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Evaluation of the performance of micromoulding blocks using micromanufacturing technologies

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ABSTRACT

The production of micromoulding blocks for the mass production of plastic microparts is associated to the decision of the more adequate micromanufacturing technology for the quickest time to moulding operation. The integration of subtractive and additive micro manufacturing technologies and micromoulding techniques made the development of plastics microcomponents in several domains of activity possible at feasible costs. However, the lifetime expectancy of their replication tools is directly dependent on the tool material properties and the thermal and mechanical characteristics of moulding process. Besides the tool manufacturing costs, post-treatments to achieve the enhancement of tool properties as surface roughness or abrasion resistance must also be considered, so that the mass production process results technically and economically effective. Thus, a trade-off is required to establish the break-even point between the overall tool cost and the tool lifetime. An analysis was made on the design of plastics microparts considering their performance requirements and implications on the tooling manufacturing route and expected production life. It was considered the use of additive and subtractive technologies for the microtooling manufacture using current industrial equipment. This study enabled a possible approach using the Analytical Hierarchical Process (AHP) towards the detailed analysis of the life cycle and production costs of common routes in microinjection moulding. A study of this type requires the continuous update of micromanufacturing technological developments in order to score actual process features. This analytical hierarchization approach enables decision makers to input market requirements and to obtain suitable manufacturing solutions, considering the continuous technological challenges and economical aspects.

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1. Introduction

The production of micromoulding blocks for the mass production of plastic microparts is associated to the decision of the more adequate micromanufacturing technology for the quickest time to moulding operation. Microinjection moulding is one of the most flexible, reliable and effective replication methods for microcomponents in microsystems for high-demand client industries such as medical applications, personal well-being, automobile and aero-space industry, and military and defence applications [1]. This process has played a major role in bringing at reasonable end-user prices to the market microsystems such as microelectro/mechanical components, microoptic systems and microfluidic devices [2, 3]. The integration of subtractive and additive micromanufacturing technologies and micromoulding techniques made the development of plastics microcomponents possible at feasible costs. However, the lifetime expectancy of their replication tools, the moulds, is directly dependent on the tool material properties and the thermal and mechanical characteristics of the moulding process. Besides the tool manufacturing costs, post-treatments to achieve the enhancement of tool properties as surface roughness or abrasion resistance must also be considered, so that the mass production process results technically and economically effective.

This context suggests that a trade-off is required to establish the break-even point between the overall tool cost and the tool lifetime. In this study an analysis was made on the design of plastics microparts considering their performance requirements and implications on the tooling manufacturing route and expected production life. The use of additive and subtractive technologies for the microtooling manufacture using current industrial equipmentswas considered. An approach towards the detailed analysis of the life cycle and production costs of common routes in microinjection moulding is envisaged as an end goal of the work.

2. Micromanufacturing technologies

Micromanufacturing is a high added value key-element in a large number of industrial sectors. Besides the creation of high aspect-ratio 3D microparts, the achievable accuracy and the possibility to produce microdetails are a challenge in micromachining. The subtractive approach is the current technological manufacturing option for reducing feature sizes with commercial equipment, comprehending continuous improvements on accuracy and surface finish. The additive approach following the new options offered by rapid prototyping techniques is strongly associated to significant advances towards the micrometric scale, enabling the development of new hybrid methods of manufacture [4] or even the integration with the subtractive approach to overcome geometrical or material limitations. Frequently many factors interact and the arrangement of these factors determine the capabilities of a technique [5]. For that purpose, additive and subtractive technologies currently used in the microtooling manufacture with current industrial equipment are considered in this study.

2.1 Subtractive micromanufacturing

The more common subtractive techniques used by the micromouldmaking industry include laser beam machining (LBM), micromilling and micro-electrical discharge machining (EDM), which have pros and cons that often lead to their combined use in the manufacturing of microtools.

Micro milling
Milling plays a key role in the production of microstructured moulding blocks, exhibiting advantages for low volume production, such as the ability to process hardened tool steels, the flexibility for getting complex geometries, and a comparatively small capital investment. Micromilling is currently associated to microinjection moulding and hot embossing which imply the machining of thin features [6]. A common challenge in several application areas is the machining of microfeatures with dimensions smaller than 100 μm [7].Operation with end mills of 100 μm in diameter are available up to an aspect ratio of 10:1 [8].

