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The Micro Injection Moulding Process for Polymeric Components Manufacturing

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1. Introduction

In recent years, there is an increasing demand for small and even micro scale parts and this trend towards miniaturization makes the micro system technologies of growing importance. Microfabrication process capabilities should expand to encompass a wider range of materials and geometric forms, by defining processes and related process chains that can satisfy the specific functional and technical requirements of new emerging multi-material products, and ensure the compatibility of materials and processing technologies throughout these manufacturing chains. Example technologies to be investigated either individually or in combination are technologies for direct- or rapid manufacturing, energy assisted technologies, microreplication technologies, qualification and inspection methods, functional characterisation methods and integration of "easy and fast" on-line control systems.

The processes should demonstrate significantly high production rates, accuracy and enhanced performance or quality, creating capabilities for mass manufacture of microcomponents and miniaturised parts incorporating micro- or nanofeatures in different materials. Processes should also provide high flexibility and seamless integration into new micro- and nanomanufacture scenario. Micro- and nano-manufacturing technologies can provide the basis of the next industrial revolution that could dramatically modify the way in which businesses are setup, run and marketed.

Micro injection moulding can be defined as one of the key technologies for micro manufacturing because of its mass production capability and relatively low production cost. It is the process of transferring the micron or even submicron features of metallic moulds to a polymeric product. During the process, the material, in form of granules, is transferred from a hopper into a plasticizing unit so that it becomes molten and soft (Fig. 1a). The material is then forced, under pressure, inside a mould cavity where it is subjected to holding pressure for a specific time to compensate for material shrinkage (Fig. 1b). After a sufficient time, the material freezes into the mould shape, gets ejected and the cycle is repeated.

This technology was firstly introduced from traditional injection moulding since late eighties but no appropriate machine technology was available and only modified commercial units of traditional injection moulding machine could be used. Only in the middle of nineties, special new micro injection machines were developed specifically

addressing micro moulding parts and thus, research efforts have still to be done. Currently, the injection moulding process offers several advantages in terms of mass manufacturability, variety of materials and accurate replication of micro-scaled features, and it is being used commercially for producing some types of devices. A number of limitations, however, need to be overcome before the wide-scale fabrication of micro components can be realized by micro injection moulding. In particular, the nature of end-shape processes puts limitations on the allowed geometrical designs to ensure smooth demouldability. Moreover, the study and optimization of the process parameters, especially for high aspect ratios features, are essential for producing parts with acceptable quality. The variables, that affect the quality, can be classified into four categories: mould and component design, performance of moulding machine, material, and processing conditions [1].
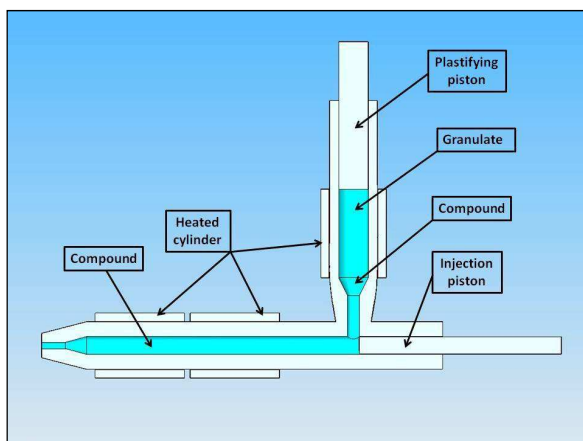
(a)
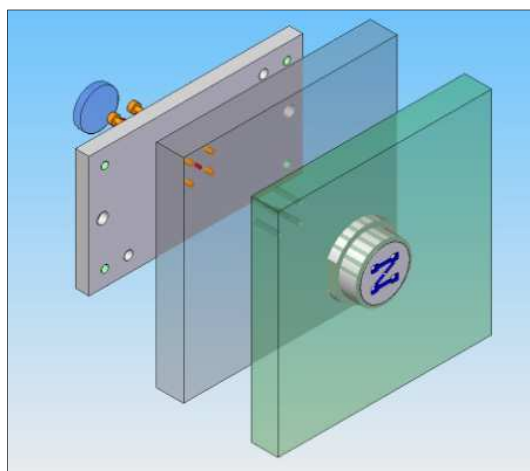
(b)

Fig. 1. Example of micro injection moulding machine (a) and 1 half mould (b)

This chapter intends to review the state of the art of micro injection moulding for micro components, to highlight both the potential developments and research gaps of this process. Tool design principles, plastic materials and process parameters commonly reported in literature are critically reviewed towards the identification of the most effective processing conditions, given a specific application. Finally, the injection moulding process of a micro part (a miniaturized dog bone shaped specimen for tensile tests) is presented and discussed as case study.

2. Definition of micro moulded components

Several definitions of micro-component can be found in literature, relying either on the overall manufactured or process characteristics. A product manufactured by micro-injection moulding process can be defined [2] as reported below [2]::

1. the mass of the part is few milligrams;
2. the part exhibits dimensions with tolerances in the micrometric range;
3. some features are in the order of micrometers.

Nowadays, micro components are widely used and they can be classified also with respect to their application as reported in Table 1. Some examples are reported in Fig. 2.
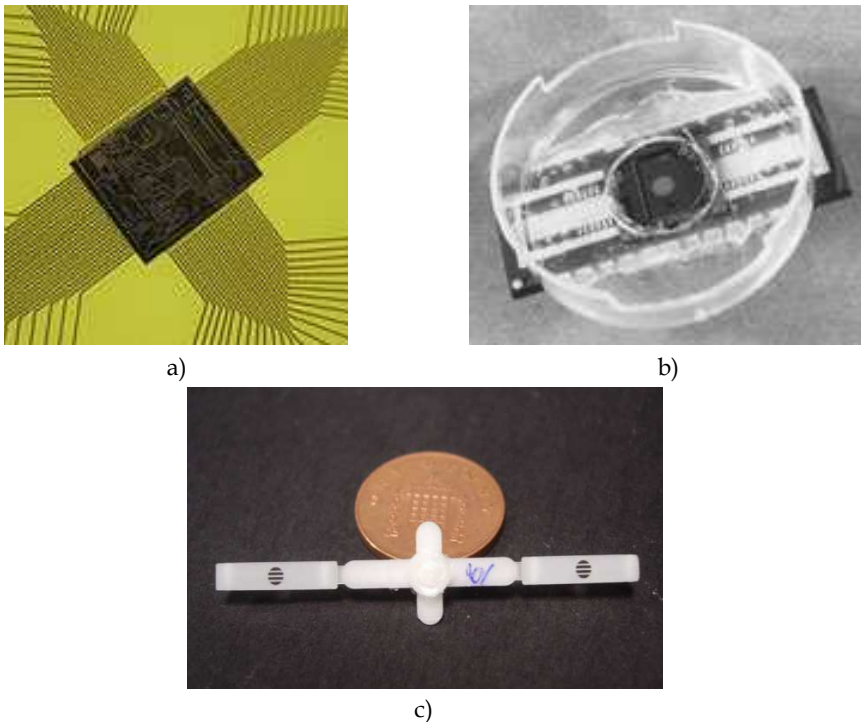

a)

b)

c)

