Micromoulding: engineering challenges and opportunities

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ABSTRACT: The increasing interest in miniaturized components (with submilimetric overall dimensions and submicrometric features) is driven the development of micromoulding technology. Accurate plasticating, dosing and injection of very small shots (in the range of 0.001 g), quality assessment and surface featuring details are the main processing challenges. Moreover, tool design and manufacturing require a new set of technologies and specific engineering approaches.

1 INTRODUCTION

The global trend in the plastics injection moulding industry slants towards precision moulding and miniaturisation components in plastic. Micromoulding technologies are opening completely new possibilities for many applications and concepts. Small size of microdevices makes smaller and more compact apparatus possible and is promising for portable and hand systems. The ability to produce acceptable metering accuracy and homogeneity of very small quantities of plastic melt is a key challenge in the micromoulding.

To control the metering accuracy and homogeneity of the very small quantities of melt in the micromoulding process, a new generation of machines that use a separate screw plasticising unit and a plunger injection system has been developed. During the moulding process, plastic pellets are fed into the extrusion screw, where they are plasticised by the heating and shearing, and then enter into the dosing barrel through a melt control valve at the end of the screw.

Microsystem technology is an interdisciplinary engineering science. The micromoulding activity include the full spectrum of polymer moulding from product design to tool design and fabrication, and the application of innovative injection techniques.

Moulding machine, tooling, material and process, as well as component handling and inspection, need to be specially addressed. The new generation of micro injection moulding machines, new mould design concepts and methods have to be adopted to meet the requirements of new machines.

2 MICROSYSTEMS

Microsystems are microstructured products with features and structures in the micron range, that have their technical function provided by the shape of the micro-structure. Micro-systems combine several micro-components, optimized as an entire system, to provide specific functions, and may include microelectronics. [1].

The growing interest in micro-systems in recent years is due to the number of possible applications in several areas, as shown the Figure 1.

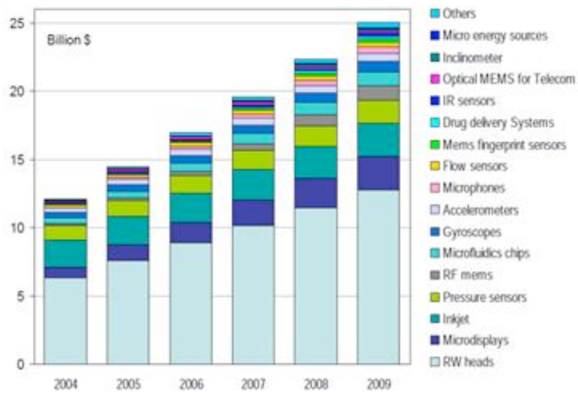

Figure 1: Total market for Microsystems products [3]

According to a recent study, there was a market increase in the production of microsystems, see Figure 2 [3].

Most existing procedures for engineering of microsystems time consuming and costly which demands for improvements. There are an increasing number of researchers working in this emerging field of production.

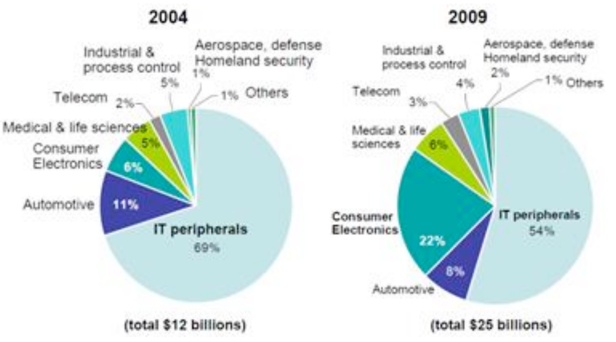

Figure 2: Micro-systems application fields in 2004 and 2009. [3]

The development in this field started with microelectronics in the seventies and has been expanding to consumer goods, such as electronics. The evolution of biosensors and medical devices using microparts also contributes to the growing demand [2,3].