Laser beam machining
The energy source of LBM is a laser that focuses high density light energy on the surface of the work-piece. The maximum depth where absorption occurs is the penetration depth and leads to the conduction of heat to the material [9]. However, LBM exhibits disadvantages, such as the formation of heat affected zones (HAZ), poor surface rough-ness and low aspect-ratio [10].

MicroEDM/ MicroWEDM
Electrical discharge machining is often used for machining complex workpiece geometries in tools for injection moulding. Low surface roughness and filigree structures in microtools are obtained with very small discharge energies, requiring additional process parameters that make

micro EDM different from conventional EDM. In micro EDM the energy of the discharge must be minimized and the frequency of the discharges increased in comparison to conventional EDM [11]. Micro EDM is very suitable with conductive materials which cannot be machined by micromilling, e. g., hard alloyed, chemically highly resistant 1.4539 steel used in chemical microreactors. Due to its contactless nature, this manufacturing process is often used to machine very hard materials, being also suitable to machine high aspect ratio holes, up to 18 : 1 [12]. The disadvantages result from only conductive or semi-conductive materials being machinable, limited surface roughness possible, the occurrence of HAZ and the wear of the electrode.

2.2 Additive micromanufacturing

The additive manufacturing technologies rely on the phase transformation of a specific material to form a tridimensional object, this enabling the creation of freeform geometries [13]. Whether it is a photo-polymeric liquid or a microsized powder, additive techniques use energy sources that can supply a light beam for the curing process or a heat source for the sintering process [14]. In this study, stereolithography (SLA) and selective laser melting (SLM) were used and their capacity to create freeform geometries and the base material analysed.

Stereolithography
Stereolithography that has been considered the top precision additive manufacturing process has evolved successfully to the micrometric level, this resulting from various approaches to decrease the minimum layer thickness and the laser spot size, thus increasing this micromanufacturing process capacities [15]. Considering the requirement of using current industrial equipments, a Viper Si2 equipment (3D Systems, USA) operating in high-resolution mode was selected. In view of the final application, the Nanoform 15120 resin (DSM Somos, The Netherlands) was chosen to produce the micromoulding inserts, due to its proven capacities for the moulding process [16, 17].

Selective laser melting
The application of SLM to the production of components with details at the micrometric level is still highly conditioned by the grain size of the powder materials and the laser spot size [18]. The industrial equipment used in this study was an EOSINT M270 (EOS, Germany) working with GP1 steel powder with a grain size of 30 μm, enabling a minimum layer thickness of 20 μm.

3. Post-treatments

Post-treatments can be applied to tools, obtained by additive or by subtractive manufacturing to enhance tool properties. Microtool features such as surface roughness, abrasion resistance and tensile strength must be considered, so that the replication process results technically and economically effective [19]. Concerning the additive manufacturing processes, whenever support pillars are required to obtain undercuts, these have to be generated with the same base material, requiring a removal procedure afterwards. Regarding to the base material, polymer resins require UV cure and thermal post-cure while metals require surface improvement and/or hardness increase to endure on long run series. Like any other moulds, steel-based micro replication tools may require property enhancement by heat treatment. Since the feature size is too small for manual polishing, the surface finish of metallic surfaces can be improved with electron beam polishing [20]. Another possibility of post-processing is surface coatings. Diamond-based and CrN-based coatings have been used successfully in injection moulding. Plastics parts obtained with diamond coated moulding surfaces exhibited exceptional dimensional accuracy [21].

4. Production time and associated costs

The analysis of customer case-studies was used for the determination of average values for comparison of manufacturing time for all processes in this study. For the manufacturing time calculation it was accounted for: the preparation time, the processing time and the post-processing time, such as cleaning or support removal for the additives processes. Furthermore, the material and all operational costs were also considered to account for the productivity and the feasibility of each process. One important aspect to consider here is that the subtractive processes were only used to machine the mould cavity on a blank insert previously prepared. Table 1 shows some of the key parameters for subtractive manufacturing processes.