Fig. 2. a) Microelectromechanical systems chip (source Wikipedia), b) Neurochip developed by Caltech (source Wikipedia) and c) micro bars test part (courtesy of University of Nottingham)

APPLICATION FIELDS	EXAMPLES
Micromechanical parts	• Locking lever for micro mechanical industry or micro switch; • Latch for the watch industry; • Catch wheel for micro switch; • Operating pin; • Gear plate for motive power engineering.
Micro gear wheel	• Dented wheel for watch industry; • Rotor with gear wheel for watch industry; • Gear wheel for micro gear; • Spur wheel in the field of electrical technology; • Spiral gear in the field of electrical technology/metrology; • Spline in the field of electrical technology/metrology.
Medical industry	• Micro filter for acoustics, hearing aid; • Implantable clip; • Bearing shell/bearing cap; • Sensor housing implantable; • Aseptic expendable precision blade.
Optical and Electronic industries	• Coax plug/switch MID for mobile phone • SIM card connector for mobile phone; • Pin connector for mobile phone; • Single mode and multi mode ferrules.

Table 1. Micro components applications

An open research issue in micro injection moulding is related to fabrication of parts with a higher and higher aspect ratio (as micro bars in Fig. 2c). The aspect ratio of a shape is defined as the ratio of its longer one to its shorter dimension. It may be applied to two characteristic dimensions of a three-dimensional shape, such as the ratio of the longest and shortest axis. The aspect ratio, achievable in replicating micro features is one of the most important characteristic of the micro fabrication processes and it constitutes a constraint in applying injection moulding. High Aspect Ratio (HAR) components can be found in many applications and therefore have to be investigated to break trough previous barriers in miniaturization. Concerning achievable aspect ratios, there is a limitation which is a function of the geometry of the micro-features, their position on the sample, the polymer type and the process parameters [3]. The literature suggests that the critical minimum dimensions which can be replicated successfully by injection moulding are mainly determined by the aspect ratio. Polymeric materials with minimum wall thickness of 10 µm, structural details in the range of 0.2 µm, and surface roughness of about Rz < 0.05 µm have been manufactured [4].

Beyond geometry and HAR, also physical phenomena have to be taken into account in the micro world differently from macro as for example the "hesitation effect". This effect (Fig. 3) is a phenomenon that can occur during the filling of polymers, and it is common when an injection moulded part contains different thicknesses [5]. It may take place also when HAR microstructures (usually having large than 2) are placed on a relatively thick substrate, which is the case for example of microfluidic devices [6]. The polymeric melt tends to flow more easily into cavities with relatively low resistance areas of greater cross section while the flow stagnates at the entrance of micro-structures; the result is that the melt freezes in this area because the filling time of the substrate is usually greater than the freezing time of the micro feature. It was recommended in the literature that injection moulded parts with HAR microstructures should have a thickness in which a quick filling of the substrate can allow for filling of the micro-cavities before solidification starts [7]. In addition the literature shows that, in unidirectional flow, the depth of filling in micro channels is sensitive to the channel width [8].
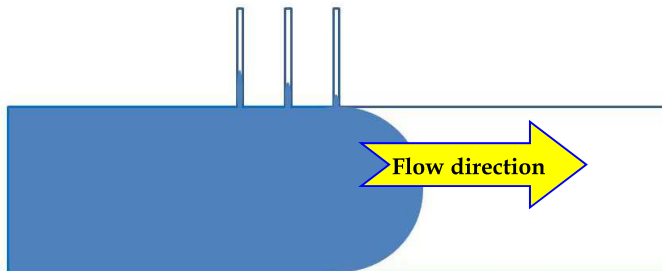

Fig. 3. Hesitation effect of the melt flow in the proximity of micro channels

3. Design of components mouldable by micro injection moulding

Unlike conventional injection moulding, where manufacturability issues are considered in product design phase, very little has been done so far for micro injection moulding. The research community is still assessing the process capabilities. The open questions in micro injection moulding are: 'how small can we go with the product'? Which is the maximum achievable aspect ratio?' Still there is not a consolidated approach towards the design for manufacturability.

Part dimensions, position and shape of the parting line, existence of undercuts, mould-cavity features in addition to tolerances and surface finishing are commonly considered in part design for conventional injection moulding. A number of studies have suggested techniques to evaluate the complexity of injection moulded shapes with respect to replication and demoulding [9,10]; but the overall small dimensions of micro moulded parts do not always allow the use of the above mentioned strategies. In the following, the design factors affecting the overall quality of a micro-injected part are critically discussed.

3.1 Mould cavity design

An important aspect to take in consideration in mould cavity design is related to the large surface to volume ratio of many micro components leading to fast cooling or even freezing

of the injected melts into tools. Despite the fact that polymers have a low thermal conductivity and usually show a 'self-isolating' effect, the injected materials rapidly freeze on the tool wall and the microcavities could not be filled completely. As a consequence of the thin walls and large surfaces of micro components compared with their volume, the mould temperature of the materials adapts to the mould within milliseconds.

The evacuation of the air from the mould cavity is another important issue for the evaluation of the quality of produced micro component in order to prevent compression-induced defects in the material. If the cavities contain micro features that are so small that they cannot be vented in the standard way through the parting plane or special bore holes, it is necessary to develop a system dedicated to the evacuation of the air from the cavity. Some applications are reported in literature of creating the vacuum in the mould [11,12,13].

In micro injection moulding it is quite difficult to design the cooling system because of the dimension of the mould, where in few centimeters, are located the cavity and the ejection mechanism and this means that a temperature variation across the moulded part should be expected depending on the geometry [14]. In any case, by literature it was seen that the cooling of mould is not always required, especially when it is desired to keep the mould temperature above the "Glass Temperature" (Tg), the temperature below which an amorphous material behaves as a glassy solid. Thermoplastic polymers may have a further value of Tg: a low temperature below which they become hard and brittle taking easy tendency to shatter. In addition, at temperatures greater than Tg, polymers have such flexibility and ability to undergo plastic deformation without encountering fractures, a characteristic that is particularly exploited in the plastic material technology.

Demoulding is another important aspect to take care in micro mould design. A factor that affects demoulding is the orientation of the polymeric chain being injected, because this influences the direction at which shrinkage is most observed [3]. A geometrical useful method to obtain a successful demoulding consist in the use of draft angles. A positive draft angle, greater than ¼°, has been successfully used for demoulding in plastic micro injection moulding [15].

