Researches regarding injection moulding of polymeric products in moulds with micro-profiled surfaces

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Abstract. Injection moulding is one of the most commonly used manufacturing processes for composite polymeric products, with high challenges. Dimensional accuracy, optimal mechanical-physical properties as well as very good aesthetic of the polymeric products are requiring a precise controlled injection moulding system. The mould precision influences the product's tolerances and the good functioning of the injection moulding system. The mould surfaces are important for aesthetic but also for filling, packing and de-moulding of the product. In this paper we present an analysis of 4 different technologies for manufacturing the micro-profiled mould surfaces of a folk motive pattern from Neamț County Romania and few geometric figures on the direction and perpendicular on the direction of the flow, with details of 100, 250 and 500 µm with height from 10 to 100 µm: high speed milling, electrical discharge machining, laser engraving and chemical etching. The goal is to find out the applicability domain for each technology, economic and precision criteria. The experiments consisting in building the micro-profiled surfaces mould and in injection moulding a recycled re-granulated polystyrene basis polymer evidenced the cost / precision ratio for each technology and which one is better economically suited depending on the requirement.

1. Introduction

Injection moulding of polymeric thermoplastic composites products is one of the most used process for manufacturing large quantities products required by automotive, medical, electronics, construction industries [1]. The melted polymer is injected in a mould cavity with high pressure. On second stage, with packing pressure the mould cavity is filled completely and a certain cooling time is needed for solidifying the thermoplastic composite polymer [2]. The quality of the mould surface structure is a very important factor for aesthetic but also for filling, packing and de-moulding of the product. Studies of injection moulding micro-profiled structures of mould surfaces were considering the influence of the moulding process method on the replication of micro-structure (injection moulding versus injection moulding with vacuum and injection moulding with compression [3, 4], the influence of the packing pressure on the mechanical-physical properties of the part [5], the influence of mould surfaces on de-moulding the product [6]. For the study of the influence of the moulding process method, a brass insert mould was machined on a precision lathe with a diamond pin tool to obtain an optical prism pattern consisting in saw-tooth grooves defined by prism height (investigated on the range 0.100 to 0.221 mm), prism angle (30° to 60°) and raft angle (2°); the micro-machined brass inserts were clamped to a movable plate of a prototype mould compatible with the three injection moulding technologies; a total of 228 tests were done with a commonly used PMMA grade for automotive lighting optical parts; The
analysis of the tests evidenced that the INJECTION COMPRESSION MOULDING is most precise and offers repeatability of the process; The Vacuum Injection Moulding evidenced minor improvements against conventional Injection Moulding; packing pressure was the most influencing factor of all processes [3]. Other studies were investigating the influence of the packing pressure on the mechanical-physical properties of the part [4], or, the influence of mould surfaces on de-moulding the product [5]. The research of the process of micro-injection moulding of a part of 11 mm x 3 mm – 1 mm on a special micro-injection moulding machine evidenced the great importance for the manufacturing of the polymeric micro-components production in the biomedical, optical, information technology, automotive applications [6]. The majority of the studies indicated the packing pressure as one the most important factors for a good replication of the micro-profiled surfaces of the polymeric products.

2. Experimental procedures

In this paper we analyse four technologies available at a reasonable cost for manufacturing the micro-profiled planar surfaces: milling, electrical discharge machining, chemical etching and laser ablation. For the study was used as a pattern a folk motive from Neamt County, Romania to which were added few geometrical figures with details from 0.1 to 0.5 mm and a maximum depth of 0.1 mm, figure 1. The study analyse the manufacturing technologies and also the surfaces of the polymeric product obtained by injection moulding process.

![Figure 1. The drawing of the part, folk model from Neamț County, Romania and geometric figures with a height of 0.1 mm; Dimensions in millimetres [mm].](image)

For the experiments we manufactured an injection mould with 4 cavities, figure 2, each cavity's micro-profiled surfaces made by a different technology. The cavities are 35 mm x 21 mm with a thickness of 1 mm and the injection through a balanced runner with a shaped section fan-gate for obtaining a constant speed of the flow of the melted polymer. The cavities were machined on the mobile part of the mould in an Aluminium EN 7075 plate by conventional drilling, boring and milling. The micro-profiles were made in a 54 HRC steel plate which was attached to the Aluminium EN 7075 plate of the fixed mould half, figure 3. An EURO standard mould base 100 x 130 mm was used to complete the injection mould.