The miniaturization of parts is a vital step in the evolution of technology, where the functions would be more and integrated in less space [4, 5]. The progress of new microdevices is dependent on manufacturing systems that can economically produce microcomponents in large series of production [6]. Micromoulding appears as one of the most suitable technology to produce microstructures, allowing for the production of devices with reduced dimensions and integration of various components at low cost [4, 7, 8].

Micro-systems range in size from a micrometer to a millimeter. They may function as actuators, motors, generators, switches, sensors, and have applications in fields as diverse as telecommunications, automotive and aerospace, astronomy and ophthalmometry, biotechnology or logistics. Various physical principles are applied in microsystems. The first microsystems are based on electrostatic principles. Today's micro-systems also exploit piezoelectricity, electromagnetism, ferromagnetism, magnetostricition, shape memory effects. Microsystems is a fast evolving domain and it is expected that other effects will also be exploited [2].

Microsystems are of interest for many reasons:

• Cost: batch processing using techniques developed by of microelectronics industry means that the price of an individual machine is very low.

• Size: they don't take up much space and weigh, are good for portable applications (as mobile phones) or applications with space limitations (as implantable devices).

• Energy efficiency: they hold great potential for the environment, increasing fuel efficiency in modern cars and houses of the future will intelligently control energy consumption.

• Intelligent machines: electro-mechanical elements can be integrated with electronics onto one substrate, acting as the arms, legs and the brain of the machine [2]

Although microsystems are in the market since the 60s, the nomenclature is not standardized. The term "micromachines" is widely used in Asia, but in Europe preferred term is "microsystems". In the USA the symbol "MEMS" (for Micro-Electro-Mechanical Systems) remains the dominant to refer not only electro-mechanical devices, but also micromachined structures in general. 'MOEMS' standing for Micro-Opto-Electro-Mechanical Systems, can also be found when optical components are involved. Perhaps the more inclusive term is 'MST' (Microsystems Technology), although being little used [3].

MEMS technology is used to produce mechanical, electromechanical, and electrochemical microsystems. This emerging technology utilizes mechanical structures, fabricated by microfabrication techniques perfected by the semiconductor industry, to perform sensing and actuation functions. Commercial applications for this technology include pressure sensors, fluid regulation and control, optical switching, mass data storage, chemical and biological sensing and control, and many others constantly turning up in the market [3].

3 MICROMOULDING

Microinjection moulding, or simply micromoulding, is a relatively new technology, which appears as variant of conventional injection moulding. The first work on thermoplastic micromoulding was published in 1970 by a group of researchers from the RCA laboratories in Princeton, USA. Much later in the mid-1980s, the development of micromoulding continued in Karlsruhe, Germany. The first components based in micromoulding were made for micro-optical applications. Since then, several new components were developed, as micropumps, microvalves and microsensors [9]. By the mid-90s, the first efforts by companies in mechanical engineering in co-operation with research institutes were made to develop specific injection units for micromoulding and equipment to produce microparts [10], allowing for major developments in the mid-90s [11].

Nowadays, there exist equipment manufacturers offering different technological solutions, and companies already have micromoulding equipment and know-how of their own [*e*.g. WITTMANN BATTENFELD]. Thus, the use of micromoulding in the industry and the number of scientific institutions working in this field should increase in coming years [9]. To improve the quality of the process, researchers around the world are investigating in many fields to develop further the technology, aiming at optimizing the process, developing new technologies and tools, and improving the materials rheology, moulding tools and manufacturing process [12].

3.1 *Micromoulding definition*

Micromoulding came from the idea of transferring the high potential of conventional injection moulding for the efficient production and economic microsystems. It allows for the large scale production of components with very fine detail.

This process stimulates a new way of thinking to select innovative solutions in varied fields such as microelectronics, micromechanics and telecommunications. However, the current knowledge of the process and its influence on the polymer performance is still limited [5,13].