The use of inserts is another typical application of the injection moulding process and it becomes very important in micro injection moulding when, for example, micro cavities for microfluidic applications are realized and then fitted in the main mould body. The main goal of using mould with changeable inserts resides in the ability to test different micro-part geometries (removable cavities) without discarding the basic structure of the mould, specifically designed for micro-components injection [16]. The use of moulds with inserts reduces the overall cost of process setup, where the finalized mould design is produced by a number of iterative steps in which parts are injected and the mould design is changed [6]. The concept of replaceable cavities can be applied in design of mould for different applications and the efficiency of the product development stage is greatly improved. The inserts allow easy testing of the design prototypes especially in those products where clear design guidelines are not available. Another advantage of using inserts is related to the material with which they can be manufactured. Infact, the material can be different from the one used for the mould, usually made of steel, and it can depend on the manufacturing technology available and on costs.

Another special feature usually used in injection moulding, that are still under evaluation for micro injection moulding, is the system to measure the mould cavity pressure. In literature there are different methods proposed to measure the cavity pressure as for example a piezoelectric force trasducer located behind the injection pin [2] or a miniaturized quartz sensor to direct measure the pressure in the micro mould cavity applied at the end of the sprue channel [17].

3.2 Micro component design

One of the main goals related to the design of a micro mouldable component is the reduction of the shrinkage affecting shape stability in the form of induced warpage. The warpage is due to the non-uniformity of the shrinkage induced by the complex thermal variation inside the mould [14]. Warpage prediction is important for parts with relatively large area compared to their thickness.

Different techniques have been suggested to decrease the effect of shrinkage:

- to increase the value of holding pressure, which, on the other hand, will also increase stresses inside the part [18];
- to have a long cooling time so that the part can thermally equilibrate inside the mould cavity and become approximately uniform [14];
- to increase the cycle time, as a trade-off of a long cooling time.

A second aspect that have to be considered is the geometrical configuration. In order to explain the dependence of the degree of filling of the distance from the gate, from where the polymer enters inside the cavity, it was introduced the parameter time to pressure [19]. The measurement of this parameter, compared with the injection speed for sections with different thickness demonstrates that the shear stresses and accordingly the pressure drop required to fill the feature, are in general much higher than that to fill the substrate. Concerning aspect ratios, it was suggested that there is a limitation regarding the achievable aspect ratio [3]. The maximum achievable HAR, which is a function of the geometry of the micro-features, the position on the sample, the polymer type and the process parameters. As suggested in the literature [20], standard testing shapes can be helpful in comparing filling of structures with different wall thicknesses but the same aspect ratio. This will help in investigating the relation between wall thickness and flow path length and their limits. They can also be used for a wide range of polymers, since material properties affect flow behavior.

4. Moulding machine

The micro injection moulding technology was firstly applied modifying units of traditional injection moulding machine [21]. Lately, special new micro injection machines were developed specifically addressing micro-moulding parts. In the conventional reciprocating screw injection moulding process, polymer materials are melted and injected into mould cavities through a screw-barrel system and there are limitations regarding the reduction of screw dimension for constructive problems. Moreover, cycle times are usually longer than necessary using conventional machine for micro injection moulding. At the moment, commercial micro moulding systems are produced from Ferromatik Milacron, Arburg and

Sumitomo Demag as microinjection units for conventional machines and Wittmann-Battenfeld, Babyplast and Desma as dedicated micro injection moulding machines.

Ferromatik Milacron developed two types of microinjection units: a two stage injection unit with an extruder and injection plunger and a fully electric injection unit with 14 mm screw. Arburg launched its new micro-injection module, which operates with an 8 mm injection screw that guarantees a high degree of dosing precision and it is combined with a second screw, which is responsible for melting the material. Sumitomo Demag developed a customized unit for shot weights of 5 g to 0.1 g. In addition Chang et al. [22] developed a novel concept of micro-injection moulding system designed as a separated module, which is a hot runner plunger-type injection moulding module and could be applied to small size (30–100 t) reciprocating screw hydraulic or fully electric injection moulding machines.

Instead, the dedicated micro moulding machines use a separate screw or piston in the plasticizing unit and a plunger injection system. The new born Wittmann-Battenfeld MicroPower is a modular fully electric production cell in which the plasticizing is realized by means of 14 mm extruder screws, the piston injection by means of 5 mm pistons and the maximum injection speed is of 750 mm/s. The injection unit allows processing of all injectable materials with shot volumes of up to 3 cm^3 and feeding of all common standard granulate sizes. The injection process guarantees processing of thermally homogeneous melt, which ensures an outstanding quality for micro parts. Babyplast from Cronoplast is a fully hydraulic machine and it is ideal for producing small and microscopic parts and suitable for processing all injectable thermoplastic materials. The DesmaTec FormicaPlast has a two phase piston injection units: pre-plasticization is realized with a 6 mm piston while a 3 mm piston is used for the high precision injection [23]. Moreover, a fast electrical drive is used, ensuring a high precision of control for the injection speed and the plunger position. The maximum injection pressure and injection rate of the machine are 300 MPa and 3.5 cm^3/s respectively. Finally, a prototype of a micro injection moulding machine was built and tested at IKV-Institute of Plastics Processing at RWTH Aachen University [24]. For this micro injection moulding machine, a concept using a two plungers unit was followed: during the plasticizing phase, the upper plasticizing plunger pushes resin through a die heated at melting temperature as the injection plunger is cored back at the same time. Injection follows when the desired shot volume is reached. A ball check valve between injection plunger and metering plunger prevents the melt from flowing back into the metering cylinder. Thermoset micro parts with a shot weight in the area of 0.05 g to 3.0 g can be manufactured with this setup. These applications, though difficult for thermosetting polymer grades, are advantageous in bio-medical applications.

A recent pursued objective is the realization of two-component injection moulding which allows for the production of multi-material and, hence, multi-functional micro components modifying also the injection machine. The main technical challenges are the process parameters which have to be suitable for both materials and the design of the necessary moulding tools and machine which at least have to be equipped with two feeder systems. In particular, the micro injection moulding can be used for the generation and direct assembly of hybrid micro system. Using this process one process step leads to compound part consisting of two thermoplastics or a thermoplastic and an insert part (metal, silicon, glass, ceramic). Michaeli et al. [25] studied the generation of hybrid-micro

system for medical applications. This part consist of a carbon-fibre reinforced PEEK puncture needle, which incorporates three lumens and in order to attach additional equipment a plastic connector needs to be overmoulded on the needle. The investigation demonstrates that the resulting bond strength between needle and connector is that required from standard even if the standard deviation between experiments is high. Further perspectives are the manufacturing of micro joints by using polymers with different shrinkage values and the production of microstructured preforms for a subsequent electroplating process.

5. Analysis on the polymeric materials and their selection

Several polymeric materials have been used for producing micro moulded parts, thus affecting the experimental results. The high shear rates occurring in the micro processes encourage the use of materials that exhibit high shear thinning rheology, allowing cavity filling at the lowest possible injection pressure [2]. The interaction between the type of used polymer and the quality of the moulded part makes a challenging task to define the useful material for each application without testing it under different conditions. The most common polymers used in micro injection moulding are reported in Table 2 [26,27].

