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Product-process analysis to assess the influence of micromould engineering in the overall efficiency of replication processes

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Abstract
A methodology created to assess, during the development phase, the global efficiency of innovative micromoulds for non-metalllic parts, as well as their related fabrication and microreplication manufacturing processes, is here presented. A life-cycle strategy is used to account not only for the mould production burdens but also for the impacts of design alternatives of the mould throughout the related replication process (Use-phase). As there are no guidelines or standards to support the sustainable design of a mould, a set of micromould's specific performance indicators were defined to assess the micromould performance and the microreplication process efficiency in several dimensions, supporting the decision-making process regarding the selection of alternative tooling concepts and its fabrication technologies' solutions, towards a more sustainable production of microrreplicated parts. The methodology is based on two parallel analysis: 1) a product analysis, where the functional unit is the micromould, and 2) a process analysis, focused on the microreplication process and restricted to a set of mould-affected operations, which are considered as the process functional unit. The assessment tools used were adapted from existing LCA, eco-efficiency and multi-layer stream mapping tools. The application of this methodology to representative microreplication cases with different technology readiness level, appointed from the biomedical sector, was developed and demonstrated in the European project FaBiMed.

Keywords: Micromoulds, microreplication, efficiency, holistic assessment, non-metal biomedical parts

1. Introduction

The methodology here proposed was thought to complement the evaluation of the technical performance of new micro-manufacturing scenarios, with the cost and environmental analysis, insuring the holistic assessment of the performance of the most relevant scenarios being proposed in the Product Development Phase. This includes not only the micro-mould fabrication's strategy but also its related impacts on the respective micro-replication processes, particularly the mould-affected process steps.

2. Methodology

Two parallel analysis related to two different functional units are considered: 1) a product analysis, to assess the impact of mould micromanufacturing technologies in the overall life-cycle of the new tool, and where the functional unit is the mould piece and i2) a process analysis, focused on the detail analysis of the Use-phase of the mould, to assess the operational efficiency of the replication process affected by the new mould tool concept, restricted to a set of mould-affected operations, considered as the process functional unit. The assessment tools adopted were adapted from Life Cycle Assessment (LCA), eco-efficiency and stream mapping tools, developed to support the sustainable mould design in mould-making companies [1-3].

3. Case study

This methodology was applied to non-metal biomedical microcomponents which significantly differ on the level of technology readiness and complexity, namely:

- Case 1) Polymeric microfluidics film, produced by Hot Embossing (HE) or IM with submicron and nanotextured mould surfaces- a fully new product, comprising a set of advanced functionalities, which include the functionality inherent to the reference product but not only, fully dependent on the characteristics of the mould surface and related adaptations to the current replication processes;
- Case 2) Ceramic microneedles, to be produced by Epoxy Gel Casting (EGC) with direct Laser-structured PDMS moulds - an existing product which expression in the market but limited by the extremely low overall efficiency and/or high cost of the current manufacturing conditions;
- Case 3) Ceramic microtransducers to be produced by Epoxy Gel Casting (EGC) with direct Laser-structured PDMS moulds, a low volume product of relatively long cycle time, which industrial scale-up depends on a full restructuring of the manufacturing route, including mould-affected and critical post-replication operations, apart from the mould concept on its own.

A common set of relevant performance parameters and indicators, and the respective metrics and assessment tools, has been selected and demonstrated to be applicable to all the three cases under study, independently of their significant differences, though some of the parameters/indicators might be adapted for each specific case. All scenarios analysed run under lab-scale conditions.

4. Results and Discussion

4.1. Phase1 – Reference Scenarios for Benchmarking

This first stage is dedicated to the collection, classification and analysis of the available data regarding the resources and main operational data related to reference scenarios. A list of Key Performance Parameters is built to compile the data related to the product (the mould), providing information regarding general performance aspects of its life-cycle, including operational, cost and environmental parameters.

In parallel, the replication process flow, including pre- and post-replication process steps as well as inspection/ testing, are defined. The general operational/processing capacity and conditions per operation are inventoried, together with the set of critical resources (labour, materials and energy) required to properly execute each operation, mapped to the corresponding operating and cost expenses and then aggregated into unit-based figures. The proper analysis of these data enable to identify, already at this stage: 1) the main limitations of the reference manufacturing scenarios, revealing the opportunities to consider in both mould concepts and replication conditions; 2) the main detractors to the performance of the established processing conditions, and the improvement potential to be assumed by the new mould solutions.

