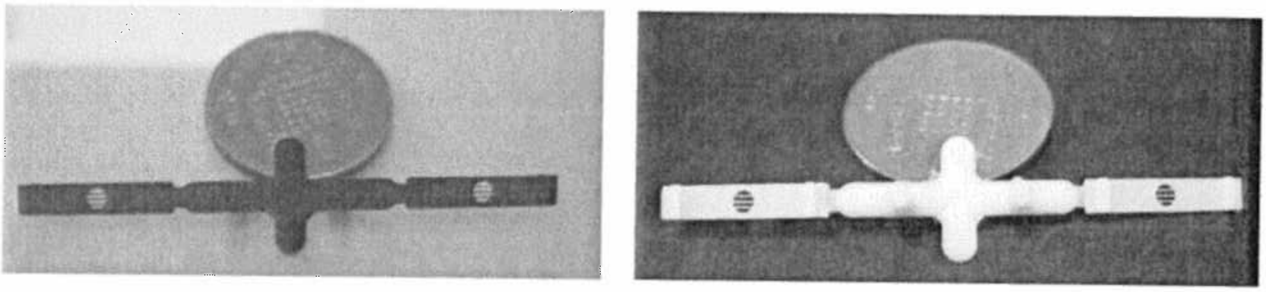


Fig. 1 Test part realized in LCP (left) and POM (right)

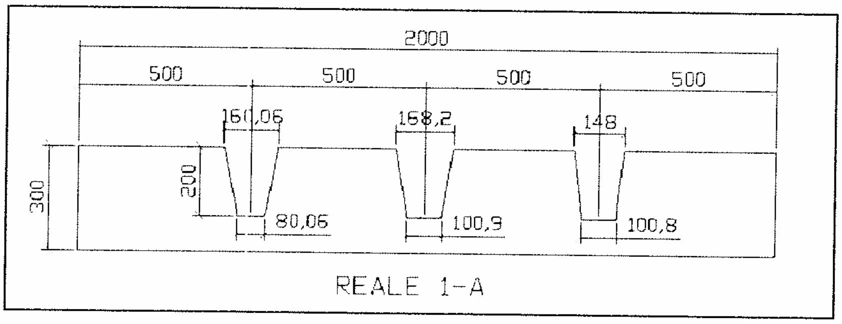


Fig. 2 Bars dimensions (μm)

The experimentation has been divided into two steps: a screening in order to identify the working technological window and an experimental plan including only fundamental parameters most influential according to literature and screening. All tests were carried out in a controlled chamber, thus making negligible the influence of environment on the process. The tests started using the parameter settings suggested by Ticona sheets for the selected materials referred to macro injection moulding about melt temperature, injection velocity, injection pressure and holding pressure. The screening results show the operative parameters ranges ideal for complete filling. Thus, it was decided to further investigate the process parameters to optimize the parts quality and also to study the machine performance. A full factorial design of experiment was implemented in order to consider all kinds of main effects and interactions. In particular a three-factors two-levels full factorial design method was used in the DoE studies performing 2^3=8 moulding experiments (Tables n.1 and 2). Ten replication were produced for each of the eight experiments. In order to analyze the results of the experimental design, analysis of variance (ANOVA) was utilized to investigate the relationship between a response variable and one or more independent variables. A number of 3 parts was selected for each of the 10 experiments to carry out all the measurements related to the full factorial design of experiments.

Factors	Symbol	Level 1	Level 2
Melt temperature	T [°C]	320	330
Injection velocity	v [mm/s]	200	300
Injection pressure	P_{inj} [bar]	500	600

Tab. 1 LCP process parameters settings

Factors	Symbol	Level 1	Level 2
Melt temperature	T [°C]	230	240
Injection velocity	v [mm/s]	250	280
Injection pressure	P_{inj} [bar]	600	700

Tab.2 POM process parameters settings

The fixed processing conditions are the following:

- Injection volume = 150 mm^3
- Holding pressure = 100 bar
- Holding time = 1 s
- 8 runs
- 10 replications for each process parameters combination

Characterization

The quality control of products is an essential step during the manufacturing process and during this project the quality control was devoted to the investigation and optimization of typical defects of injection moulded parts such as weld lines. Defect inspection and dimensional measurements were performed using the Scanning Electron Microscope (SEM) Hitachi S2600N adopted in Variable Pressure (VP) mode. VP mode is a SEM technique which helps to overcome the problems of non conductive materials, because a small amount of gas (between 1 and 270 Pa) is introduced into the system to counteract out-gassing of charging on polymers. Hence the samples may be imaged without the need to apply a metallic conductive coating.

Defects on injection moulded parts as short shots, bars flash, dimension variations and weld lines were investigated on obtained samples. Short shot is a common production defects and it is the incomplete filling of the mould and, according to the literature, it is due to the low injection speed and pressure or low mould temperature. Presence of flash is another quality problem for injection moulding of polymer materials that have to be checked. Also the bars dimension are important because, by comparing measured values with real values, the optimization of process parameters can be refined for parts with tight tolerance. Weld lines is the last studied quality aspect. It is observed when two melt flows join together, and these lines lead to worst appearance but also weaken the part strength.

Firstly by visual inspection, it was observed that the parts were completely filled by the melt in all parameters combinations. Moreover, it is evident that LCP parts (Fig. 3):

- show little quantity of flash;
- have weld lines at different position (Fig. 4);
- present some breaks for intrinsic brittleness of material;
- have the exit of the glass fibers.

