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Economic trade-offs of additive manufacturing integration in injection moulding process chain

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Abstract
Additive Manufacturing has emerged as an innovative set of novel technologies capable of replacing established manufacturing processes due to fabrication of highly complex parts and its continuous improvements of efficiency and cost effectiveness. This study is based on the idea that through the creation of synergies between additive and conventional manufacturing technologies it is possible to achieve greater cost advantages and operational benefits than by substituting injection moulding with additive manufacturing. The analysis presented explores the cost advantages that can be secured when additive manufacturing is used to support the fabrication of mould inserts for the product development phase of the injection moulding process chain. This study shows that fabrication of soft tooling by mean of AM is economically convenient with a cost reduction between 80% and 90%. Break-even points analysis based on the lot size of the product development phase is also investigated and it shows that the use of AM is cost effective up to 3400 units for the smaller geometry and up to 500 units for the larger insert geometry.

Additive Manufacturing, Injection Moulding; Soft Tooling; Break-Even-Analysis; Cost Advantage

1. Introduction

The purpose of this research is to analyse the cost benefits and trade-offs related to the integration of Additive Manufacturing (AM) in the conventional manufacturing process chain of Injection Moulding (IM). Highly precise AM technologies such as Digital Light Processing (DLP) belonging to the vat-photopolymerization AM processes [1] can be employed to manufacture mould inserts involving substantial cost reduction. The high level of detail, good mechanical properties, surface finish and durability of photopolymer mould inserts manufactured on a DLP machine can open new opportunities for manufacturers that are interested in manufacturing functional parts and short pilot runs in a cost effective way.

The tested inserts are two cuboids with dimension of 80 x 60 x 10 mm^3 and 20 x 20 x 2.7 mm^3 respectively as show in figure 1 and 2. For simplicity, it is referred to the insert of figure 1 with the name "medal" and "micro" for the insert of figure 2. A cost model for the employed DLP technology, has not at this time been developed or discussed in literature [2]. This study proposes a cost estimation model to quantify the economic advantages related to manufacturing soft tooling with DLP technology. Instead, cost models and economic considerations regarding AM have been built so far on the idea of substituting injection moulding with AM for fabrication of end use part [3].

2. Method

The investigated AM mould inserts were printed on the EnvisionTEC Pre-factory 3 Mini Multi Lens with machine nominal building speed of 1 min/layer and layers of 16 µm. A cost model for DLP technology was developed and used to calculate the cost per inserts manufactured with the AM technology. It follows the necessity to define a cost estimation model also for IM in order to calculate and compare the economics of moulding with AM and CNC machined inserts.

Several articles are available in literature regarding cost estimation models for AM and its use to replace IM [3]–[5]. Review of available literature and case studies shows that the use of AM to replace IM is convenient on a cost level only for the fabrication of few parts. On the other way, in this research the aim is to develop a cost estimation model for fabrication of parts through DLP technology that can be fitted in the IM process chain.

2.1. DLP cost estimation model

The cost of an AM part, manufactured with DLP technology is made of five main cost elements as shown in Eq. (1): the cost for pre-processing C_{P_p}, running the machine C_{Pr}, material C_M, post-processing C_{PP} and the cost for overheads C_{Ov} (*€/part*).

$$C_{DLP} = C_{P_p} + C_{\mathrm{Pr}} + C_M + C_{PP} + C_{Ov} \quad (1)$$

$$C_{P_p} = \frac{C_{Op}}{N} \times T_{SW} \quad (2)$$

$$C_{\mathrm{Pr}} = C_h \times \frac{T_B}{N} \quad (3)$$

$$C_h = \frac{C_I}{Y} \times \frac{1}{\sigma \times H} \quad (4)$$

$$C_M = C_{M_{Kg}} \times V \quad (5)$$

$$V = \frac{V_{Part}}{0.7} \quad (6)$$

$$C_{PP} = \frac{C_{Op} \times T_{PP}}{N} \quad (7)$$

$$T_{PP} = T_{Sr} + \alpha \times (T_{pc} + T_{pd} + T_m) \quad (8)$$

$$C_{Ov} = \frac{C_{El} + C_{Sr} + C_{Me}}{N} \quad (9)$$

For convenience, the variables of the model are described in the present section following the order of their introduction. C_{Op} is the hourly cost of the operator (*€/hour*), N the number of parts that can be printed simultaneously and T_{SW} (*hour*) is the time to setup the machine.

