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Modelling injection moulding machines for micro manufacture applications through functional analysis

G. Fantoni[a], G. Tosello[b*], D. Gabelloni[a], H.N. Hansen[b]

[a]*Department of Mechanical, Nuclear and Production Engineering, University of Pisa, Largo Lucio Lazzarino, Pisa 56126, Italy*

[b]*Department of Mechanical Engineering, Technical University of Denmark, Produktionstorvet, Building 427S, Kgs. Lyngby 2800, Denmark*

* Corresponding author. Tel.: +45-4525-4893; fax: +45-4593-0190. *E-mail address*: guto@mek.dtu.dk

Abstract

The paper presents the analysis of an injection moulding machine using functional analysis to identify both its critical components and possible working problems when such a machine is employed for the production of polymer-based micro products. The step-by-step procedure starts from the study of the process phases of a machine and then it employs functional analysis to decompose the phases and attributes functions to part features. Part features are subsequently analyzed to understand the causal chains bringing either to the desired behaviour or to failures to avoid. The assessment of the design solution is finally performed by gathering quantitative data from experiments. The case study investigates the design motivations and functional drivers of a micro injection moulding machine. The analysis allows identifying the correlations between failures and advantages with the design of the machine parts.

Keywords: functional analysis, micro injection moulding

1. Introduction

Functional analysis (FA) is a powerful tool for the analysis of artefacts. It allows identifying the functions performed by products and components of the structure that carry on these functions. For the designer FA is a rigorous method to design and improve the product itself. Moreover, functional analysis is useful to both design new products and redesign existing products to improve their functionalities.

FA started from the value analysis developed by Miles [1], who identified the functions performed by the products and analyzed the value of each function. Hence, the designer could decide to eliminate the functions (and so the components linked to the functions) with lower value in order to reduce the final cost of the product. One of the most well-known functional modelling methodologies used to analyze a product, is that presented by Pahl and Beitz in [2]. They described the functioning of a product by modelling functions acting on the flows of energy, material and signals.

To provide a standard language, Stone and Wood [3] developed a function and flow dictionary, called the functional basis.

In the present research work it has been adopted a set of flows and verbs very similar to Hirtz's functional basis [4], that reconciles and integrates two independent research efforts (the functional basis of Stone and Wood and the technological dictionary developed by the National Institute of Standards and Technology [5]) into an evolved functional basis. Furthermore, the model applied in the present work takes advantages of several past contributions:

- FBS framework – Umeda's model [6] describes the relationships between structure, behaviours and functions. Here, the analysis of the product features is first performed to determine the behaviours related to each feature, and then each derived behaviour is transformed into the interpreted functions.

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- Axiomatic Design [7] – Axiomatic Design (AD) aims at correlating functions with requirements. Functional Requirements (FRs) are defined as the "minimum set of independent requirements that completely characterize the functional needs of the product in the functional domain". Among the different formulations the following have been adopted: axiom 1 (Independence Axiom) "*An optimal design maintains the independence of functional requirements*", axiom 2 (Information Axiom) "*The best design is a functionally un-coupled design that has the minimum information content*" was selected. The two axioms can be read together as "*Among all the design that satisfy the independence axiom, the one with the minimum information content is the best design*". It means that Design Parameters (DPs), that are the physical variables, are related to Functional Requirements (FRs) in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other FRs.

The AD has been previously employed to study the injection moulding process. Suh et al. discussed the application of AD principles to gain controllability of the injection moulding process [7] and to improve the quality and the performance of the process [8][9]. However, FA of injection moulding machine and its implication on micro moulding applications have not be addressed so far.

2. Method

The analysis of the microinjection moulding machine starts from its functional decomposition. First, the machine has been split into its groups, each group into components/parts and each part into its features. **Features** can be defined as the specific characteristics of a single part of the product, in terms of the geometrical entities that define it and in terms of the properties of its material (e.g. the Young's modulus, resistance to flames, etc.) [10]. Such concept of feature is very close to Suh's DPs [7]. However, features are more general and closer to designer's lexicon [10] and common understanding.