POLYMER	FULL NAME	APPLICATIONS
POM	Polyoxymethylene	Micro gears and micro filters
LCP	Liquid Cristal Polymer	Connectors, ferules and microelectronic devices
PC	Polycarbonate	Optical application as lens and sensor discs
PEEK	Polyetheretherketone	Micro bearings and pistons
PMMA	Polymethylmethacrilate	Optical fiber connector
PA	Polyamide	Micro gear wheels
PSU	Polysulfone	Housing for microfluidic devices
PE	Polyethylene	Components for micro actuators
PLA	Polylactic acid	Biodegradable implants

Table 2. Materials and applications for micro injection moulding

The properties of the chosen plastic, such as its flowability, heat transfer ability and cooling shrinkage, affect moulding efficiency. Recent investigations report a series of measurement of melt viscosity within small dimension geometries using high-fluidity amorphous ABS and PS resin [28,29], and high-low density PE, as well as high crystallinity POM resin [30]. From the measured pressure drop obtained from pressure transducers and melt volumetric flow rate, it is possible to calculate the viscosity values. The investigation of ABS, PS and POM resin found that as micro-channel size decreases, the percentage reduction in viscosity value increases, when compared with data obtained from traditional capillary rheometer. The ratio of slip velocity relative to mean velocity was found to increase as the size of the

micro-channels decreases for ABS and PS. It seems that wall slip plays a dominant role when the melt flows through micro-channels, resulting in a greater apparent viscosity reduction when the size of micro-channel decreases. In addition, the wall-slip effect becomes more significant as melt temperature increases. Compared with PS resin within the micro-channels, the percentage reduction in the viscosity value as well as the ratio of slip velocity relative to mean velocity, all increases with decreasing micro-channel size, but appears to be less significant for POM resin.

The viscoelastic nature of the polymeric melt becomes more significant at the micro scale because of the high shear rates involved in, for example, narrow gates. It has been mentioned in the literature that increasing the shear rate decreases the melt viscosity to values that are different from those that may be specified in data sheets [31].

In order to obtain the required accuracy and prevent premature material freezing when producing high-aspect-ratio micro features, materials with low melt viscosity are desirable. Among the best candidates, thermotropic liquid-crystalline polymers (LCPs) are well known for their low viscosity and their pronounced shear-thinning behaviour. Berton and Lucchetta [32] proposed also the addition of LCP to improve the properties of Polyamide 66 (PA66). The results show that LCP strongly affects the rheology of the blend, lowering the shear viscosity and increasing the extensional viscosity. The most of the LCP effect in decreasing the PA66 viscosity is reached for a content of 10% by weight.

Another important aspect that has to be considered is the skin–core crystalline morphology behaviour of injection- moulded semi-crystalline polymers. Once a plastic fills a mould, the plastic should have enough heat transfer so parts do not warp because of differential cooling in the mould. A relatively uniform mould temperature also helps optimum part characteristics to develop as crystalline resins crystallize or amorphous ones anneal. Mould cavities are sized to account for shrinkage as a thermoplastic solidifies from a shot, so finished part dimensions fall within tolerances. The skin–core crystalline morphology of semi-crystalline polymers is well documented in the scientific literature. Crystalline morphologies of a high - density polyethylene (HDPE) micro- moulded part and a classical part are compared with different techniques [33,34]. Results show that the crystalline morphologies vary between the two parts. While a 'skin–core' morphology is present for the macropart, the micro-part exhibits a specific 'core-free' morphology, i.e. no spherulite is present at the center of the thickness. In fact, the high flow strength and cooling rates promote the homogeneity of the morphology through the thickness, with a flow-induced crystallization. As a result, highly oriented structures are created within the micro-part, conferring anisotropy to the final product. This could be a challenge to overcome, as this anisotropy affects both polymer shrinkage and the overall final part behaviour. The results of Lu and Zhang [35] show that all types of manufactured micro columns (φ60, 90, 110, and 130 μm) present a "skin-core" structure composed of skin layer, shear zone with column crystal, and spherulites core. PP spherulite size diminishes gradually with the decrease of diameter of the manufactured micro columns. Different structures of micro columns have different hardness and modulus and the hardness and modulus of the same column increase gradually from core zone to skin layer.

In the field of sustainability and with the ever increasing price of oil, the use of recycled polymers have to be promoted and it is becoming an economical alternative for the injection moulding. In particular, polyolefins represent the largest plastics constituent in the municipal waste stream (high-density polyethylene-HDPE bottles). Recycling of these containers yields a stream of recycled plastic that is highly homogeneous and consistent [36] and the resultant recyclate has essentially the same rheological properties as the virgin resin. Therefore, a possibility could be the recycling of HDPE into products manufactured by injection moulding. Nevertheless, HDPE has a very high melt viscosity and usually recycled polymers are blended with virgin polymers to obtain the best trade-off between cost and low melt viscosity. In literature [37], a new approach to the optimization of blends composition in the injection moulding of recycled polymers has been proposed for the macro world but in the next future it have to be extended also to meso and micro injection moulding.

Recently, the use of plastic material with added reinforced fillers has become a potential alternative approach due to its high strength and the ease of batch fabrication. The use of filler materials can improve the mechanical performance of the resins, but the small feature dimensions present in micro mould cavities deny the use of conventional fillers, such as glass or carbon fibres. Nano fillers such as exfoliated clay platelets, polyhedral oligosilesquioxanes (POSS) and carbon nano tubes show potential for use in the micro moulding environment [2]. The addition of montmorillonite nano clays to polymer systems has emerged as a viable method to improve mechanical, barrier and flame-retarding properties [38]. The maximum benefits of clays, however, are only realized if care is taken to disperse the platelets evenly throughout the material (exfoliation). Exfoliation is best achieved through pre-polymerization dispersion of the clay in the monomer, but can also be achieved by shear-driven melt processing (usually extrusion). Dispersion of the nano tubes, within a polymer matrix, is possible using conventional polymer processing technology. The polymer with added nanomaterials effectively increased the hardness achieved [39]. In addition, a nanoceramic material, such as ZnO, improved wear resistance by 70% when nanoparticles were uniformly dispersed in the polymer and a suitable surfactant solvent was chosen. However, wear resistance decreased significantly if the nanoparticles were not processed well and a proper surfactant solvent was not chosen. Other results [40] show that the polymer degradation during compounding affects the plasticizing behaviour and provoke a reduction of the Charpy impact strength when nanosized c-alumina particles were added to polycarbonate. Although the Young's modulus remained almost constant, the impact strength as well as the glass transition temperature were reduced with increasing nanofiller content, which can be attributed to polymer chain degradation effects.

