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BIG CHALLENGES IN DESIGNING SMALL PARTS FOR MASS PRODUCTION

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ABSTRACT

Micro manufacturing involves the production of parts or products with features on a micro scale. The technology is used to produce parts for several business sectors which have experienced dramatic growth in recent years and forecasts are that this growth will continue in the years ahead. With the loss of traditional manufacturing jobs to lower-cost locations many companies in Ireland see micro manufacturing as having significant potential to preserve and increase revenue. A move into micro manufacturing will present significant opportunities for those companies willing to take the risk of producing parts with micro dimensions.

Such a transition is a risk because micro manufacturing is not simply about reducing the dimensions of existing products by scaling the manufacturing equipment. Whilst the manufacturing equipment might be smaller, significant problems can arise due to the scaling effects of materials and processes. Such effects can cause problems at all stages of product development from design right through to final assembly.

This paper explains the concept of micro engineering and, focussing on the micro moulding process, details potential problems and challenges that can arise during each stage of the design and manufacturing process. Attention is given to what product and process designers can, and need to, do if they want to overcome such issues. Following the process outlined, and addressing these challenges at an early stage of product development, will help Irish engineers to minimise the associated risk and maximise the probability of a successful outcome when designing small parts for mass production.

KEYWORDS: Micro engineering, micro moulding, micro manufacturing

1. INTRODUCTION

Ireland has experienced the loss of manufacturing jobs to lower-cost locations in recent years. As a result many existing manufacturing companies in Ireland are seeking new opportunities through which they can preserve and increase revenue. A move into niche areas with a high skills requirement, for which a price premium can be charged, will help to offset the loss of competitiveness, either real or perceived, of the Irish economy. Some see the production of micro parts and micro manufacturing as such a niche area. MicroMan, an industry-led network, was established in 2002 to examine the potential for micro manufacturing in Ireland.

Micro parts are defined as those having a mass in the range of a few milligrams, having features in the micrometer range or larger parts having dimensional tolerances in the micrometer range [1]. Examples of such components are inkjet heads, hard disk reading heads and micro

displays for the IT component industry, pacemakers, hearing aids, micro fluidic channels and tiny pumping mechanisms for the medical industry, intelligent packaging for the food industry and motion or airbag sensors for the automotive industry. Examples of typical micro products are shown in Figures 1, 2 and 3. Due to ongoing miniaturisation trends, these industries experienced dramatic growth in recent years and this growth is forecasted to continue in the years ahead. [2]

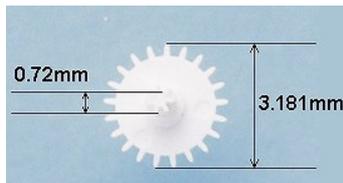


Figure 1: Micro gear and pinion [3]

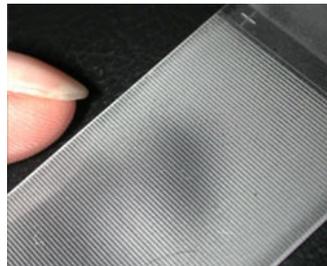


Figure 2: Micro fluidic channels [4]

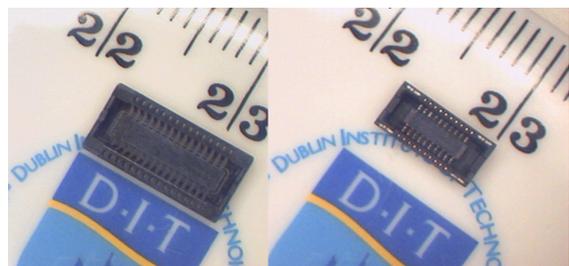


Figure 3: Micro miniature connector housing and assembly (0.4mm pitch)

Many processes can potentially be used to produce micro parts and the number of associated technologies continues to increase. Micro parts and micro structures can be produced by scaling up nano-scale processes, using silicon-based technology and by scaling down conventional manufacturing processes. Both up-scaling and down-scaling creates challenges relating to process stability and the behavior of materials. With the availability of a large range of different polymers and grades, producing micro parts from polymer material provides greater flexibility to engineers when designing parts for specific cost, mechanical, environmental and electrical requirements.