Table 1 Parameters for subtractive manufacturing processes

Process	Material removal rate (mm^3/h)	Minimum feature size (μm)
LBM	10	1
Micro milling	25	20
Micro EDM	0.02	10

Additive processes are required to build the whole insert or a specific part of it, when there is the need of creating conformal cooling circuits or undercuts. Therefore, an approach for an overall comparison of all processes must consider these differences. Table 2 summarizes some of the key parameters for additive manufacturing processes.

Table 2 Parameters for additive manufacturing processes

Process	Build rate (cm^3/h)	Layer thickness (μm)
SLA	13.6	0.15 (hi-res mode)
SLM	5.8	0.20–0.40

The costs and the machining capability associated to each of the various manufacturing approaches in this study were analysed. The graphs depicted in Fig. 1 show an overview of the equipment hourly costs, surface roughness achievable, accuracy, material removal rate (for additive manufacturing) and build rate (for subtractive manufacturing). The post-processing costs for property enhancement are not included is these data.

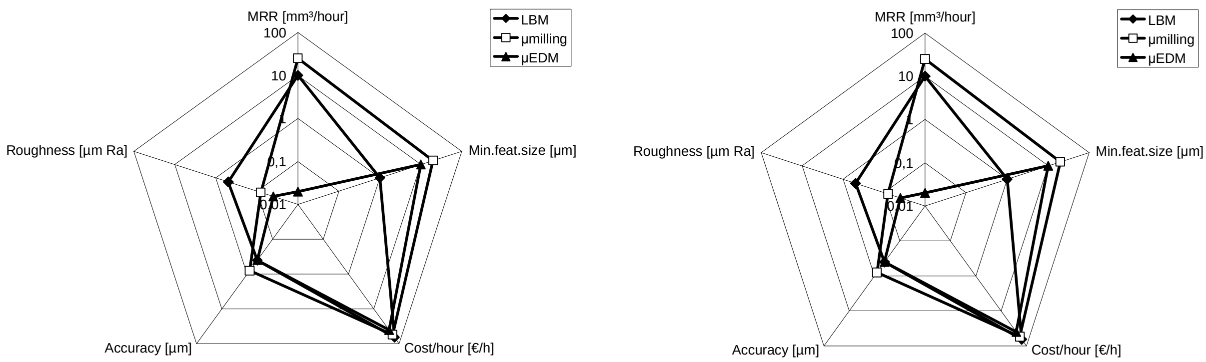

Fig. 1 Overview of equipment features for subtractive (left) and additive manufacturing processes (right)

It is necessary to consider the base material costs, since the additive manufacturing processes require specific materials to build the microreplication tool. On the other hand, subtractive manufacturing, despite the low material removal rates, have lower finishing costs as they normally achieve better surface finish.

5. Microtool life expectancy

The mechanical and thermal demands of the moulds in microinjection moulding are particularly relevant in the microtools produced by SLA that uses a polymer composite. Despite the fact that Nanoform 15120 has been used successfully in short series of production [16, 17], its mechanical properties cannot withstand longer production series. Fig. 2 depicts damages caused by the polymer flow, such as fractures and delamination, observed in a 100 μm height microdetail and a 200 μm diameter pin.

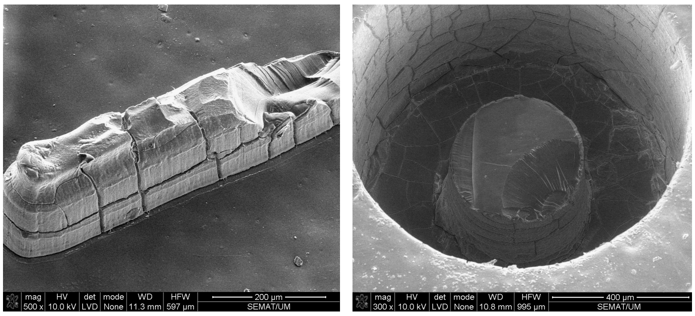

Fig. 2 Damage caused by polymer flow on 100 μm height Nanoform 15120 microdetail (left) and 200 μm diameter pin (right)

The other additive manufacturing processes that work with metals are fully able to withstand the mechanical efforts imposed by microinjection moulding. Additionally, the higher thermal conductivity contributes for much shorter cycle times. Thus, no damage was detected on metallic microtools, but wear was noticed on micromilled and micro EDM surfaces where the surface roughness was significantly reduced due to polymer flow. Fig. 3 shows SEM images of the as-machined surface before injection moulding [5].