Micromoulding applies to parts when:

- Their mass is less than a few milligrams or micrograms;
- Their dimensions have tolerances in the micrometre range;
- They have features with detail size of the order of micrometres, such as diffraction gratings or microfilters [12-16].
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One of the major challenges in micromoulding is simply due to the physical size of the product. The products can be very difficult to see clearly without microscopy aids, and conventional mechanical testing cannot be used with such small geometries [13].

Micromoulded parts may have a mass of 0.00012 g and more than 500 parts can be produced with only a material pellet [17]. The size range of conventional injection parts is generally in the order of centimeters to meters, while with micromoulding is the order of micrometers to millimeters [18]. It is already possible to produce 1μg microparts [13]. This gives an idea of the requirements and difficulties of running the process.

3.2 *Applications*

Two of the most promising areas of micromoulding are medicine and biotechnology [19]. using sensors, optical and electronic systems [20]. Leading application fields include electronics and optical circuit boards, acceleration sensors, and simple electrical switches [7, 9].

The most widely seen micromoulded product is probably the well-known DVD for media data storage. Another wide spread article is the hologram featured in credit cards. There is a variety of micromoulded fluidic devices, such as nebulizers, capil-capillary analysis systems, devices for investigation of living cells, pressure sensors, and flow sensors [9]. Specific examples of micromoulding applications are shown in Figure 3: automotive (microswitch, ABS-Systems); computer (head of an ink-jet printer); telecommunication (mobile phone, MID); connectors (plug connectors, opto couplers); Electronics (microparts on circuit boards); Microequipment (valve technology); Medical technology (hearing aids, implants); Sensors (airbag sensors, sensor disk); Micromechanics (micromotors, rotors); Optics (lenses, displays); Watches (gear wheels, microtransmissions); Glass fiber conductors (ferrules, connectors); Precise suppliers (various parts); Special materials; Institutes, Universities (material, technology research) [21].

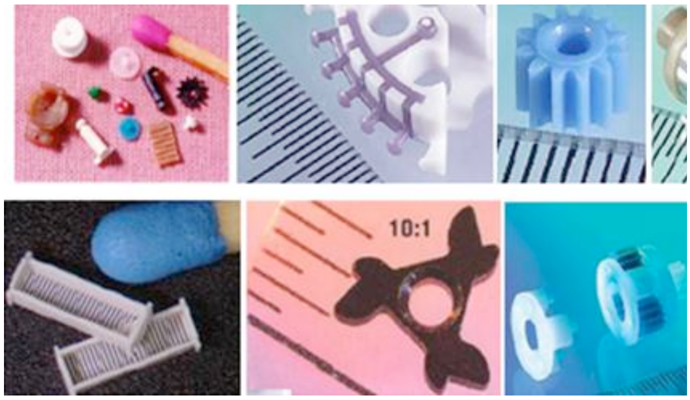


Figure 3: Micromoulded parts. [20, 21]

3.3 *Micromoulding machines*

The success of micromoulding requires strict material and processing control, and in their own mouldings. These requirements are more strict than in conventional injection moulding because [11]:

- The positional control of the machine must be precise enough to ensure the correct dosing of the material;
- The plasticizing screws must be downsized for producing microparts, since the high residence time of the molten material inside the barrel can lead to degradation;
- There is potentially a large amount of wasted material, since the volume of material required to fill the runner channels and cavity is smaller

It's possible to get micro-parts using the conventional machines, but the rejection rate is very high and degradation may occur during the various stages of processing, due to the low precision control of the machine which is not precise to get such parts. **The size of the injection unit (Figure 4) and clamp unit must be reduced to limit the amount of material and energy consumption, t**hese leading major manufacturers to develop new machines [4, 11].