Following axiom 2, each feature is related to at least one functional reason. Therefore, all the features carry on at least one function in a certain moment of the product lifecycle and very often some features concur in performing a single function. In a good design, each and every feature of a product performs or contributes to at least one function [10]. Therefore, a useless feature can be removed without affecting the product performance and saving manufacturing/assembly time and/or cost.

Features are the starting elements for the FA. Therefore, to find them and reconstruct their functional role into a product, the following step-by-step procedure is proposed:

1) Analysis of the **process phases** – When the physics/chemistry/logics of the process changes the phase changes as well.
2) **Functional analysis** of the machine – Different technical choices affect differently the detail of the process and also the result of the process itself. The functional breakdown is necessary to correlate design and performance.
3) Identification of the **key features** performing each function – The performance (namely the level of the flows) of each function is due to a subset of features, directly linked to it through causal chains.
4) **Analysis** of the functional map – The map describing the machine can be used to highlight the negative functions and those functions that are in contradiction. This is the main step of the procedure to investigate bad design and over-engineering.
5) Suggestions for machine **redesign** – The previous analysis usually brings to some redesign hypotheses.

2.1. The rationale behind the choice of the case study

Micro injection moulding is one of the most important manufacturing processes for the mass fabrication of micro parts. It represents a low cost process capable of a very high throughput and it matches some of the requirements of micro products, as part dimensions down to the sub-millimetre range, features dimensions in the micrometer range and below, and low tolerances (in the order of few micrometers down to sub-micrometer range) [11][12].

The reasons for the choice of microinjection moulding machines as a case study are the following:

- the scale change necessary in the design of micro injection moulding machines implies different physical laws and problems from those of the same machine that injects macro components;
- new machines recently appeared in the market and the trend seems continuing with various producers entering in the field [13][14][15][16][17];
- during the last years microinjection moulding has become a key process for polymer-based micro components and also for powder injection moulding (e.g. for piezoelectric ceramic 3d microparts)[18][19].

3. Case study

A small injection molding machine based on the conventional injection moulding technology (i.e. equipped with a plastication-screw), has been studied and analyzed in order to fully understand the reasons of its design, the opportunities of its use for micro moulding applications and to correlate design choices with final results.

3.1. Process phases

In order to identify all the functions of the machine, it is very useful to consider the various phases that occur during the process. A phase can be defined in a top-down approach as the status (e.g. of environment, user and product) in which certain logical or physical structures persist [10]. In a bottom-up approach, a phase is an homogeneous set of functions where the physics used to describe the set of functions is almost the same, and the involved flows do not change (except for their values). Each phase is linked to the previous one by a logical, causal and time chain. In order to distinguish among the various phases, the interactions between the product and its super-system (the environment in which the user makes use of the product) can be used. Following this approach, the main phases of the micro injection process, described in literature, are plastication, injection, filling, packing, cooling and ejection (Fig. 1) .

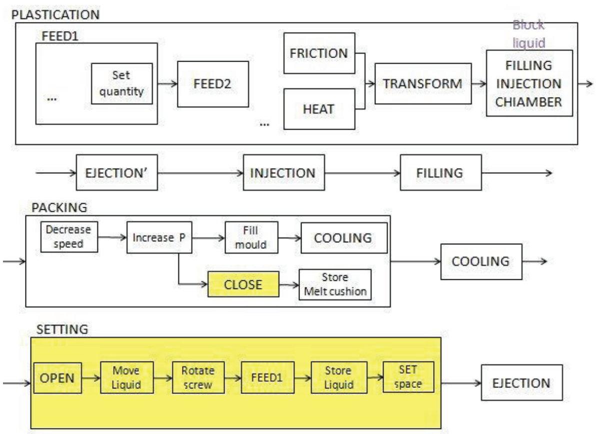


Fig. 1. Functional analysis of a conventional injection moulding machine

Although standard phases are those described above, a more detailed process work flow is proposed, according with the stated definition of phase: Plastication | Ejection' (→ ejection of the part produced during the previous moulding, i.e. n-1, cycle) |Injection | Filling | Packing | Cooling | Screw's setting (→ screw positioning and preparation for the next moulding, i.e. n+1 cycle) | Plastication (→ melt preparation for the next moulding, i.e. n+1, cycle) | Ejection (→ ejection of the part produced during the current moulding, i.e. n cycle).
The new process work flow focuses on the ejection of the previous cycle and on the setting of the screw, key phase of the process.