Instead the POM parts (Fig. 3):

- show the presence of flash (Fig. 4);
- result sometimes in short shot;
- do not present weld lines;
- result in degradation of material with electron beam scansions:

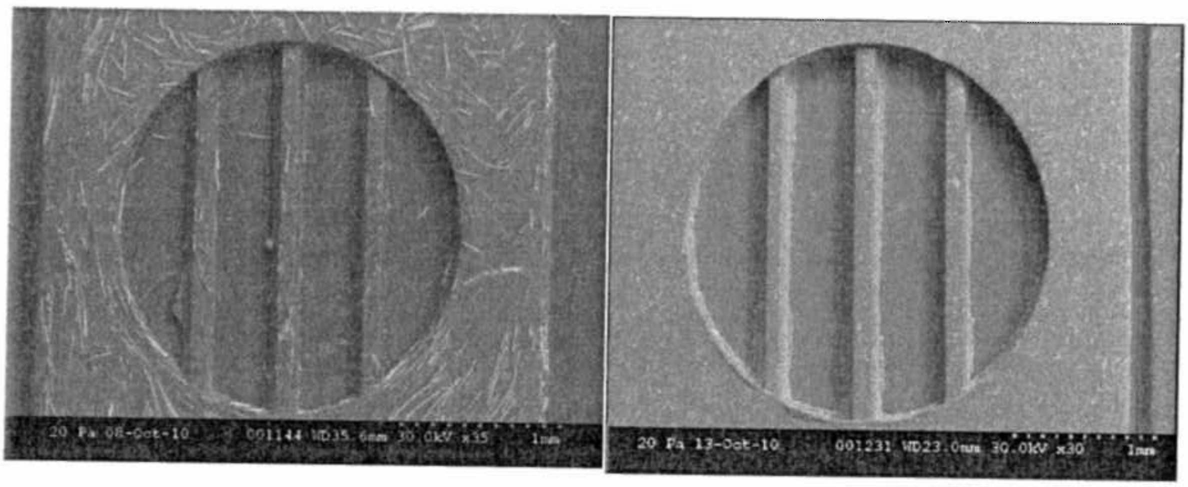
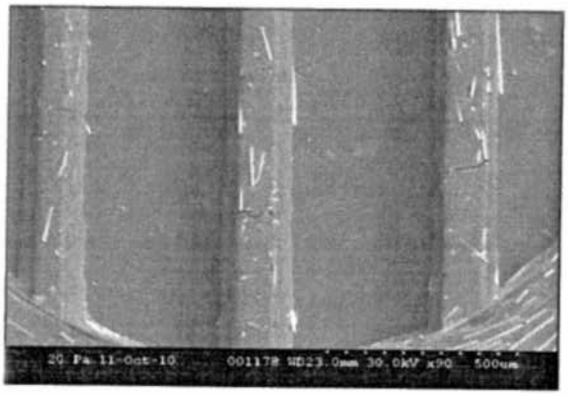


Fig. 3 SEM pictures of LCP (left) and POM (right) bars



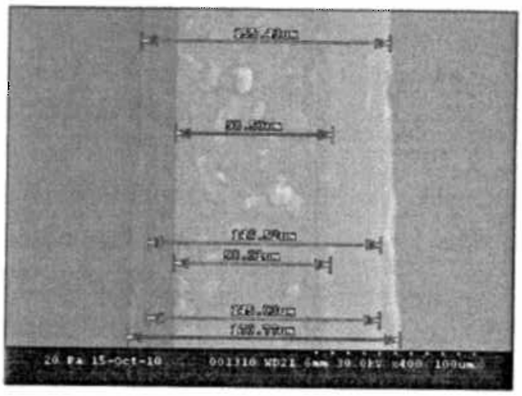


Fig. 4 Weld lines in LCP part (left) and flash and dimensional measurements in POM part (right)

Conclusions and future works

For both materials, the parameters that seem to be the most important for quality of the moulded parts are the melt temperature and injection speed. Relatively high melt temperature can avoid the occurrence of short shot but it also can result in the bar flash to happen. A general rule is that, when process operation window can guarantee to produce complete parts without short shot, keeping relatively low temperature and injection speed will be preferred for flash reduction.

It has been also observed that the weld lines easily appear in three regions of the samples because of separation and recombination of melt flow there. They can be diminished by selecting appropriate material and varying the process parameters, such as melt temperature and injection speed. Infact, viscosity variation during moulding is the main reason to affect the quality of moulded samples. Generally, higher viscosity fluids have higher resistance to flow. Thermal energy can overcome the viscosity of polymer fluid and cause it to flow. Viscosity of polymer fluid decreases with the increase of shear rate. High injection speed can increase shear rate, thereby decreasing viscosity of material to make it flow more easily.

The injection moulding analysis realized during the project at University of Nottingham have been presented. Polymer micro parts were produced using micro injection moulding machine. A process analysis method based on the weld lines position, flash presence, dimensional measurements and short shot has been implemented. Conclusions regarding the effect of different process parameters on the filling of the polymer melt into micro cavity were obtained. The collected data will provide a good basis for developing a new process models for micro-injection moulding that have to be published in a joint conference paper.

Although this research has been carried out systematically to study the effects of process parameters on the part accuracy and filling quality, there are still some more investigations to be carried out. Because of the encouraging preliminary results the experimentation and characterization will be extended designing a new mould with smaller features and high aspect ratio geometries.

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