The possibility of using biodegradable polymers is also a frontier in micro injection moulding that received attention from many scientists [41]. Since two decades ago, researchers in pharmacy, chemical engineering, and other disciplines have striven to design biodegradable polymers with desired degradation mechanisms and mechanical properties. This polymer can be used, for instance, as drug carriers: they have advantages over other carrier systems in that they need not be surgically removed when drug delivery is completed and that they can provide direct drug delivery to the systemic circulation. The

drug and polymer may be combined in a number of different ways depending upon the application of interest. Biodegradable polymers for controlled drug delivery, contains usually poly(lactic acid), poly(glycolic acid) or their copolymers.

Plastic selection is a complex task that involves many considerations not limited only to the material properties, such as:

1. Temperature: looking at thermal stress during normal and extreme end-use conditions, as well as during assembly, finishing and shipping.
2. Chemical resistance: evaluating the effect on the part of every solid, liquid or gas that can contact it.
3. Standardization: factor in governmental and private standards for properties such as heat resistance, flammability, and electrical and mechanical capabilities.
4. Assembly: ensure the proposed plastic works with all assembly steps, such as solvent bonding, mechanical fasteners or ultrasonic welding.
5. Finishing: also ensuring the plastic can provide the desired gloss, smoothness and other appearance values as it comes from the mould or that it can be finished economically.
6. Other conditions: considering all other items relevant to fabrication, assembly and end use. These include maximum loads, deflections and other mechanical stresses, relative motion between parts, electrical stresses, color and tolerances.
7. Cost: using total finished-part cost to guide design. In addition to resin pricing, factor in manufacturing, maintenance, assembly and disassembly to reduce labor, tooling, finishing and other costs.
8. Availability: make sure the resin is available in the amount needed for production.

Summarizing previous considerations, the most innovative frontiers in the research about materials are [42]:

*   biocompatible materials;
*   novel polymers especially nanocomposites;
*   controlled architecture polymers, plus ceramic and metal powder formulations;
*   recycled polymers.

On the other hand, polymers have some limitations related to their properties or manufacturing processes. These include, for example, limited operation-temperature range, high auto-fluorescence and limited well-established surface modification techniques [6] that have still to be overcome.

6. Process parameters influence on components quality and their optimization

Determining the most effective processing conditions for micro injection moulding was the subject of many studies, which used different experimental conditions and test parts. It has been shown that the main process parameters affecting the part quality include:

*   Mould temperature;
*   Melt temperature;
*   Injection speed;

- Injection pressure;
- Holding time;
- Holding pressure;
- Cooling time.

Quality parameters in the micro injection moulding are usually associated with the ability to completely fill the micro size cavities of the mould during processing, even if this process could require a number of quality criteria to be met simultaneously. Quality responses are usually associated with the evaluation of the replication by complete filling of the mould cavity. The most widespread responses reported in literature include filling quality of micro sized channel [43], feature dimension [44,45], part mass [46], flow length [47], filling volume fraction [48], weld-line formation [49], demoulding forces [50], mould cavity pressure [51, 52], and minimizing injection time, pressure and temperature distribution using a three-dimensional simulation packages [53]. The different chosen responses of statistical studies can lead to different main results. Huang et al. [54] applied the robust parameters design to the fabrication of a micro gear and found that the significant parameters for diameter dimensions are mould temperature, injection speed and holding pressure whereas for tooth thickness are holding pressure, cooling time and mould temperature.

Not only the process-parameters but also part geometry affects the quality of filling for micro parts. Especially for a complex part some results showed that the holding pressure can be the significant process parameter for different shapes as also the injection speed and mould temperature [46]. Song et al. [55] have been performed injection moulding experiments and numerical simulation on ultra-thin wall plastic parts. Especially ultra-thin wall plastic parts have great application potentialities on MEMS even if the process becomes difficult and complicated with the reducing of the part thickness. The results show that part thickness is a decisive parameter because the filling capability of the melt declines rapidly with the reducing of part thickness; metering size and injection rate are the principal factors in ultra-thin wall injection moulding and appropriate metering size and accelerating injection rate are the necessary condition for moulding.

Different authors report that usually the increase of parameters can improve the quality of filled part and in particular the increase of temperatures (barrel and mould) and of injection speed improve the polymer melt fill in micro-cavities even if the time needed to heat up and cool down the mould is longer [43,44,56,57]. Moreover Zhao et al. [58] found that metering size and holding pressure time are the process parameters that have the most significant effects on part quality but the process is also significantly affected by the interaction of these two parameters that have to be taken in account.

Also the interaction with process of the surface roughness of the mould is of paramount importance. Griffiths et al. [47] studied the factors affecting the flow behaviour in the interaction between the melt flow and the tool surface and PP, ABS and PC polymers were employed to perform moulding tests using cavities with the same geometry but different surface finish. It was found that there is a relationship between the tool surface finish and the level of turbulence in the melt flow. The trails for all three materials in the cavity with the highest surface finish indicate the existence of two distinctive phases in the polymer flow, while the patterns are mixed and not so clear for the other two.

As mentioned above, quality factors related to cavity pressure can provide useful information directly connected with the dynamics of the process as well as with the filling of the cavity by the polymer melt. Griffiths et al. [51] reports an experimental study on the manufacture of micro fluidic parts on three different polymers studying four parameters (melt temperature, mould temperature, injection speed, and packing pressure). In order to predict the pressure state of the polymer inside the mould cavity a condition monitoring system was set-up to conduct various pressure measurements. The two parameters derived from cavity pressure data collected by a pressure sensor have been defined: pressure increase rate during filling and the integral of pressure over time (i.e. pressure work). As effects, similar trends have been found for all three materials: higher injection speed in decreasing the pressure work and of a lower mould temperature in decreasing pressure rate. Also the Institute of Plastics Processing at RWTH Aachen University [52] developed a system that controls the quality determining directly variable cavity pressure and realizes a desired course of cavity pressure in the injection and holding pressure phases. The cavity pressure course in the holding pressure phase is controlled online on the basis of pvT behavior of the processed plastic material. The pvT optimization of the holding pressure phase enables a balancing of disturbance variables on the process through an active adaptation of the pressure course. In addition, the optimization is also capable of almost entirely compensating the influence of the melt and mould temperature changes on the moulded part weight. The direct control of the cavity pressure in combination with the pvT optimization in the holding pressure phase ensures increased robustness against disturbance variables caused by process fluctuations.

The final stage of process parameters investigation in micro injection moulding is the optimization. For the parameters optimization different tools can be applied. Attia et al. [46] applied response surfaces and desirability functions to minimize process variation. As results, they have shown that increasing the melt temperature decreased the standard deviation in part mass. Ozcelik and Erzurumlu [59] proposed an efficient optimization methodology using artificial neural network and genetic algorithm to minimize the warpage of thin shell plastic parts. The results indicate that packing pressure, mould temperature, melt temperature, packing time, cooling time, runner type and gate location influence warpage by 33.7, 21.6, 20.5, 16.1, 5.1, 1.5, and 1.3% respectively.