4.2. Phase 2 – Support to the Development Phase

For the cases in view, masterless mould concepts and/or the multi-scale integration of mould layers was sought, promising to increase mould-driven product functionalization and design flexibility. However, such advanced moulds might also drive down process yield or throughput due to the related higher replication (Mould's Use-phase) complexity. The collection of a set of parameters per new process step/operation is essential to support the selection of reliable scenarios of new moulds and the related replication routes, including the following: a) critical equipment and standard operating conditions; b) batch size and the operation's yield figures, i.e. the effective production volume per step, c) operating time, including cycle time and setup time, maintenance frequency and maintenance duration, and d) resources, e.g. labour, materials and energy consumption and related costs, at each new process step.

A comparative analysis with the reference scenarios is then followed, allowing to understand the economic implications of alternative mould design specifications and process conditions on the technical, operational and cost performance, across all manufacturing operations. This enables to identify dominant cost-drivers and/or operations where technical improvements are most critical to lowering costs and increase efficiency of the new mould concepts. Following an iterative optimization process, this revealed improvements to be exploited to increase the global efficiency of the micro-manufacturing processes being developed, to be addressed already in the development phase or on their future scale-up strategies.

4.3. Phase 3 – Feasible New Micromanufacturing Scenarios

The most promising moulds and respective microrreplication conditions are then selected for validation. In any case, higher process efficiency shall be pushed by maximizing the batch size and minimizing the operating time per equipment/operation. Major technical improvements to create the conditions considered appropriate for the demonstration phase and leading to increased process efficiency start to be identified and prioritized, targeting potential future scale up for semi-industrial environment. Temperature cycles optimization, automation of current manual operations or the design/production of control jigs are among those.

The inventories of the demonstration phase are then collected, computed and summarized to work as inputs for the LCA and KPPs of the mould. These results are then integrated in Eco-Efficiency Indicators (EEI) (Table 1), according to ISO 14031 and ISO 14045, providing for intuitive quantitative factors of normalized values easily understood by both mould manufacturers and end-users. By linking the mould value with the mould environmental and operational performance, these indicators allow for the direct comparison of reference and new moulds and replication strategies, and the quantification of the mould performance in different aspects throughout its life-cycle. The goal is to support sustainable decisions with normalized indicators that are capable of characterizing the key figures of mould performance and easy to incorporate in the replication industries.

Table 1. KPPs and EEIs defined for microfluidics coated mould (Case1).

Parameter Scope	Parameter Description	Unit
Mould Materials	Total amount of bulk materials used	kg/mould lifetime (#parts)
Mould Materials	Total amount of coating materials used	kg/mould lifetime (#parts)
Mould Materials	Recyclability	%
Mechanical proc.	Total amount of materials removed	kg/ mould lifetime (#parts)
Chem./optical proc.	Total proc. time*n reoccurrences (re-coating)	sec/ mould lifetime (#parts)
Additive processes	Total coated area	mm^2/mould lifetime(#parts)
Processed material	Total amount of material used	g/cycle
Processed material	Total amount of material reused	g/cycle
Operation	Total amount of energy used	kW/cycle
Operation	Cycle time	sec/cycle
Quality	Mean time between maintenance (MTBM)	cycles
Quality	Total inspection time	sec
Quality	Inspection frequency	#parts/cycle
Waste	Rate of defective products	%
Waste	Total amount of waste generated	kg/kg processed material

Life-cycle oriented	Unit	Functional	Unit	Performance	Unit
Mould Cost / EI Materials Acq.	€ / Pt	MTBM / Overall EI	cycles / Pt	Replic. cycle time / # parts per cycle	sec / part
Mould Cost / EI Production	€ / Pt	Useful proc. material / Overall EI	kg / Pt	Replic. energy / # parts per cycle	kWh / part
Replication Cost / EI Use	€ / Pt	Waste proc. material / Overall EI	kg / Pt	Mould Overall EI / # per cycle	Pt / part
Mould+Repl.Cost / Overall EI	€ / Pt	Replic. cycle time / Overall EI	sec / Pt	Mould+Replic.Cost / # parts per cycle	€ / part

Conclusion

A methodology to assess the overall efficiency of micro-moulds and their microrreplication processes is here described. A set of mould's specific performance parameters and indicators were defined to assess both the mould and the replication process efficiency in several dimensions, supporting the decision-making process regarding the selection of alternatives in tooling concepts and its fabrication technologies. In-between both reference and new products/ technologies, several adaptations had to be followed, due to the different technology readiness level and market share of the products and production technologies under study, which determined the type and quality of the life-cycle inventories data available. This is also expected to affect the conditions for the foreseen up-scaling scenarios of any new fabrication process from a lab-scale to an industrial-scale manufacturing process. Nevertheless, this methodology successfully revealed the essentials about the eco-efficiency of these systems: 1) any mould or process concept affecting the consumption of energy or other resources on a replication process can lead to significant reductions in both cost and environmental impacts, and 2) the influence of mould engineering in the overall efficiency of the replication processes is far from being irrelevant, as this is highly dependent on the mould design and fabrication solutions.

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