Use of conventional polymer materials suggests the use of conventional production processes. However micro manufacturing is not simply about reducing the dimensions of existing products by scaling the manufacturing equipment. As component size reduces significant challenges arise at all stages of product development due to the scaling effects of materials and processes.

This paper addresses the key challenges injection moulders face during the design, processing and assembly of micro products. An understanding of these challenges and an appreciation of how to overcome them at an early stage of product development will help Irish companies attempting to make the transition from conventional to micro moulding. Section 2 describes the concept of micro engineering using a model of the development process for micro products. This model breaks the process into distinct phases; product design, tool design and fabrication, component processing and final product assembly. Section 3 details the challenges and potential solutions that occur during the product and tool design and tooling fabrication. In section 4 the challenges and potential solutions relating to component processing and final product assembly are discussed.

2. MODEL OF DEVELOPMENT PROCESS FOR MICRO PRODUCTS

A generic model, inspired by Alting et al. [5], to explain the concept of micro engineering for the development process of micro products is presented in Figure 4. This model shows how micro engineering relates to the entire process of product conception, tool and product design, component processing and product assembly.

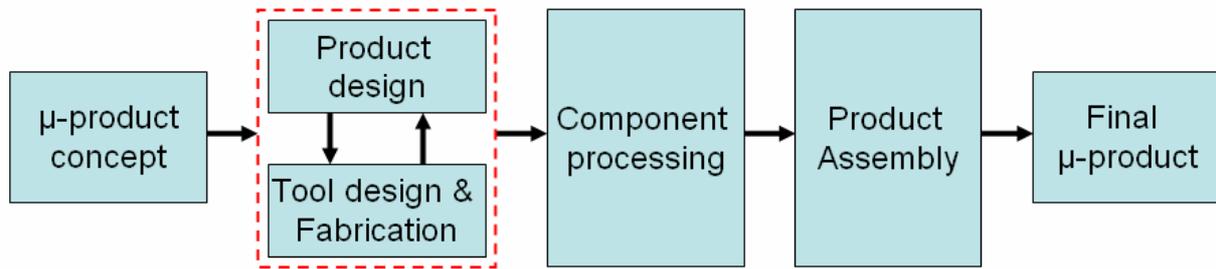


Figure 4: Generic model for development process of micro products.

3. PRODUCT DESIGN, TOOL DESIGN AND TOOL FABRICATION

Design of new products is a core competency of product development companies. Innovation and product development in the world of micro engineering thrives in the presence of multi-disciplinary competences [5]. Design engineers must strive to become multi-disciplinary and keep abreast of new manufacturing technologies. The design of micro products and micro moulding tools are inherently linked and should be addressed systematically to ensure designs are matched and optimised. This helps ensure that product and tooling costs are optimised.

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| Product design | Tool design and fabrication |
|----------------------------------|------------------------------------|
| Thin walls/skin effect | Shrinkage |
| CAD & simulation | FEA simulation |
| Gate design/location | Weld/meld lines |
| Ejector design.location | Runner balance |
| Location for marking | Injection pressure/cavity pressure |
| Variation/tolerances | Mould venting |
| Lack of existing capability data | Tool/insert alignment |
| Weld/meld lines | Surface roughness |

Table 1: challenges for product design, tool design and fabrication.

Product designers have a difficult job of balancing conflicting requirements. Products should be designed for optimal functionality, suitability for mass production, minimum cost in manufacturing, assembly and packaging, ease of testing, environmentally friendly and optimized material choice. In addition to balancing these requirements designers must strive to continuously analyze risks associated with their designs. Such risks include those related to project feasibility, risks to humans and/or the environment. Similar risk management approaches are taken with conventional product designs and software to manage such analysis exists. An example of software for conducting Failure Model and Effects Analysis (FMEA) is FMEA-Pro [6].