7. Simulation

The process design of micro injection moulding involves the determination of a number of processing parameters like pressure (injection, holding, and melt), temperature (coolant, nozzle, barrel, melt and mould), time (fill, holding, cooling and cycle), clamping force, injection speed, injection stroke, etc. In such process, due to the irregular geometry in micro scale and the complex thermo-mechanical history during the injection molding cycle, it is generally necessary to resort to numerical simulation methods to properly simulate the moulding process and develop the capability of predicting the final configuration of the moulded part.

Nowadays, one of the main challenges related to the micro injection molding technology is the possibility to simulate the process. The main goals, that researchers all over the world try to achieve, can be summed up in the following steps [6]:

- Visualization of the flow and prediction of the last-filled sections of the mould. A method to evaluate all these aspects is the short-shots method, in which the mould is filled with different amounts of material in order to evaluate the distribution of the flow during the injection phase. This method is useful to identify some defects that are usually in the last filled parts like incomplete filling, weld lines and voids.
- Optimization of the design of the moulds before manufacturing in order to prevent high cost of reconstruction or remaking. The simulation approach would be very useful to try different geometrical designs, sprue and gating systems, flow-paths to determine the optimum mould design.
- Simulation of the thermal conditions of the flow during filling and cooling which would be useful in estimating the cycle time and determine the critical processing areas.
- To identify post-processing properties, such as residual stresses, shrinkages and warpage. In fact during micro injection moulding process, the material is subject to the increasing of pressure and temperature due to significant shear deformation, followed by a rapid decay of temperature and pressure in the mould cavity. This leads to solidification, high residual stress, complex molecular orientation, that determine the moulded part quality.
- Supporting the experimentation and in particular the design of experiments in determining the most influential processing parameters on the part quality.

Several factors affect the accuracy of modelling For the process [60,61]. For micro-injection moulding, three-dimensional modelling becomes significant because, on the micro-scale, it is not possible to approximate the melt shape as flowing between two parallel plates, as it is usually in conventional injection moulding. Also mesh elements also meshing elements should be chosen carefully: two-dimensional elements (as shell elements) give over-predicted filling.

The Hele-Shaw approximation is also commonly used to model injection moulding process, providing simplified governing equations for non-isothermal, non-Newtonian and inelastic flows in a thin cavity. It has been applied also to simulate micro-injection moulding, but it does not allow to model some specificities of the micro-injection process, as fountain-flow, jetting, particle tracing, filler/matrix secretion and transverse pressure gradients. In addition, this approximation simplifies the modeling of near corners, bifurcations and changes in the part thickness. In Hele-Shaw model, applied to micro injection moulding, there are some assumptions that need to be changed compared to conventional injection moulding; for example, the pressure in flow fronts might not be zero since the surface tension produce extra pressures and the frozen layer of polymer melts, near to mould wall, may slide due to the high shear stress resulting from high shear rate.

Some effects, that are neglected in conventional injection moulding, become significant in the micro-scale due to the increased surface-to-volume ratio, such as surface roughness, surface tension, heating of the melt by viscous friction and cooling of the melt front due to increased heat loss. In addition, models should account for the differences in dynamics of heat and mass transfer in the micro-scale. The heat transfer coefficient between the polymer and the mould, for example, was shown to be significant on the micro-scale [62].

By using precise material data and considering the melt compression in the barrel, the actual volume rate and the temperature of the melt at the entrance of the cavity can be correctly calculated. The heat transfer coefficient increases by decreasing cavity thickness or injection speed. It is believed that the pressure level in the cavity is mostly responsible for the thermal contact between the polymer and the mould wall. A pressure-dependent model for the heat transfer coefficient would be more suitable to describe the thermal contact behavior in micro injection moulding, especially in case of micro-cavities of high aspect ratio. To take this phenomenon into consideration in the numerical simulation, three different aspects have to be considered: surface roughness of the mould, material properties of the polymer in the molten and solidifying state, as well as the pressure distribution along the mould wall [17]. Special processing conditions, such as the Variotherm processes, or air evacuating, should be considered in modelling.

In a moulding simulation, the advancing of the flow front is quite an issue. The volume of fluid (VOF) method and the level set method (LSM) have been widely adopted for a variety of applications including boiling, casting, different moulding processes and broken column flows since they can be easily incorporated with a fixed grid system [63,64]. Each method has its own strengths. The LSM has better performance at curvature representation while the VOF method is stronger in cavity filling prediction. For simulation of slip and surface tension, the surface curvature is more important [65].

In literature, two different approaches can be found regarding the choice of simulation packages: the first is to develop in house finite element codes specifically for simulating micro injection moulding [60], while the second approach is to enhance the commercially available software packages for conventional injection moulding, in order to accurately simulate micro injection moulding [66].

Some packages over predict the filling of the cavity; other packages instead give acceptable qualitative simulation results, but fail to give reliable quantitative values [67,68,69,70]. Moreover, recent CAE tools allow convenient interfaces to user codes that facilitate realizing user material models and boundary conditions [71]. However, a better understanding of the heat transfer phenomena in micro-scale is necessary for predicting the phase change and morphology evolution during the melts fill into the cavity.

8. Case study

In this section, the injection moulding process of a micro part (a miniaturized dog bone shaped specimen for tensile tests) is presented and discussed as case study realised by authors.

Micro electro discharge machine technology (using a Sarix SX200 available at CNR-ITIA premises) [72] was used for preparing the mould for the micro injection production of the specimen under investigation. The geometry and dimensions of the specimen are illustrated in Fig. 4. This part is representative for micro moulding because it has features in the order of micrometers and a part weight of few milligrams, falling in the category of micro moulded products.
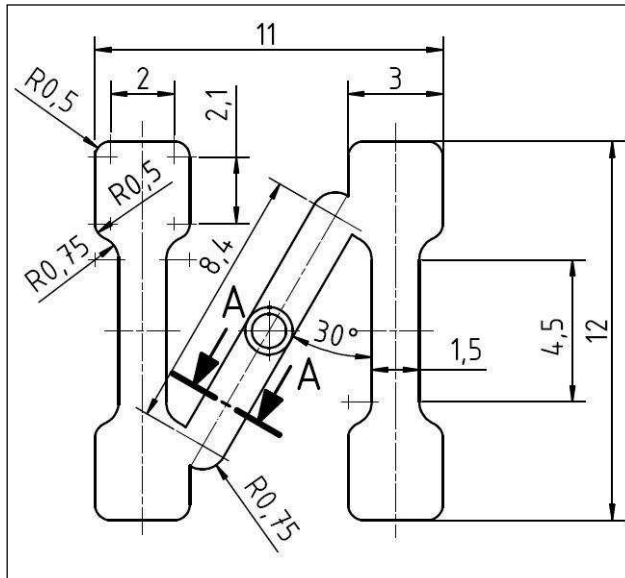
Fig. 4. Project design and dimensions (mm) of the specimen.