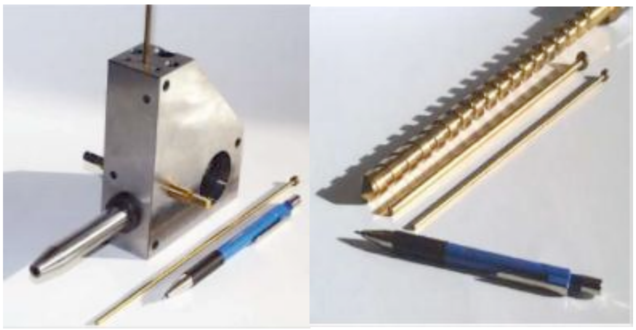


Figure 4: Injection unit and plasticating screws using in the micromoulding. [11]

The design solutions adopted by various manufacturers differ in the form of material dosing, the structure of the equipment and the machine ancillaries. [11, 22].

The structure of a micromoulding machine must have high rigidity to ensure precise movements, make exact dosing, and have high injection rate and short response time (as the example on Figure 6) [9, 16]. Another specific development of these machines is the transition mode from the injection pressure to the holding pressure (switchover). It is generally based on the injection plunger position and not on the injection pressure [4, 6].

3.4 *Materials*

Many materials are successfully processable in micromoulding, as listed in Table 2. In addition to these materials, nanocomposites are being introduced in high performance applications. Materials for micromoulding should have specifications, such as a good flowability, allowing the cavities to fill with low pressures, easy ejection of microparts, and ability to mix additives effectively [20]. Due to the size of the parts, typically small quantities of materials are required, making it difficult to find manufacturers who are ready to deliver such small orders [10, 22]. However microparts in high cost materials become advantageous for the very short material usage [9, 10].

A good reproduction of the cavity surface is achieved with LCP, COC or PC, but easy flow is achieved with PA, POM, PBT, PEI, PPE and PSU. High temperature materials such as LCP, PEEK and PEI are suitable for subsequent welding. Better ejection is achieved with PEEK, PEI, PAI, PC and PMMA. Low shrinkage (between 0.1% and 0.8%) is typical of LCP, COC, PAI, PEI, PPE, PS, PC, PEEK, PMMA and PSU [14].

3.5 *Moulds*

The design and manufacture of moulds for micromoulding are a current area of work, the importance of the tool increasing exponentially due to reduced tolerances and other specifications [8]. The concepts and methods of conventional mould design must be adopted/changed to the process of micromoulding technology [23].

The choice of the machining technique for the micromoulding blocks greatly depends on geometry, surface quality, aspect ratio and economic constraints [4, 28, 33]. Various methods are applied for shaping the micromould surface: mechanical micromachining (microgrinding; microcutting, micromilling or microdrilling), laser structuring, microelectric discharge machining; electrochemical machining using ultra-short pulses; LIGA process (lithography, electroplating, moulding); and others [9, 19, 20, 33]

For moulds used for microparts, microcavities are usually produced by inserts, which are mounted in the main structure of the mold, inserts can be manufactured from other materials, depending on the technology used. This is because the hardened steel requires specialized tools and features and faces for machining microchannels [19, 22]. Also the use of rapid prototyping techniques is being considered for these blocks [30, 34].

In micromoulding the mould (Figure 5) must comply with the following functions: totally filling the cavity with good quality and ejection the moulded parts. It requires a vacuum system and a process variotherm. The vacuum system will remove all the air in the cavity during the injection of the material. The variotherm system allows heat to the mould so that the small amount of material processed doesn't solidify immediately upon contact with the mould. Before the ejection the mould must be cooled again [9, 22, 24].

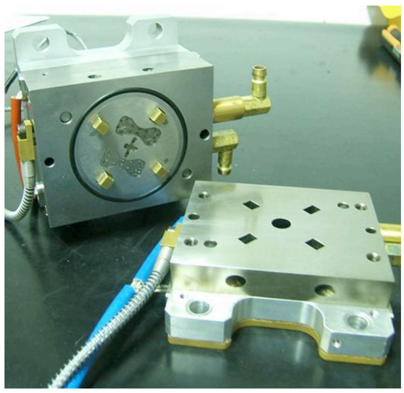


Figure 5: Example of mould for micro-parts (courtesy Nanologic).