3.2. Functional analysis of the machine

A conventional plastication-screw injection moulding machine adapted for micro parts injection has been studied. The structure of the machine and related detail process has been described in natural language. Functional description has been tagged as follows: bold for **verbs** and italic for *flows,* respectively.

- Structural description – The conventional injection moulding machine (Engel ES80/25HL, screw diameter = 18 mm, clamping force = 250kN) is a machine adapted for manufacturing micro parts. An injection moulding machine consists of a material hopper, an injection ram or screw-type plunger, and a heating unit plus a clamping device. [20].
- Process description in natural language – First of all, *pellets* **moved** *by gravity* are **feed** to the *screw* system, during the plastication phase, the *screw* **is rotating** to **build up** the *melt polymer* necessary for the injection phase. The volume close to the tip of the screw **is heated** by *electrical units* and the *pellets* **melt.** During the rotation the *molten polymer* is **fed downwards**. The *pressure* **pushes** the *screw* backwards. When sufficient *polymer* has **built up** (i.e. shot volume is plasticated) **rotation stops**; when the *mould* is **closed**, the *screw* is **pushed** (injection), the *melt polymer* **fills** the *sprue*, the *runners* and the *mould cavity* (filling), the *screw* begins **rotating** again to build up more *polymer* (packing); cooling and ejection – after the *polymer* **is solidified** (cooling), the *mould* **opens** and *ejector pins* **remove** the *moulded part* (ejection).

The machine description in natural language is transferred into functional maps shown in Appendix A.

The analysis of the functional maps leads to the following observations:

1) As it emerges from the features playing a role in the map and from the concurring flows, one of the most important components of the injection moulding machine is the screw, performing most of the functions. For this reason this is the most critical component and it will be investigated thoroughly.
2) The functions in yellow in Fig. 1 are those related to the setting of the screw. Such functions are subsidiary with respect to the main function and are completely coupled (see axiom 1). They are responsible for a set of operations oriented to feed and meter the quantity of liquid to be injected. Unfortunately, due to the coupled design both the feeding and metering phase are not performed correctly since the back flow of molten plastic[a].
3) During the conventional injection moulding process the sprue solidifies on the nozzle of the injection chamber. The sprue is then extracted with the moulded part during the phase of ejection. As a

[a] The evidence of such a fact is that in new machines the design of this part is completely different and it is oriented towards the separation of functions and to decouple the coupled functions [13][14][15][16][17].

consequence, the process is associated with a loss of material. On the other hand, the sprue is necessary because it performs a very important function: in cold runner moulds it blocks the fluid and prevents it from entering into the mould before filling phase.

Previous observations bring to one of the main problems of this kind of machines: the process is not controlled with respect to the amount of plastic to be injected in each cycle by a specific control unit and/or a dedicated device. Indeed, there is only one function devoted to deliver the right quantity of liquid (set quantity) and it is coupled with other functions of the screw (e.g. feeding). The particular design characteristic is critical for achieving the highest process accuracy, as requested in micro injection moulding. Therefore, since the functions of a machine depend on the system architecture and on the component features, their relation is described in depth in the following sections

3.3. Identification of the key features performing each function

The procedure provides the analysis of the features involved in performing each function. As previously observed, the most interesting element is the screw (see the functional description in appendix A and Fig, 2). The screw is involved in many phases and performs several different functions through its features. However, its functional analysis shows that it is not able to fulfil all the foreseen (designed) functions, especially if a micro moulding application is considered. Indeed, one of the most critical sub-phase concerns the crossing of the liquid through the valve. Its closure blocks the backflow of the molten polymer. For this purpose, a valve is integrated in the screw and its opening/closing phases are due to the screw position. During the plastication phase, the screw rotates and the liquid begins to fill the injection chamber. In this case the features that allow the liquid crossing are the diameter of the restriction of the injection chamber (see detail 1a in Fig. 2) and the open valve (see detail 2a in Fig. 2).