C_h is the hourly cost of the machine (*€/hour*) and T_B is the build time (*hour*). To account for error in the printing process the factor δ is introduced in $T_B = T_B/(1-\delta)$.

C_I represents the investment in the machine (€), Y is the machine lifetime (*year*), the factor σ refers to the machine utilization and H is the number of hours the machine works in a year (*hour*).

$C_{M_{Kg}}$ is the cost of the material (*€/kg*) and V the volume of the build (*liter*). Based on observation the volume filled by the part is around the 70% of the resin volume used hence it follows Eq. (6).

T_{PP} is the time used for post-processing activities (*hour*) and it accounts for the time used to remove support material T_{SR}, the time to post-cure the photopolymer insert T_{pc}, the time to dry the part T_{pd} and the time to machine the insert T_m.

Equation (8) introduce the factor α to account for the time an operator is required for post-processing activities. Lastly, Eq. (9) describes the overheads cost as the sum of the cost for electricity C_{El}, the cost for space rental C_{Sr} and the cost for machine maintenance C_{Me} (*€/part*).

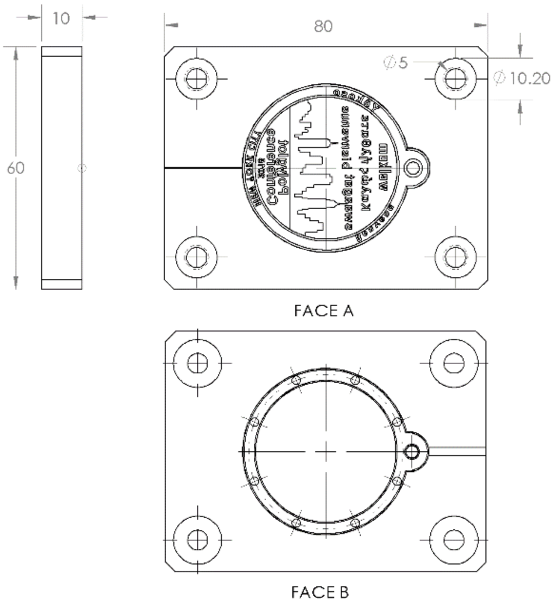

Figure 1. Drawing of the miniaturized insert (medal) based on [6] (dimensions in mm)

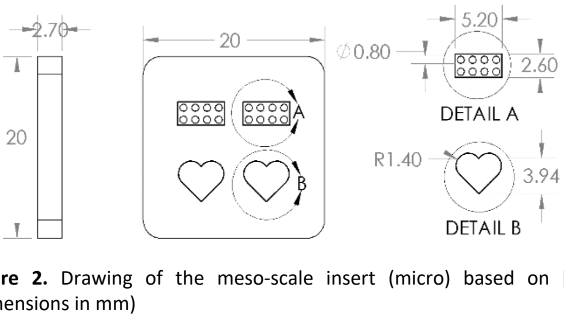

Figure 2. Drawing of the meso-scale insert (micro) based on [7] (dimensions in mm)

2.2. Injection moulding cost model

Three are the main cost elements that largely contribute to the cost of a moulded plastic part: tool cost C_T; material cost C_M; and production cost C_{Pr} (*€/part*), as shown in Eq. (10). Part complexity, size and geometry are among the main factors that affect the cost of a moulded part together with the material selection. Among those, the production volume is another factor that highly affects the cost per part as depreciating the highly expensive investment in tooling for a small or large volume can greatly influence the cost per part. Brass and aluminium mould inserts require an expensive investment hence at larger production volumes the ratio of cost due to tooling decreases as the investment is depreciated over a larger production volume.