The nozzles of micromoulding machines are usually designed so that they can reach the partition plan of the mould (see Figure 6). Thus, minimizing the path of the melt to the impression and reducing the runner waste [23].

Ventilation is also important, the more effective solutions being stepped clamping force build-up and evacuation of the air with a vacuum pump [20]

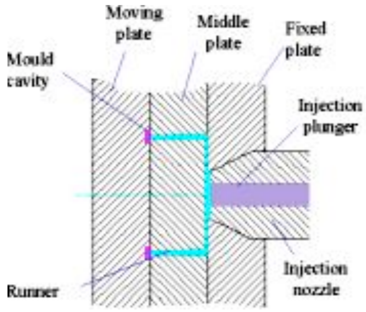


Figure 6: A mould with injection nozzle extended to the middle plate. [23]

The ejection followed by free fall may cause failure due to static electricity, as the part is "glued" to the mould. To avoid this problem, it should be used ionized air or a suction vacuum robot to manipulate the part [20, 22]. The stress concentration caused by conventional ejector pins, is not desirable due to the deformation or failure it may cause. Modern pin ejectors with less than 0.2 mm in diameter may help in this situtation. There are other systems, as vacuum system, which can only be used to demould the parts where low forces are required; or a system that retracts the cavity, its accuracy depending on the geometry of the part; or ultrasonic vibration, which actually doesn't seem to improve demoulding [4].

Therefore, the volume ratio between runner systems and microparts can be very large and that will waste most of the plastic. **A design challenge of micropart mould is to miniaturize the size of the runner and the sprue.**

3.6 *Process parameters*

The melt temperature, the mould temperature and the injection rate are the main factors affecting the quality of replication and the duration of micromoulding filling [12, 22]. Different studies have studied the main process parameters: mould temperature, injection speed, injection pressure, holding time and holding pressure [4, 11, 18, 29, 35].

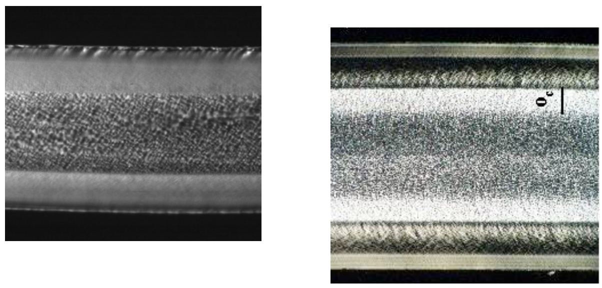
In the process higher temperatures for the polymer melt and mould are used, as well as faster speeds and higher pressures [5]. Small variations in the process can produce defective products [15, 18].

The injection rates should be high enough to allow the complete filling before cooling. The ideal situation is when there is a hot mould during the injection and cold during the cooling phase [22]. However, these higher rates lead to the occurrence of wall slip that may affect the surface quality [31-33].

The cooling of the melt is quick leading to a large increase in viscosity, which can promote the development of defects in the microparts. This effect should be reduced by increasing the melting temperature or using a mould with a temperature higher than those suggested by manufacturers. The temperature of the mould can be near to the melting temperature (T_m) or near the glass transition temperature (T_g) [4, 13].

The rheological behaviour of the polymer varies with the size of the filling microchannel. The shear rates produced come in between 1×10^5 to 5×10^6 s^{-1}, these values may be higher than those admissible for the polymer, leading to the degradation of the material [5, 13, 22,32].