Other computer and simulation tools are vital to the successful development of micro parts. For example a suitable CAD package must be selected so engineers can create a model of the required parts with a geometrical resolution that suits the dimensional requirements of the micro features. Such packages often have inbuilt mould advisor software to analyze parts and highlight any areas where undercuts, which may necessitate side actions in the tool, are present. It has been possible to simulate mould-filling on a conventional scale for some time but difficulties in accurately modelling the filling of micro moulds and the impact of the moulding process on the optical properties of lenses have been experienced. Advances in this area have been reported which

make such simulation feasible [7]. Such simulation software allows engineers to predict filling of the cavities and runner system, packing, cooling and it can also highlight areas which may be at risk due to warpage.

The biggest challenge with micro moulding is the moulding of thin walls and high aspect ratio (height to width) features. This is due to the frozen skin effect where the plastic melt flow freezes on contact with the mould wall. Frozen layers on opposite sides can contact and prevent further flow of the plastic into the cavity. As with conventional moulding this can result in short shots, or incomplete filling of features. The type and grade of plastic material being moulded will of course have a large impact on the wall thicknesses which can be successfully moulded. For example Liquid Crystal Polymer (LCP) will have much better flow than, for example, PBT. It has been suggested that an apparent lack of enthusiasm by material suppliers to develop materials specifically for micro moulding is due to the relatively low material usage in producing such parts [8].

Micro moulds, like conventional moulds, are formed from a fixed and moving half in addition to sliding cores needed to mould any undercuts present. Micro moulds for mass production are predominantly created from steel, normally using different tooling inserts, or details, suitably arranged to form the required cavity. These tooling details can be created by different sources using different technologies [9]. Technologies to produce such tooling include: laser machining, chemical milling, electrochemical machining, petrochemical milling, EDM-WEDM, etching, thin film deposition, ultrasonic machining, ion machining and CNC machining.

The positioning and alignment of different tooling elements to form the mould cavity, while maintaining micron tolerances throughout the tool life, demands a high level of skill. At this scale tooling details can be fragile and prone to damage. This can be a particular problem if a plastic material with high glass content is being moulded since the material can be quite abrasive. For this reason it is common to have a camera/vision system to ensure parts are completely ejected and that key mould details are intact before each moulding cycle.

Where fine dimensional tolerances are required, and the volume requirements allow, it can be advisable to reduce the number of cavities in the mould. While this will decrease the overall output, and may increase overall costs, it helps to reduce variation between cavities and can also help prevent downstream problems caused by cavity variation, thereby increasing part consistency and reducing overall scrap levels. This also allows the use of smaller injection moulding machines and helps reduce potential problems relating to the residence time of the plastic in the barrel as will be described in section 4.

Since polymers shrink on cooling the mould cavity is normally made larger by an amount proportional to the amount the plastic will shrink. Shrinkage data is readily available from material suppliers. Micro components with micro dimensions shrink by a small amount, but if very high precision is required such shrinkage can account for a large proportion of the allowable tolerance.

Due to their small size it can be difficult to find a suitable location to gate micro parts. If mould opening is used to automatically degate parts the protruding gate marks can cause cosmetic and dimensional problems during subsequent processing and use. Size and cosmetic requirements can also make it difficult to find suitable locations for ejector pins.

Weld lines and meld lines are related to a number of factors including mould balance, the position and number of gates, the cavity geometry and the cooling system integrated in the mould. The Moldflow simulation software mentioned earlier can be used to predict where weld and meld lines are likely to form. This should be considered during product design to ensure that they will not be located in a highly stressed area of the part.