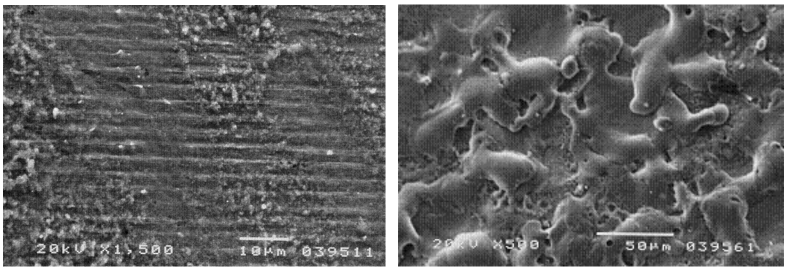

Fig. 3 Aspect of surfaces obtained by micromilling (left) and microEDM (right), before microinjection moulding

The use of steel powder as base material for SLM makes this machining solution suitable for the production of injection moulds. However, with the current state-of-the art the resulting surface finish makes it not quite suitable at the micrometric level. Besides the coarse surface roughness, the elevated edge effect that is visible on the top face of the tool (Fig. 4) is an additional handicap [22].

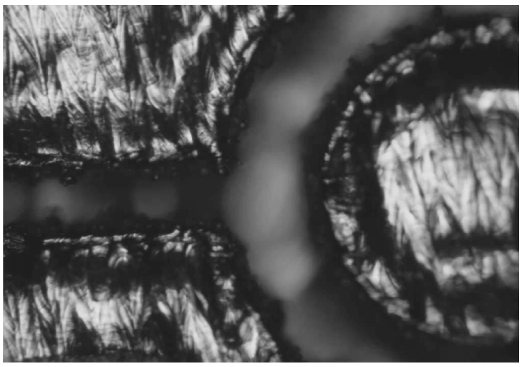

Fig. 4 Microscopic image of the top face of the tool showing the elevated edges effect

6. Micromoulding quality

The overall quality of the produced micromouldings is significantly higher when the surface finish of the microtools is better. This condition is achieved in parts obtained with moulding blocks produced by SLA, micromilled or microEDMed. Microdetails and a flat surface of a micromoulding obtained with a SLA microtool are shown in Fig. 5.

The surface finish of a microEDMed tool face is visible on the moulding zone shown in Fig. 6. Two different areas are depicted: the larger area was micromilled and the smaller area was finished by LBM.

Fig. 5 Microdetails replicated on the plastic part using a SLA microtool

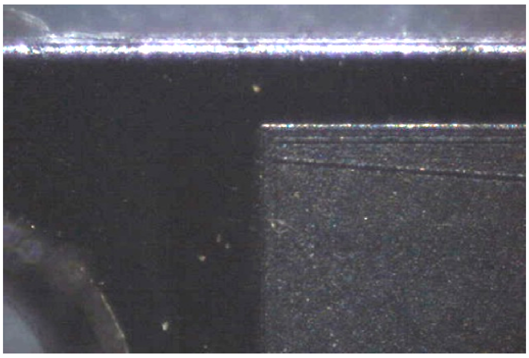

Fig. 6 Replication of a micromilled surface (larger area) and a LBM finished surface (smaller area) on a POM micromoulding

7. Micromanufacturing process selection

The criteria used in the process selection must be ranked by specific methods, such as hierarchization or scoring methods. A possible approach to determine these weights is the Analytical Hierarchical Process (AHP) [23]. AHP is a mathematical decision making technique that allows the consideration of qualitative and quantitative aspects. The technique uses subjective evaluation measures obtained by human comparison of objectives and alternatives through pairwise comparison [24]. It is widely used for addressing multi-criteria decision-making problems, since it assures the consistency and stability of the subsequent decisions [25] and it is considered the most accurate way for humans to perfectly compare two at a time many criteria [26].