The feeding of the material towards the volume in front of the screw pushes back the screw itself. After, the injection phase starts, the screw stops rotating, then moves towards the mould: the area, where the liquid passes through, narrows until the valve is completely closed (end of the packing phase). Finally, while the part is first cooled and then ejected, the screw moves back until the starting position, the valve opens again and the cycle can restart. The functions “to couple” and “to block” (see phase 5) are here performed by the diameter of the screw and by the diameter of the restriction of the injection chamber.

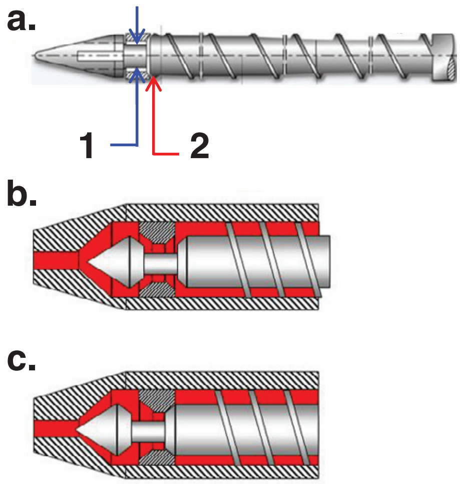


Fig. 2. (a) Screw features: (1) diameter of the restriction of the injection chamber and valve (2); features (1) and (2) positions during (b) plastication and (c) injection.

3.4. Machine experimental assessment

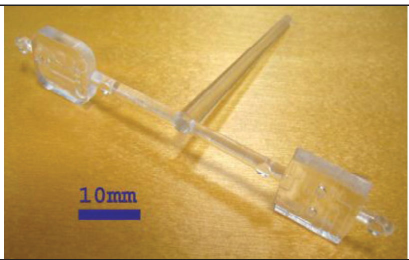
The focus of this step is to correlate how the process is carried out by the machine with its design. A rigorous FA of the machine allows highlighting the physical reasons for the different components and of their features while experimental results provide the measurement of the adopted solutions. In particular, an injection moulding machine using a reciprocating screw employed on moulding micro parts presents the following issues:

- A problem which occurs with the small shot weight typical of micro parts is related to the size of used pellets. Conventional injection moulding machines utilizes screws with diameters down to 14 mm. Hence, when the screw moves just 1 mm, about 185 mg of plastic are already injected. Even one single pellet of polymer weights 10-25 mg. Often this exceeds the part weight.
- It is difficult to control the melt metering accuracy as a result of the screw structure and the limitation to reduce screw size. A screw position accuracy of ±0.025 mm leads to an uncertainty in metering size of at least ±3-5 mg depending on material density and increasing with the screw diameter.
- The machine can produce precise components but large sprues are necessary to achieve the minimum shot weight to perform properly the process. Very often over 90% of the polymer is wasted and this waste can be an important cost factor due to both material consumption and cycle time. Considering plastic material for high accuracy optical and medical applications, it is not unusual to have costs in the range of 30 €/kg for COP to 70 €/kg for PEEK. Also,

the large sprue increases cooling time and therefore cycle time.

- The small shot volumes needed for micro moulding and the relatively large screw diameter reduce drastically the injection shot lengths, and also, due to the large mass of the screw, it is difficult to accelerate/decelerate with high precision in short times and to achieve high repeatability of stroke length (especially for short screw displacement as required in micro injection moulding). As a consequence, the actual injection speed is difficult to be controlled (the screw never reaches a constant speed value during cavity filling) and the injection volume is affected by a limited repeatability (see Table 1).

Table 1. Experimental data showing typical values obtained during micro injection moulding of PC micro fluidic system using an injection moulding machine with a reciprocating screw (diameter = 18 mm).

Parameter	Description
Machine characteristic	Conventional Injection Moulding machine
Moulded polymer-based micro product	
Application	Microfluidic system
Material	Polycarbonate (PC)
Experimental average shot weight	2052 mg
Experimental moulding weight repeatability (1σ std. deviation)	5 mg
Filling time	500 ms
Cycle time	12-15 s

4. Conclusions

A step-by-step functional analysis methodology has been applied to investigate the injection moulding process and its criticalities. The analysis permitted to identify the design reasons behind the injection moulding machine feature and the related processing phases.