The tests were made on an injection moulding machine with 350 KN clamping force and an injection unit of 60 cube centimetres capacity (30 mm diameter of the screw).
2.1. Chemical etching
The 54 HRC steel plate comes from a specialised supplier of pad printing clichés. The chemical etching, figure 4 and 5 (also being referred to as photo etching) is a process used in manufacturing high precision patterns (linear scales transducers, micro and nano technology domains, microprocessors, texturing moulds surfaces, etc.) and consists in a controlled corrosion process performed in a series of five steps: cleaning the surfaces of the metal to be engraved, masking with light-reactive properties photo-resist, exposing in ultraviolet light with the pattern film or exposing the pattern with a laser, then developing (washing away the unexposed resist and leaving the areas to be etched unprotected), then etching, typically with a solution of acid, frequently ferric chloride. Finally, the metal is cleaned, and the remaining photo-resist is removed, the part again cleaned and dried. For obtaining our pattern we subcontracted the chemical etching process, figure 4, to a specialised supplier for pad printing clichés. Pad printing (also called tampography) is a printing process that involves an image being transferred from the cliché with a silicone pad to the object to be printed. We made the 3d drawing in an engineering modelling software. For the chemical etching pattern film a vectorised type drawing was required. We exported a 2d dxf (Drawing Exchange Format) and an ai (Adobe Illustrator vectorised graphics) format files which were used in making the pattern film with the mention that surfaces to be etched were hatched with a step of 0.025 mm. For the chemical etching the supplier required 50 \textit{UNITS of COST}, UC (in our study we will compare the processes by referring to \textit{units of cost} and not to a specific currency).
2.2. Milling

The second cavity micro profiled surfaces were made by milling, figure 6 and figure 7, with a 0.075 radius 45° pin point engraving tool with 22,000 rotations per minute and a feed of 250 mm/minute using a “pocket” strategy programming. The milling process and the tool were estimated to 75 units of cost, UC.

2.3. Electrical Discharge Machining

The Electrical discharge machining (EDM), also known as spark eroding is a process whereby the shape is obtained by removing material from the metal work piece (work piece electrode) with an electrode (tool electrode) by a controlled current discharges in a dielectric liquid. For our job we used a graphite tool electrode made by milling with a 0.075 mm radius pin point engraving tool with a “parallel” strategy for roughing and “contour” for finishing. The electrical discharge process was performed on a numerical control machine with 64 Ampere generator and with parameters settled to obtain a surface Ra = 1.1 um. The EDM process evidenced an important wear of 65% of the tool electrode, so, the depth of the EDM micro profiles was 0.035 mm, figure 8 and figure 9. Programming, the graphite material, milling the electrode, the tool and the EDM process were estimated to 125 UNITS of COST.

Figure 4. Chemical etching cavity.  
Figure 5. Detail of chemical etching [mm].  

Figure 6. Cavity made by milling.  
Figure 7. Detail of milling machined cavity.
2.4. Laser ablation
Laser ablation is the process of removing material from the surface by shooting with a laser beam (usually pulsed laser in which the optical power appears in pulses at some repetition rates) and in which small volume of material is heated in a very short time and evaporated. [10, 11]. The laser ablation of the micro profiles was performed to a sub-contractor on a pulsed fibre laser with 20-watt power used for marking and engraving works and it costed 250 UC, figure 12 and 13. We noted that for laser work dxf and ai format files (same as for the chemical etching) are required and the surfaces were hatched too. To be mentioned that the laser beam is programmed to travel on the vectors defined into the graphics with an optical numerical controlled device. Thickness of the “line” (vector), repetition rate and feed speed influence the most the laser ablation process [9]. To be noted that the skill of the operator and experience in working with the equipment are important factors too. Further tests with laser ablation evidenced that precision level could be affected by the increasing of the depth.
2.5. Analyze of the technologies: chemical etching, milling, electrical discharge and laser ablation.
Marks from 0 to 10 were used, on a scale from 0 – very poor to 10 – very good; we counted the following criteria: precision, visual, user friendly (in house versus out sourcing/communication level) and costs (as previously mentioned on a unit of cost basis and not a certain currency), table 1.