AHP involves structuring a problem from the overall criteria forming a hierarchy structure. It is based on predetermined measurements and decision maker judgments throughout the criteria interaction and their impact on the micromanufacturing process selection decision [27]. For that purpose, each criterion is compared against the others in order to measure the strength of importance by pair-wise comparison. The scale of importance between two criteria is a 1–9 scale with three levels, where 1 means equal importance, 3 means more importance, and 9 means the absolute importance of one criterion over the other. This pair-wise comparison can be supported by quantitative data (such as build rate in cm^3/h or hourly costs) or, for criteria that cannot be effectively quantified, in a numerical worth due to their intrinsic characteristics.

By performing for each scenario the pair-wise comparison of all criteria, three pair-wise comparison A matrices are obtained for the following scenarios:

1. the manufacturing of microtools with high geometrical complexity, featuring undercuts or conformal cooling,
2. the manufacturing of tools containing microdetails that require high precision for the replication process and
3. the manufacturing of tools with tight tolerances and designed for large production series.

Based on that, three vectors *C* representing the degree of importance for each criterion were obtained for each scenario. One additional advantage of AHP is to provide a measure of potential inconsistencies made by the decision maker. This is measured by the Consistency Ratio (CR) [24]. If this value is greater than 10 %, serious inconsistency may exist and AHP may not yield meaningful results.

For each scenario the production of replication tools was analysed, considering the following set of characteristics (Table 3).

Table 3 Replication tool characteristics

Characteristic	Acronym	Description
Production time	PT	Preparation, processing and cleaning (if required)
Production cost	PC	Total of operational costs
Aspect-ratio	AR	Feature height divided by the width at base
Freeform geometry	FG	Complex geometry (3D surfaces and undercuts)
Surface finishing	SF	Roughness R_a
Tool Durability	TD	Expected tool life

The final score of each scenario is obtained by process classification, which characterizes each manufacturing process according to its features from 1 to 10, where 1 means low performance and 10 means excellent performance. In Table 4 the general micro manufacturing process capacities is established in relative terms. Therefore, each process score is calculated by multiplying its performance classification by the correspondent weight factor or vector *C*.

Table 4 Micromanufacturing process capacities

	PT	PC	AR	FG	SF	TD
LBM	10	8	7	3	2	10
Micromilling	5	6	5	3	10	8
Micro EDM	1	4	10	5	6	10
SLA	2	4	5	10	8	1
SLM	4	10	3	10	1	8

7.1 Scenario 1: Microtool with high geometrical complexity

The most relevant features in this context are: high aspect-ratio ribs, pins, undercuts or any other geometric feature that causes a challenge, both on the manufacturing process and on the micromoulding process. For that matter, it should be considered that there is no point in building a non-demoulding feature. However, the capacity of building a conformal cooling circuit is certainly relevant here. Two main premises are considered: the aspect-ratio achievable by the micromanufacturing process, and the surface finish of the feature side walls that might cause problems on ejection and, eventually, part damaging. Table 5 shows the pair-wise comparison for this scenario and Table 6 shows the resultant vector *C*.

Table 5 Matrix A of pair-wise comparison for Scenario 1

	PT	PC	AR	FG	SF	TD
PT	-	1	1/3	1/9	1/3	3
PC	1	-	1/3	1/9	1/3	3
AR	1/3	1/3	-	1/3	1/3	3
FG	1/9	1/9	1/3	-	3	9
SF	1/3	1/3	1/3	3	-	3
TD	3	3	3	9	3	-

Table 6 Vector *C* for Scenario 1

	PT	PC	AR	FG	SF	TD
Weight	6.9 %	6.9 %	13.9 %	48.1 %	20.2 %	4.1 %

The vector *C* for this scenario has a CR of 5.58 %. The score was determined by applying these weights to the grades established previously in Table 4. The final scores are shown in Table 7.

This scenario privileged the capacity of generating freeform geometry (FG parameter weight factor is 48.1 %), which brought up the additive manufacturing processes. Tool durability was disregarded here, which enabled SLA to lead this score.