Runner balancing is important for conventional moulding and particularly important for micro moulding where the process window can be substantially smaller. If the melt flow in the mould is not balanced then some cavities may flash while others may be short and the overall quality of the moulded parts produced can suffer. Meltflippers can be used to help ensure a more uniform flow by repositioning shear-induced variations in runner delivery systems during the moulding process [10]. A typical product produced without/with a meltflipper is shown in Figure 5.

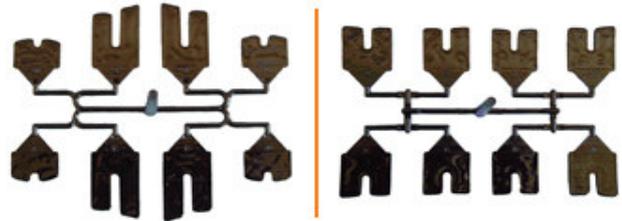


Figure 5: without and with use of meltflipper[10]

Conventional moulding is generally controlled by measuring injection pressure. Injection pressures used in micro injection moulding can be up to ten times higher [11]. Measurement of cavity pressure for micro parts is considered to be an efficient indicator of process variation. This requires the mould be designed and built so that a pressure sensor can be incorporated directly into the cavity, often resulting in increased cost and complexity.

Adequate mould venting is important to ensure that air is not trapped within the cavity since this could result in cosmetic defects. The fitting tolerances of conventional moulds, particularly in the areas of ejector pins, slides and between mould halves help ensure adequate venting. The fine tolerances and close fits needed in micro moulds, to prevent flash and cause cosmetic defects, which do not allow such venting needs to be carefully considered. Porous mould materials have been proposed to allow venting of mould gases as the cavity fills.

The surface roughness of tooling is important. Various coatings have been proposed to reduce the surface roughness of mould details and simplify ejection of parts from micro moulds. Coatings such as TiN, TiC and CBN can be used to reduce friction and improve surface finish.

Table 1 summarises the primary challenges to be considered when engaging in product design, tool design and tooling fabrication to produce micro products.

4. COMPONENT PROCESSING AND FINAL PRODUCT ASSEMBLY

When the tooling components have been fabricated, assembled and debugged the micro moulding system is ready for mass production. It has been reported that some companies integrate their moulding and assembly processes, particularly in the case of medical components, where the combined machine is shrouded to create a clean-room environment. For the purposes of this paper component moulding and assembly is treated as two distinct activities. The primary challenges to be faced during component processing are listed in Table 2 and those associated with final product assembly are shown in Table 3.

4.1 Component processing

If standard injection moulding machines are used to mould micro parts with minimised runners then the residence time of the plastic in the barrel may exceed that recommended by material suppliers. Increased residence time can cause material degradation. This can be overcome by using a specialised micro moulding machine.

The issue of thin wall moulding, the frozen skin effect, has been described. To overcome this problem plastic suppliers often recommend that moulders use a very high injection speed. This can induce severe shear effects and may ultimately cause mechanical degradation of the plastic [12]. The frozen skin effect can also be reduced by using mould temperature control. This technique, often referred to as thermal variant moulding, involves heating the surface of the mould to reduce the onset of freezing. Running the mould at higher temperatures will help part filling and so reduce short shots but at the expense of increased process times.

The issue of part size causing problems for the gating and the subsequent degating in addition to suitable locations for ejector pins has already been mentioned. Conventional mouldings are generally released from a mould using suitable ejector pins and the parts are then dropped into a suitable container using gravity. In the case of micro parts static electricity can prevent the parts lying in containers. As a result direct transfer methods have been developed to move parts from the moulding cavity to a suitable handling container.

Successful component processing demands a system to view and accurately measure small features of the parts. In the case of parts with complex curves it can be difficult to accurately locate parts for measuring. Dedicated gauges are normally required in addition to high-powered microscopes. Such reliable and repeatable metrology systems are needed to perform process capability studies in order to understand the true process stability and evaluate the true process variation

At the micro-level very small temperature differences can make a substantial difference to measurement results so many micro moulders enclose the entire machine and/or inspection area in order to create a controlled working environment [9].

| |
|------------------------------------|
| Component processing |
| Thin walls/skin effect |
| Metrology |
| Wall shear effects |
| Part handling |
| Residence time |
| Temperature of working environment |
| Component variation |

Table 2: challenges during component processing.