Table 1. The comparison of processes.

| Process          | Precision | Visual | User Friendly | Costs | Total |
|------------------|-----------|--------|---------------|-------|-------|
| Chemical etching | 10        | 10     | 9             | 10    | 39    |
| Milling          | 8         | 5      | 10            | 8     | 31    |
| EDM              | 9         | 8      | 10            | 7     | 34    |
| Laser ablation   | 9         | 9      | 7             | 5     | 30    |

Table 2. Description of processes.

| Process          | Part Drawings | Part drawings Format | Control/Post Processor | Operator skill | Environment Friendly |
|------------------|---------------|----------------------|------------------------|----------------|---------------------|
| Chemical etching | 2D            | DXF, ai              | Optical/- NC/ISO G-code| Medium         | Poor                |
| Milling          | 3D            | STEP, IGES, etc.     | Optical/ NC/manual ISO 6983/ | Medium | Medium |
| EDM              | 3D/2D         | STEP, IGES/ DXF      | Optical/ ISO 6983/ NC/ manual | Medium | Poor |
| Laser ablation   | 2D            | DXF, ai              | Optical/ NC/ manual Optical | High | Poor |

In table 2 are presented the format types used by the studied processes, the operator's skill and the impact on the environment. (D – dimensions; DXF – Data Exchange Format; ai – Adobe Illustrator format; STEP - Clear Text Encoding of the Exchange Structure as defined in ISO 10303-21; IGES – Initial Graphics Exchange Specification as ASME Y14.26M (of the ANSI committee); NC – numerical control; ISO 6983 G -code, programming language designed by Massachusetts Institute of Technology)

2.6. Analyze of the injection molding
Injection moulding was performed on a hydraulic injection moulding machine with a clamping force of 350 KN and an injection unit screw of 30 mm diameter, with 60 cube centimetres capacity at 1200 bar maximum injection pressure. The tests were made using a recycled polystyrene ROCASTIR rPS, supplier ROMCARBON S.A. - Romania. The measurements of pressure (in machine hydraulic system) and times were observed on the machine controller and manometers. The measurement of the weights was done on an electronic scale with a minimum measurement of 0.002 Kg and precision of 0.0001 Kg.
(0.1 grams). For an accurate result we considered the complete assemble of the 4 cavities and runners with a total theoretic volume of 4001.28 cube millimetres and a corresponding mass of 4.04 grams, (see table 3).

**Table 3.** Properties of ROCASTIR rPS polystyrene.

| Properties                          | Value | Unit       | Test Method |
|-------------------------------------|-------|------------|-------------|
| Density                             | 1.01  | grams/cm³  | ASTM D-792  |
| Melt Flow Index                     | 4 – 6 | grams/ 10 min | ASTM D-1238 |
| Tensile Modulus                     | >1800 | MPa        | ASTM D-638  |
| Tensile Stress                      | >20   | MPa        | ASTM D-638  |
| Tensile Strain                      | >2    | MPa        | ASTM D-638  |
| Flexural Modulus                    | >1400 | MPa        | ASTM D-790  |
| Flexural Strength                   | >30   | MPa        | ASTM D-790  |
| Notched Izod Impact Strength (23°C) | 6 – 8 | KJ/m²      | ASTM D-256  |
| Heat Deflection Temperature         | 85    | °C         | ASTM D-648  |

First experiments consisted in moulding only with the first stage injection pressure at different times, same speed and temperature in order to find out the time of filling the cavities 95%. The machine constructor is indicating an injection rate of about 70 cube centimetres per second, so we choose injection times 0.1, 0.15, 0.2, 0.25 and 0.3 seconds. 5 sets of tests were performed for each injection time. For each of it was measured the mass and calculated the average as shown in figure 14.

**Figure 14.** The injection flow: shot weight in grams [g] vs. injection time in seconds [s].

On figure 15 we can observe that the shaped gate was good designed as the flow had constant speed on the width of the cavities. Tests evidenced a good replication of the micro-profiled surfaces for injection times of 0.15 seconds when cavities are under 50% filled – proving that the polymer forced by injection pressure, a thin layer is solidified along the walls of the mould.