Table 7 Final scores for Scenario 1

Process	Score
SLA	7.57
SLM	6.71
microEDM	5.73
micromilling	5.24
LBM	4.46

7.2 Scenario 2: Tool with microdetails and high surface finishing

As already mentioned, the surface finish plays an important role on ejection when the part geometry is difficult to demoulding. Besides that, there are industrial demands for high surface finish in products as lenses or light wave guides. In this particular scenario, post-treatment processes are entirely relevant to achieve the required surface properties. An additional requirement for this scenario is the creation of thin features, where post-processing may be relevant for getting increased mechanical strength to withstand the microinjection process. The pair-wise comparison for this scenario is shown in Table 8. Table 9 shows the resultant vector *C*.

Table 8 Matrix A of pair-wise comparison for Scenario 2

	PT	PC	AR	FG	SF	TD
PT	-	1	1/9	3	1/3	1/3
PC	1	-	1/9	3	1/3	1/3
AR	1/9	1/9	-	9	1	1
FG	3	3	9	-	1/3	1/3
SF	1/3	1/3	1	1/3	-	1
TD	1/3	1/3	1	1/3	1	-

Table 9 Vector *C* for Scenario II

	PT	PC	AR	FG	SF	TD
Weight	7.5 %	7.5 %	37.5 %	4.7 %	21.4 %	21.4 %

The CR of the vector *C* for this scenario is 6.85 %, and the final scores are shown in Table 10. This scenario privileged the capacity of generating microdetails with high aspect-ratio (weight of AR is 37.5 %), which brought up microEDM. The tool life is somewhat important in this scenario since the material properties are important in preserving the microdetails.

Table 10 Final scores for Scenario 2

Process	Score
MIcro EDM	7.78
Micromilling	6.69
LBM	6.68
SLA	4.72
SLM	4.58

7.3 Scenario 3: Tool with tight tolerances for a long-run series

The material in which the microtools are produced is the main issue here. The tool life expectancy is clearly higher when the base material is a metal, regardless of the manufacturing process used. On the other hand, the demand for tight tolerances poses the immediate question of the material stability. Table 11 shows the pair-wise comparison for this scenario and the resultant vector *C* is shown in Table 12. The vector *C* for this scenario has a CR of 8.69 %.

Table 11 Matrix A of pair-wise comparison for Scenario 3

	PT	PC	AR	FG	SF	TD
PT	-	1	9	3	1/3	1/3
PC	1	-	3	3	1/3	1/3
AR	9	3	-	1	1/3	1/3
FG	3	3	1	-	1/9	1/9
SF	1/3	1/3	1/3	1/9	-	1
TD	1/3	1/3	1/3	1/9	1	-

Table 12 Vector *C* for Scenario 3

	PT	PC	AR	FG	SF	TD
Weight	16.9 %	11.9 %	5.9 %	4.0 %	30.7 %	30.7 %

The final scores are shown in Table 13. The tool life is clearly privileged in this scenario, bringing SLA to the bottom of this score. The previous scenarios had slight differences which caused process score to be quite different. Despite the fact that surface finish has the same weight as tool durability, this last factor brings up the metal-based processes.

Table 13 Final scores for Scenario 3

Process	Score
MIcro EDM	7.49
Micromilling	6.85
LBM	6.34
SLA	5.20
SLM	4.27

8. Conclusion

Additive processes (SLA, SLM) and subtractive process (micromilling, micro EDM) technologies were analysed in the frame of their application to the manufacturing of microinjection moulding blocks for thermoplastics.

The AHP methodology was used to make an assessment of the suitability of existing processes to the manufacturing of specific microtool. This study showed that it is possible to use it to help decision makers on the selection of the technology in each product case and not to score the micromanufacturing processes to promote a specific process instead of another.

Concerning the identified scenarios of product type - available micro manufacturing processes, these were obtained from customer case studies to obtain data for comparison. From these data it is possible to establish new scenarios to foresee process selection.

Based on the gathered data, the metal-based micro manufacturing processes are better to produce microtools for large series of production. At this scale SLM suffers from several issues that may compromise its use for the moment, but, its integration in the production chain integrated with other subtractive processes makes it viable. SLA as a composite-based and high precision process still proves to be competitive for short-run series or even prototype series, when the required time-to-market is short.

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