The experimentation has been divided into three steps: a screening phase in order to identify the working technological window, an experimental plan including only the most influential parameters as resulting from the screening and finally the optimization [73]. All the tests were carried out in a climatic chamber set at 20°C and RH 50% with the machine Formica Plast 1k by DesmaTec. The polymers chosen for this study are Polyoximethilene (POM Basf Ultraform N2320 003) and Liquid crystal polymer (LCP Ticona Vectra E130i); these two grades were selected for their properties and suitability for micro moulding. Before moulding, POM was preconditioned at 110 °C for 3 hours and LCP at 150 °C for 4 hours.

The process parameters systematically investigated were: injection speed (Vinj), melt temperature (Tm), mould temperature (Tmo), holding time (th), and holding pressure (Ph). All control parameters together with their interactions were factors affecting the capabilities of the process in optimizing parts mass that has been chosen as quality response together with the corresponding standard deviation. Part mass gives information about the filling quality of the specimen while the standard deviation of part mass gives information about the variability of the process.

To assess the effects of the selected parameters on the micro injection moulding, the design of experiment (DoE) approach was applied. In particular, a two-level five-factor randomized half fractional factorial design of resolution V (2^{5-1}) was chosen and the experiments were

conducted in a randomized sequence. The chosen plan provided sufficient information about single-factor and two-factor interaction effects. This allowed for a relatively small number of experiments to be undertaken without compromising the accuracy of the results. Table 3 presents the levels of the five factors for the tested component.

Factors	Description	POM		LCP	
		Low Level (-1)	High Level (+1)	Low Level (-1)	High Level (+1)
Vinj	Injection speed (mm/s)	100	150	100	150
Tm	Melt Temperature (°C)	190	230	335	345
Tmo	Mould Temperature (°C)	60	100	80	120
Th	Holding time (s)	1	3	1	3
Ph	Holding pressure (bar)	500	1500	500	1500

Table 3. Experimental factors and levels

For each run, the first 10 injection cycles were discarded in order to stabilize the process, then 10 parts were collected and then the masses were measured. Each treatment of the designed experiments was repeated three times in a completely randomized order. With the aim of minimize interference from external variability sources, the same mould was used during all experiments without dismounting and the same batches of polymers were utilized. The quality and the variability of the product were evaluated by measuring the masses of ten samples of each treatment of the treatment and the corresponding standard deviation. The mass of moulded parts was measured just after the ejection from mould cavity. The stabilization and maximization of part mass in general indicates stabilized processing conditions [74]. A sensitive weighing scale (Gibertini E154) with accuracy of 0.1 mg was used to weigh the parts. Data analysis was conducted with statistical software Minitab®. Figs. 5 and 6 show the average masses of the samples in run order for the three replicates. Vertical lines represent the standard deviations of the corresponding repeats for each of the 16 treatments plus the centre point.

It has been observed that, both for POM and LCP, the trend of the masses are quite similar and the corresponding standard deviation values are similar too; furthermore the larger the standard deviation the larger the difference of the average mass values as expected. It follows that the replicability and the repeatability of the process achieved are very high.

The results of the experimental design analysis showed that the holding pressure results as the main factor influencing the process. This result emphasizes the importance of a correct holding phase in the micro injection moulding to allow the completely filling of the mould before freezing and, hence, the increase of the mass specimen as desired.

Contrary to mass response, the main parameter that influences variability is the melt temperature for both the polymers. An increase of the melt temperature improves the polymer flow due to a reduction of the material viscosity and shear stress, hence these conditions help to reduce the variability of the process and of the products.
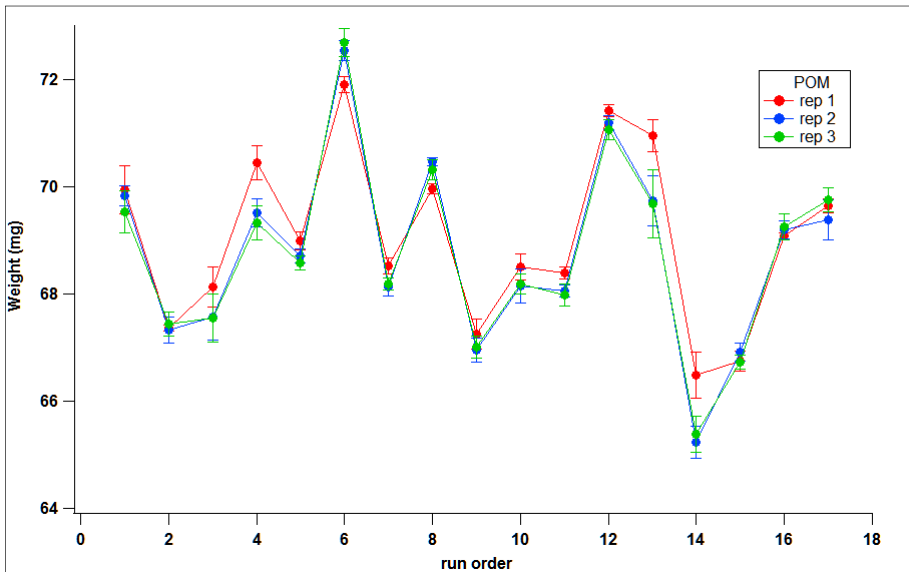
Fig. 5. Average mass for each treatment of 3 replications (replicate 1 in red, replicate 2 in blue, replicate 3 in green) - POM parts
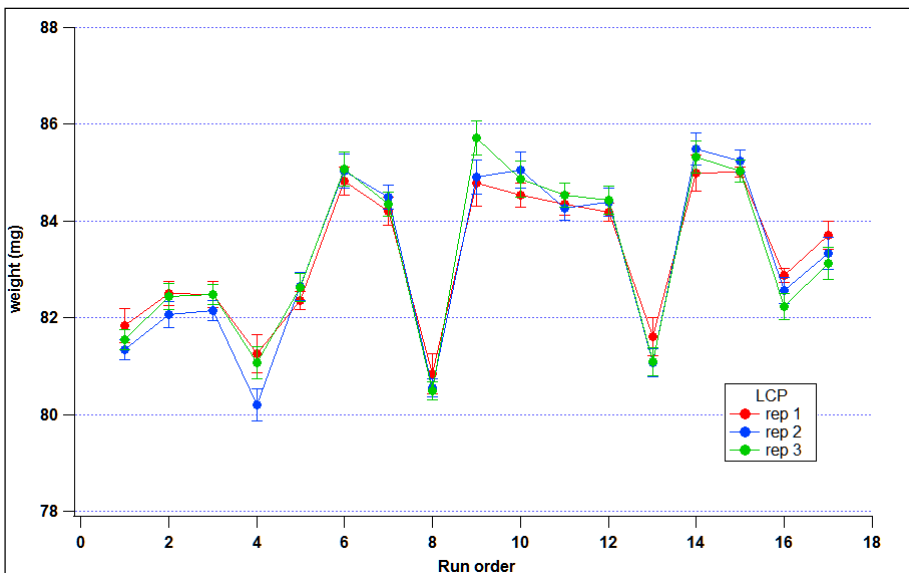

Fig. 6. Average mass for each treatment of 3 replications (replicate 1 in red, replicate 2 in blue, replicate 3 in green) for LCP parts

The final experiments were carried out with the aim to optimize the process parameters according to both responses adopting in the implemented DOE, the part mass and the corresponding standard deviation. Optimization was carried out using the desirability function approach to individuate the optimum parameter levels values that must be used. The optimized process parameters that were obtained are reported in Table 4 both for POM and LCP; the improvements in the mass and corresponding standard deviation were confirmed. Considerable improvements are observable in particular for POM; in fact, the average mass has increased of about 4.5% for POM and of 2.7% for LCP while the reduction of the standard deviation is similar for both the materials.