**Figure 15.** Flow velocity profile of molten thermoplastic polymer [7].
During experiments of filling the cavities we observed that two of the four cavities were filled faster, the length of flow was over than the two others (see figure 14, at times 0.1s, 0.15s, 0.2, 0.25s); Measurements on the shaped gates show a difference of 0.02 mm in plus for the cavities with faster filling. We noted that the shape and size of the gate can affect the flow of the polymer. For multi cavity moulds the precision of the gates is important for similar filling.

On table 4 we present the experiments on which we varied the time during the packing pressure was activated. On 3 experiments the time of packing pressure (TPP in seconds) was fixed and varied the injection pressure (IP in bar) and packing pressure (PP in bar). For all experiments the injection speed was fixed at 70 cm$^3$/s (as indicated by the constructor for the injection directed to atmosphere) and 5 probes of each set of parameters were measured on an electronic scale of 0.1 gram precision.

Table 4. The mass [grams] vs. injection pressure (IP in bar), packing pressure (PP in bar) and time of packing pressure (TPP in [s]); Fixed injection speed 70 cm$^3$/s. Temperature of material 220°C, temperature of mould 30°C. Injection Time 0.3 seconds.

| Probe | IP=500 bar | IP=500 bar | IP=500 bar | IP=500 bar | IP=500 bar | IP=500 bar |
|-------|------------|------------|------------|------------|------------|------------|
|       | PP=390 bar | PP=390 bar | PP=390 bar | PP=450 bar | PP=500 bar | PP=500 bar |
| TPP=1s| 3.9        | 4          | 4          | 4          | 4          | 4          |
| TPP=2s| 3.9        | 3.9        | 4          | 4          | 3.9        | 4          |
| TPP=3s| 3.9        | 4          | 3.9        | 4          | 3.9        | 4          |
|       | 3.9        | 3.9        | 4          | 3.9        | 4          | 4          |
|       | 3.9        | 3.9        | 4          | 3.9        | 4          | 4          |

Total [grams] 19.40 19.70 19.80 19.90 19.90 20

Figure 16. A complete injection moulding with 4 cavities and runners.

3. Conclusions

3.1. Micro-profile technologies: chemical etch, laser ablation, electrical discharge machining

Chemical etch is a high precision technology especially for low depths profiles (0.01 to 0.1 mm); very well fitted for texturing injection moulds for composite polymer products and at very good prices on planar surfaces and sizes of 100 x 200 mm; Replication is very good;

Laser ablation, due to the advance of laser fabrication, becomes a reasonable costed technology at high level of precision. To be mentioned that with normal software and when only optical control available, could appear a loose of accuracy if parameters are not settled properly (is still a process depending on the experience of the operator); The optical controlled lasers are very good for engraving micro-profiles with depths from 0.005 to 0.1 mm on planar surfaces of 120 x 120 mm.

Engraving micro-profiles by milling is a process available to all mould makers. To be mentioned that good results are depending on the tool quality, the cutting strategy and the base material to be machined
(for example the “parallel” plus “contour” technologies shown a better surface quality of the graphite electrode versus the “pocket” strategy for the engraving the steel hardened plate).

Electrical Discharge Machining is an alternative, more expensive than milling and is largely used by mould makers to improve the aesthetic of the product applying the process on part walls to reduce the visual marks of the flow or of the ribs, differences of the wall thickness. Injection moulding of micro-profiled surfaces polymer products

3.2. Injection molding of micro-profiled surfaces polymer products

Injection moulding experiments evidenced a good replication of the micro-profiles before the cavities were completely filled, a prove of the theory of flowing of the melted thermoplastics between the cool walls of the mould, “the fluid vein” at the section centre practically flows within the already solidified layers of plastic material. According the results of our study the design of the gates for an optimal flow and injection speed can influence the quality of micro-profiles replication.

We noted also the importance of the packing pressure and the time during which is applied the packing pressure for obtaining a quality product. To be mentioned that the injection pressure is an important factor.

We will continue our researches regarding micro-profiles technologies on complex (3D) surfaces and injection moulding of the polymer products.

4. References

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