$$C_{IM} = C_T + C_M + C_{\mathrm{Pr}} \tag{10}$$

$$C_T = \frac{C_{MB}}{LC} + \frac{C_{In}\times n}{B} \tag{11}$$

$$C_M = C_{M_{Kg}} \times W \tag{12}$$

$$C_{\mathrm{Pr}} = C_h + \frac{C_m}{Cap_h} + \frac{\alpha\times C_O}{Cap_h} \tag{13}$$

$$C_h = \frac{(T_S+T_D)\times C_O}{B} \tag{14}$$

$$Cap_h = \frac{3600\times n}{CT} \tag{15}$$

Since this application case, prototyping, refer to a small production series and moulded part are depreciated over a small production volume, the cost for the mould frame C_{MB} (€) is distributed over its life cycle LC (*parts*). The cost to manufacture an insert with n cavities is represented in C_{In} (*€/insert*) and depreciated over its production volume or batch size B (*part*).

The cost per kilogram of material is represented by C_{kg}(€/kg) and the weight of the moulded part including sprue and runners by W (kg).

The cost to handle and run the moulding machine is defined as C_h (*€/part*), the hourly cost of the machine including overheads is C_m (*€/hour*), the hourly capacity is described as Cap_h (*part/h*), the factor α accounts for labour intensive operations and the hourly cost for an operator is C_O (*€/hour*).

To conclude, T_S defines the time used to set-up the machine (*hour*), while T_D accounts for the time the machine is down for mould changeover or maintenance (*hour*), and CT is the cycle time of the process (*second*).

3. Results

First, it was necessary to calculate the cost of a part produced with DLP technology as shown in table 1. Secondly, the cost of inserts manufactured with DLP are used to calculate the cost per moulded part as shown in Table 2.

Table 1 Detailed cost breakdown for Digital Light Processing

	Variable	**Insert type**	
		Medal	**Micro**
Parts per build	N	1	3
Operator cost (*€/hour*)	C_{Op}	67,20	
Setup time (*min*)	T_{SW}	30	
Pre-processing cost (€)	C_{P_p}	33,60	11,20
Purchase machine (€)	C_I	90.000,00	
Depreciation time (*year*)	Y	5	
Utilization (*%*)	σ	90	
Hours per year (*hour*)	H	8760	
Machine cost per hour (*€/hour*)	C_h	2,28	
Time to build (*hour*)	T_B	10,42	2,81
Printing failure (*%*)	δ	5	
Production cost (€/part)	C_{Pr}	25,03	2,25
Cost of material (*€/Kg*)	$C_{M_{Kg}}$	400	
Part volume (*lt*)	V_{part}	0,044	0,0099
Volume of the build (*lt*)	V	0,063	0,0014
Material cost (€)	C_M	22,54	0,57
Support removal (*min*)	T_{sr}	60	30
Post curing time (*min*)	T_{pc}	30	
Drying time (*min*)	T_{pd}	30	
Machining time (*min*)	T_m	30	15
Labour in post-processing (*%*)	α	10	
Post-processing time (*hour*)	T_{PP}	1,15	0,63
Post-processing cost (€)	C_{PP}	77,28	14,00
Overhead cost per hour (*€/hour*)	C_{Ov}^h	5,90	
Overhead cost (€)	C_{Ov}	61,46	5,53
Cost per insert (€)	$\boldsymbol{C_{DLP}}$	***219,92***	***33,55***

Table 2 Detailed cost breakdown for Injection Moulding. The cost of insert manufactured with AM are calculated from Table 1 and considering a two and four mould cavity for the medal and micro insert mould.

	Variable	Insert type			
		CNC		AM	
		Medal	**Micro**	**Medal**	**Micro**
Mould base (€)	C_{MB}	23521,51			
Insert (€/*insert*)	C_I	4368,28	1130,65	879,69	134,21
№ of cavities (#)	n	2	4	2	4
Batch size (*part*)	B	100			
Tool cost (€/part)	C_T	*43,62*	*13,32*	*8,81*	*1,35*
Material per Kg (€/*Kg*)	$C_{M_{Kg}}$	1,74			
Weight (*gr*)	W	5,5	1,1	5,5	1,1
Material cost (€/part)	C_M	*0,01*	*0,002*	*0,01*	*0,002*
Setup time (*hour*)	T_S	1			
Down time (*hour*)	T_D	1			
Operator cost (€/*hour*)	C_O	67,20			
Handle cost (€/*part*)	C_h	1,34			
Cycle time (*s*)	CT	25	20	300	50
Hourly capacity (*part/h*)	Cap_h	288	720	24	288
Machine cost (€/h)	C_m	12,60			
Production cost (€/part)	C_{Pr}	*1,43*	*1,38*	*2,43*	*1,43*
Cost per part (€/*part*)	C_{IM}	**45,14**	**14,70**	**11,25**	**2,79**