Material	All runs		Optimized runs	
	Mass average (mg)	Standard deviation (mg)	Mass average (mg)	Standard deviation (mg)
POM	68.85	1.681	71.95	0.097
LCP	83.29	1.609	85.54	0.250

Table 4. Mass results for different process parameters and for the optimized process

For the POM material, tensile test have been then performed using a Shimadzu EZ-S tensile test machine settled in micro-test configuration (200 N load cell). The speed of the translating upper slide was set to 5 mm/s. Cross section areas have been measured for each specimen before the test, obtaining values in the following range: 1.45±0.01 mm².

The strain at break was calculated as the ratio between the elongation and the initial length of the specimen free from the grasp of the tweezers (4.5 mm). This is the region of the sample with a constant section and where the deformation occurs.
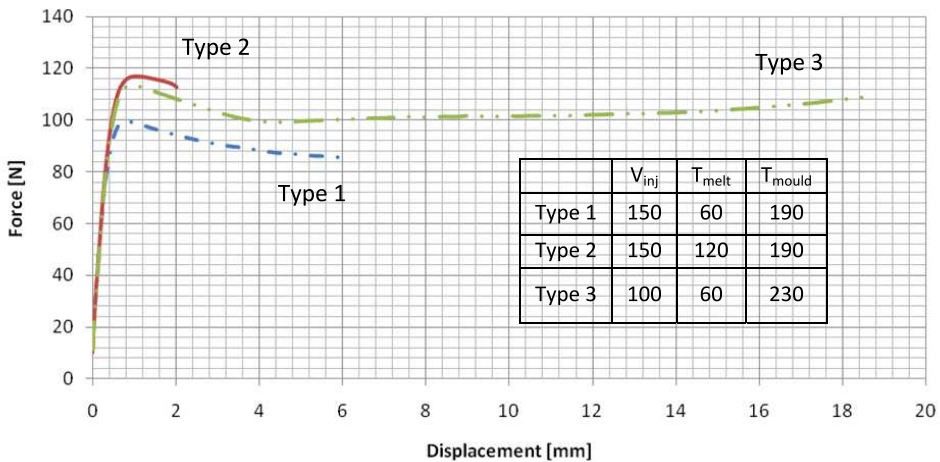

Fig. 7. Force vs displacement curves of three samples: type 1-ductile tensile behaviour with local striction, type 2-brittle behaviour with small deformation at break and type 3-very ductile with long striction and hardening strain.

Three main behaviours of the deformation of the material have been observed. In Fig. 7 the force versus displacement curves of three samples (type 1, 2 and 3) with very different trends are plotted, showing that the process parameters affect significantly the results of the tensile stress. The sample of type 2 breaks after only 2.10 mm of elongation (about 40%), with a behaviour typical of the almost-amorphous plastic materials, whereas the sample of type 3, can elongate until about 300% and shows both a long striction and strain hardening phenomena. Finally, the sample of type 1 shows an intermediate behaviour with an elongation of around 100%.

In Fig. 8, the SEM images of the three types of breaks are shown: type 1 almost brittle, type 2 ductile with striction and type 3 very ductile with long striction and strain hardening.

| (a) | (b) | (c) |
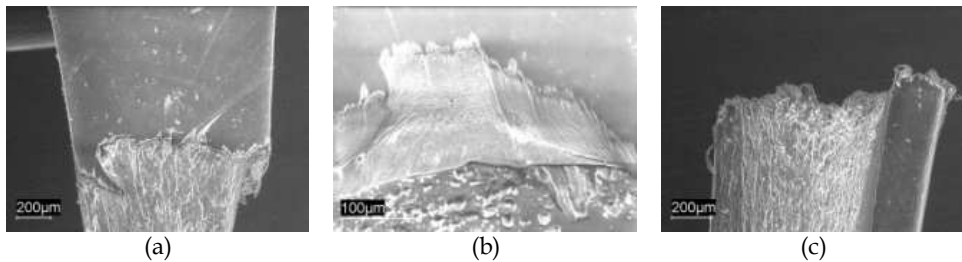
Fig. 8. SEM images of the break of a sample type 1 (a), type 2 (b), type 3(c)

9. Conclusions

Micro injection moulding process is becoming of greater and greater importance for the manufacturing of polymeric micro-components. This technology has the characteristic to play a fundamental role in the near future to sustain the growing request for miniaturization components production in biomedical, optical, and IT technology applications for these advantages:

- the ability of low cost and short cycle times process, useful for mass production;
- the increasing capacity to achieve components of high aspect ratio and micro dimensions with demanding fabrication tolerances;
- the ability of processing polymers with a wide range of properties according to the functionality requested.

Several issues have to be defined as evidenced from this review: the standardization of the process, and the best approach to follow according to part geometry or chosen polymer. The research in the micro injection moulding quickly develops and it seems able to overcome rapidly most of the actual technological limits by developing new materials, process control, simulation techniques, and quality testing methods.

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New Technologies - Trends, Innovations and Research

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The book "New Technologies - Trends, Innovations and Research" presents contributions made by researchers from the entire world and from some modern fields of technology, serving as a valuable tool for scientists, researchers, graduate students and professionals. Some practical applications in particular areas are presented, offering the capability to solve problems resulted from economic needs and to perform specific functions. The book will make possible for scientists and engineers to get familiar with the ideas from researchers from some modern fields of activity. It will provide interesting examples of practical applications of knowledge, assist in the designing process, as well as bring changes to their research areas. A collection of techniques, that combine scientific resources, is provided to make necessary products with the desired quality criteria. Strong mathematical and scientific concepts were used in the applications. They meet the requirements of utility, usability and safety. Technological applications presented in the book have appropriate functions and they may be exploited with competitive advantages. The book has 17 chapters, covering the following subjects: manufacturing technologies, nanotechnologies, robotics, telecommunications, physics, dental medical technologies, smart homes, speech technologies, agriculture technologies and management.

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