4.2 Final product assembly

While micro components may be supplied to customers it is more common that a number are assembled together to form final micro products. Due to the small component size and related tolerances the assembly process requires precise part handling. The orientation and feeding of such micro parts can be complicated due to tangling of small long parts and/or due to issues with static electricity. Static electricity can cause the loss of micro parts since it causes them to float in the air [13]. As a result static guns, wands, air curtains, and grounding mats are commonplace in micro-

molding facilities. More recently static electricity has been shown to be a viable method to align and present parts for assembly [14].

Component variation can prevent the final assembly meeting the required tolerance. This is particularly true in the case of multi-cavity moulds where cavity-to-cavity variation can be experienced. Cavity sorting, where parts are “binned” or sorted according to size before being selectively chosen to have “large” parts mate with “small” ones, can reduce variation of the final assembled parts. In addition to general part variation, flash, bow and/or protruding gate marks can cause additional problems, particularly in the case of automatic handling where they can result in machine jamming.

| |
|-----------------------------|
| Final assembly |
| Metrology |
| Variation |
| Residual stress |
| Part handling & orientation |
| Bow & deformation |
| Traceability |

Table 3: challenges during final assembly.

Conventional parts are often flexed or twisted during the assembly process. On a micro scale this can cause high stress levels in the components and result in premature failure. This can be exacerbated due to residual stress in the components. Such residual stress may manifest itself in the form of bow or warpage of the components or assembly. Whilst the resulting deformation might be seen visually by measuring it may also become apparent only after subsequent processing. An example would be where the plastic housing of an electrical connector can relax when experiencing the high temperatures of a lead-free soldering process. This relaxation can cause bowing of the part during soldering and result in open solder joints.

Several joining methods may be used to create micro products, such as interference, which can result in varying stress levels due to component variation, snap-fits, which can be difficult to implement for small components and ultrasonic or adhesive bonding, which can cause problems relating to size and acceptable areas for the ultrasonic horn or adhesive.

As described, viewing or measuring micro components and subsequent assemblies can be difficult, particularly for asymmetric or curved parts without flat surfaces that can be used as a datum. Such a datum is necessary to ensure repeatable and reproducible measurements as well as positioning the parts in gauges. This is particularly relevant where customers demand that a specific process capability be achieved with a correspondingly tight tolerance. In the past a short term process capability of 1.67 was the minimum expected for key characteristics but more recently customers have been demanding a capability of 2.0 minimum. The measuring system used must be shown to provide satisfactory gauge repeatability and reproducibility results.

To allow traceability of specific part revisions, the time of manufacture, material and/or company identifier it is common to have a detail in the mould to permanently imprint the part with an identifier. In addition to such marking during the moulding process it may be desirable to add additional marks to the parts during the assembly process. For example, to confirm that the parts have passed through specific, normally dimensional or functional, checks it is common that a mark be created on the final assembly. In the case of conventional parts this is often accomplished by means of an indenter, ink or laser printing and it can be sized such that it can be seen by human eye. With the small size of components under consideration it can be difficult to find space to create such marking.

5. DISCUSSION AND CONCLUSIONS

Micro manufacturing is a growing industry and will present significant opportunities for Irish companies willing to develop the necessary skills. Key challenges that conventional injection moulding companies face as they enter the micro moulding industry have been listed and approaches to overcome these problems highlighted. Further research is needed to simplify access to this large potential market. Some areas needing further research are in the areas of: development and refinement of design strategies, thin-wall moulding to reduce the skin effects, use of coatings on tools, development of alternative processes (using lasers, additive, etc), refinement of component handling techniques, metrology improvements (for both tooling and components), new functional checks and the development of new materials.

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