An analysis of the cost components of an injection moulded part shows that the cost for machining a soft tools account for 97% of the total unit cost. The use of AM for fabrication of soft tooling decreases the tooling cost by 80% to 90% depending on the mould insert geometry tested. Processing cost increases by 69% when AM inserts are used however, they accounts for only the 3.2% of unit cost. The longer cooling time required by the photopolymer inserts to cool down efficiently is the main cause of the higher processing cost.

A break-even-analysis (BEA) was performed to assess and evaluate the economical trade-off of integrating AM in the IM process chain. Figure 3 shows that with a batch size up to 446 parts, the unit cost for parts moulded with the AM medal insert amounts to €10.21 and photopolymer inserts are favourable compared to machined inserts for such production volume.

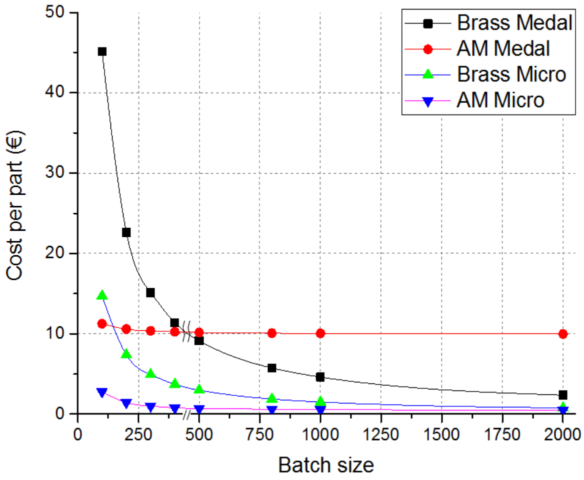

Figure 3. Break-Even-Analysis of AM and machined inserts for the product development phase

For larger production volumes, it is advisable to switch and use machined inserts in aluminium or brass as the longer lifetime of the machined inserts allows depreciating the tool over a larger production volume. The cost advantages linked to moulding small production series with photopolymer inserts prove and show the potential cost savings in supporting IM with AM for pilot production.

In the same way, it was calculated the crossover point for the micro insert and it results in a break-even-point (BEP) equal to 3400 units and a unit cost of €0.72. The factors that influence the BEP of the micro inserts are the size of the insert, which allow fabricating three inserts in the same build, the shorter amount of time spent for post processing activities and the longer tool lifetime compared to the medal photopolymer insert.

4. Conclusion

This research contributes to the analysis of the economic trade-off of applying AM to support conventional manufacturing processes rather than substituting them. Application of AM to streamline a particularly time consuming and costly operation created substantial cost savings and operational improvements.

The work presented in this research demonstrates how AM is able to reduce the tooling cost from €4368,28 to €879,69 and from €1130,65 to €134,21 for the medal and micro insert geometry respectively. Implementation of AM in the IM process chain leads to a 79,8% and 88,1% cost reduction for fabrication of tooling, which are translated into an overall unit cost reduction of 75% and 81%.

The study shows promising opportunities for further development and adoption of AM. The BEA highlights how the current level of the technology makes AM favourable for low/medium production volumes (up to 3400 units) which goes further beyond the product development requirement of moulding 100 parts. This means that an interesting area to investigate in future is on-demand production of soft tooling with AM that is not only circumscribed to the fabrication of moulded parts for prototyping and functional purposes.

The cost model represents a source of novelty in the literature since there were no other resources available discussing the cost to fabricate parts with DLP technology and especially integration of AM with injection moulding.

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