In particular, the influence of the machine's screw on the process and its importance on the overall performance of the machine. The functional behaviour of the injection moulding machine has been clarified, its performance can be now directly related to component features and has been explained with respect to micro injection moulding applications. In particular, screw diameter reduction and increased position accuracy appeared to be the most critical (and limiting) factor both from the FA and the experimental validation of the process in order to improve the micro moulding process performance and therefore the polymer-based micro part quality. To this respect, recent µIM machines [13-17] have shown specific features following the results of the conducted FA. In particular, newly developed µIM injection units uses smaller screws (diameter 14 mm, used only for plastication) and injection plungers with a reduced diameter (3-8 mm) allowing for faster and more accurate injection of the small shot volumes needed in the µIM of polymer micro products.

References

[1] Miles LD. *Technique of Value Analysis and Engineering*, 1972 (McGraw-Hill Book Company).

[2] Pahl G, Beitz W. *Engineering Design: A Systematic Approach*, 1984 (Design Council, London).

[3] Stone R, Wood K. "*Development of a Functional Basis for Design*", Journal of Mechanical Design, 2000, 122(4), 359-370.

[4] Hirtz J, Stone R, McAdams D, Szykman S, Wood K. A *Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts*, Research in Eng. Des., 2002, 13, 65-82.

[5] Szykman SR, Sriram D, Smith SJ. Proceedings of the NIST Design Repository Workshop, Gaithersburg, MD, November 1996.

[6] Umeda Y, Tomiyama T, Yoshikawa H. *FBS Modeling: Modeling scheme of function for conceptual design*. In Proceedings of the 9th International Workshop on Qualitative Reasoning, Amsterdam, Netherlands, 11-19 May 1995: 271-8.

[7] Suh NP. *Axiomatic design: advances and applications*. Oxford University Press, New York; 2001.

[8] Dastagiri M, Prasad MM. *Application of Axiomatic Design in Injection Molding Process*, Proc. of Conf "Frontiers in Automobile and Mechanical Engineering", 25-27 Nov. 2010, 222-228.

[9] Kazmer D. *Axiomatic design of the injection molding process*, ICAD2000 First International Conference on Axiomatic Design Cambridge, MA – June 21-23, 2000.

[10] Gabelloni D, Fantoni G, Apreda R, Bonaccorsi A. *On the link between features and functions*, Proceeding of ICED, , Technical University of Denmark, Copenhagen, 2011.

[11] Heckele M, Schomburg WK. *Review on micro molding of thermoplastic polymers*, *Journal of Micromechanics and Microengineering*, 2004, 14:3, R1-R14.

[12] Tosello G. *Precision Moulding of Polymer Micro Components – Optimization, Simulation, Tooling, Quality Control and Multi-Material Application*, Ph.D. Thesis, Technical University of Denmark, pp.1-242, ISBN: 978-87-89502-77-9, 2008.

[13] DesmaTec. *Micro Injection with one and two components* (10-400mg), http://www.desmatec.com/en/index.php (last access November 2011).

[14] Battenfeld. *MicroPower series* http://www.battenfeld-imt.com/en/maschinen/baureihen/micro.html (last access November 2011).

[15] Arburg. *Micro injection moulding on ALLROUNDERs*, http://www.arburg.com/com/COM/en/products/machines/applications/micro_injection_moulding/index.jsp (last access November 2011).

[16] Sodick Plustech. *V-LINE Two-Stage Plunger System - precision injection molding machines*, http://www.plustech-inc.com/technology.htm (last access November 2011).

[17] Männer. *Micro Moulding Systems*, http://www.maenner-group.com/text2/233/en/jump,233/hot-runner/micro-molding-systems/micro-maen-50.html (last access November 2011).

[18] Piotter V. *A review of the current status of microPIM: materials, processing, microspecific considerations, and applications*, Powder Injection Moulding International, v5 n.3, pp27-36, 2011.

[19] Wang M-W. *Microceramic injection molding of a multilayer micropatterned micropart*, Int J Adv Manuf Technol, 2010, 51:145–153, DOI 10.1007/s00170-010-2597-3.

[20] Rosato D, Rosato M, Rosato D. *Injection Molding Handbook 3rd Ed*. Kluwer Academic Publishers; 2000.

Appendix A. Functional maps