Some authors defend that no significant difference between the morphology developed in micromoulding and conventional injection moulding, but recent studies point differently [27, 43, 45, 47]. The main difference between these two processes is the relative thickness of different layers. There are also results that show that in the case of macro-parts we can see four distinct layers. A layer of skin (A), a shear layer (B), a thin layer of granules (C) The core (D), see Figure 7b.



(a) *(b)*

Figure 7: Typical microestruture of micromouldings (a) and conventional mouldings (b). [45, 47]

It can be observed that a heterogeneous structure along the micropart thickness results from different cooling conditions during processing. Experimental results show that the microparts have a structure type 'skin–core', an outer layer of skin (a) and a central layer of spherulites (b) [5, 25, 45, 47].

The relative thickness of the external layer (skin) is about 5% of the total thickness of macro-part and about 40% for micropart. The proportion of the shear layer to micropart, representing 60% of the total thickness, and 22% for the macro-part [45, 47].

In micromoulding, monitoring the process is essential to ensure process stability and quality of the part. **A monitoring challenge is the integration of sensors in small inserts of the.**

Currently, some microsensors are already commercially available, capable monitoring some process variables [18].

3.7 *Micropart design*

There is still a need for research regarding the designing of microparts, because most design rules cannot be transferred without change from the existing microparts on silicon or glass, or parts resulting from conventional injection moulding. The thermal expansion of polymers is important on the design of microparts. In the design of plastics microparts, adhesive bonding is widely used to join parts. During the ejection, microstructures can be deformed or destroyed, so when designing the micropart there should be attention to this fact [9]. The polymer shrinkage is also an important factor to consider, as the size of the parts is very small and the dimensional tolerances are very narrow. The ejection very much depends on the shrinkage of the polymer, and also on the orientation of the microstructures; thus it is necessary that the flow path is carefully considered. The quality of part does not depend only on processing parameters as other factors play a significant role: the molecular weight of the material, the geometry of the mould, the solution selected (quality parameter) and the surface finish of the mould.

3.8 *Quality control*

One of the main challenges associated with micromoulding is the physical size of the product. The products can be very difficult to see clearly without the aid of microscopic techniques and the techniques of conventional mechanical test cannot be applied [4, 13, 15, 46].

Nanoindenting measurements or nanoscratch tests appear as interesting alternatives to determine the local variations of the mechanical properties of microparts. Regarding thermal analysis, such as differential scanning calorimetry, sub-milligram parts require the use of several parts for making only one sample. As a result, structure heterogeneities in the parts cannot be evaluated with these experimental devices. Consequently, studies mainly use observations to qualify the validity of microparts, and few physical or chemical properties are measured. Then specific analytic methods have to be adapted to the miniaturization of the parts.

4 FINAL REMARK

The micromoulding process brings about many challenges, particularly in terms of process technology and tool manufacturing.

Conventional injection moulding machines lack the combination of high precision control with low residence times of the melt that are required in micromoulding. New specific machines have to be developed with improvements in five main areas:

1. Plastication – the extrusion screw must adequately mix and work the material to provide an homogenous melt but must also contain a minimal volume of melt to prevent high residence times and possible material degradation.
2. Metering – the process demands very accurate and repeatable metering of material to avoid part or overfilled cavities and to ensure repeatability of product properties
3. Injection rate – the extreme cooling rates present due to the high surface area/volume ratio of micromoulded products require rapid injection times to prevent premature freezing of material in the mould feeding channels or cavity during injection.
4. Handling – the relative small size of the parts (micron dimensions) made difficult its manipulation. New handling system and part design should be considered.
5. Quality control – the physical size is a driven force to find new advanced characterisation techniques and optical inspection.

The moulds for microinjection have to be developed with improvements in two main areas:

6. Variotherm mould heating and cooling - the temperature of the mould varies during the injection cycle. The replication of high aspect ratio structures often requires such a system at micro scale.
7. Vaccum Venting – was able to enhance the replication quality more effectively by supporting filling under extreme moulding conditions such as low mould temperature, low injection velocity, and narrow feature geometry

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