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Integration of Fiber-Reinforced Polymers in a Life Cycle Assessment of Injection Molding Process Chains with Additive Manufacturing

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Abstract. Additive manufacturing technologies applied to injection molding process chain have acquired an increasingly important role in the context of tool inserts production, especially by vat polymerization. Despite the decreased lifetime during their use in the injection molding process, the inserts come with improvements in terms of production time, costs, flexibility, as well as potentially improved environmental performance as compared to conventional materials in a life cycle perspective. This contribution supports the development of additively manufactured injection molding inserts with the use of fiber-reinforced vat polymerization technology. The life cycle assessment of the prototyping process chain for rapid prototyping with high flexibility provides a base for industrial applications in injection molding.

Keywords: Fiber-reinforced Polymers, Life Cycle Assessment, Additive Manufacturing, Injection Molding, Process Chains

1 Introduction

The conventional injection molding (IM) pilot production cycle is modified in a form where the cavity of the steel mold is generalized in geometry making room for inserts shaping the final geometry of the produced part. The generalized cavity is equipped with a smaller insert which is cheaper and more flexible in production and handling. Those standard inserts can be manufactured conventionally by milling of metals.

Newly developed technologies such as additive manufacturing (AM) show their major advantages in terms of flexibility and speed of production.[1–5] Moreover, finer details such as corners are limited to the voxel size of the AM machine (in the lower μm range), not the diameter of the milling machine.

Prior investigations by [6, 7] have shown a significant difference in potential environmental contributions such as Climate Change (Global Warming Potential, GWP) [8] and Human Toxicity (HT) [9] of IM inserts made from photopoly-

mer exposed in a vat polymerization (VP) process [10, 1] compared to conventional inserts made from brass and steel. Despite the described advantages, the lifetime (i.e. number of shots) of AM inserts is significantly lower than the lifetime of conventionally machined metal tools. A general review on environmental impact of AM compared to conventional manufacturing was performed by [11].

This investigation targets the life cycle of an advancement of IM inserts by fiber-reinforced polymers (FRPs) [12, 13]. Introduced by [1], FRPs in IM inserts reduced the crack propagation velocity in the insert and increased the lifetime by a factor of 2.6 at 5 %_{wt} short carbon fibers (CFs) and 5.2 at 10 %_{wt} compared to plain inserts without fiber-reinforcement as well as inserts made conventionally from aluminum, brass and steel. [1, 14, 15]

This paper elaborates on previous research by comparing plain inserts without fibers to FRP inserts in the perspective of a life cycle assessment (LCA) according to ISO 14040/44 [16] on screening level. It therefore contributes to the understanding of the effects if IM with AM inserts on environmental factors.

2 Methods

The LCA was performed on inserts produced with the proprietary photopolymer HTM-140 by the company Envisiontec. The inserts were shaped in the dimensions of 3 mm x 19 mm x 19 mm equipped with micro features such as sharp corners, cylindrical cavities and edges as shown in Fig. 1.

Fig. 1. Geometry of the investigated insert with sharp corners, cylindrical cavities and edges (left, source: [10], used with permission) and diagram of the IM process (right).

The FRP inserts were produced from a mixture of 5 %_{wt} and 10 %_{wt} of short virgin carbon fibers with dimensions 7.2 μ m diameter and 100 μ m average length [17]. They were modeled in SimaPro according to [18, 19] and will be referred to as VP 0 %, VP 5 %, and VP 10 %.

The manufactured inserts were grouped to a number of 4 inserts since the tool used 4 inserts per shot as shown in Fig. 2 whereas each insert of the compared materials had different specific weights shown in Table 1. The material is injected from the back of the machine from a granular primary material. The IM process parameters were not changed from conventional IM manufacturing. Therefore,

the process was also not included in the LCA as the focus is on the comparison of different insert materials as well as the impact of waste generation on the IM process.

The lifetime was experimentally determined for PE-LD as part material in [7, 1, 14, 15] and is listed in Table 2. It can be expected that the lifetime of ABS as part material is lower due to the higher process temperature.

Fig. 2. Single insert in the IM machine (left). The process has a capacity of 4 inserts producing one part each. All inserts are connected by hot runners (right) resulting in waste material (source: [1], used with permission).

VP 0 %	VP 5 %	VP 10 %	aluminum	brass	steel
1.3 g	1.325 g	1.35 g	3.2 g	10.2 g	9.4 g

Table 1. Weight of 1 insert of the different kinds.

VP 0 %	VP 5 %	VP 10 %	aluminum	brass	steel
500 shot	1300 shot	2600 shot	10 000 shot	10 000 shot	10 000 shot

Table 2. Lifetime of 1 insert of the different kinds for injection of PE-LD as determined from [7, 1, 14, 15].

In order to investigate the inserts' share of environmental impact of the entire IM process, the waste of injected polymer was additionally calculated and compared to the used inserts. Acrylonitrile butadiene styrene (ABS) and Low-density polyethylene (PE-LD) were chosen as injected materials. The weight characteristic of 1 shot is shown in Table 3. Polymer waste is responsible for approximately 60 % of the injected polymer weight in the process.

	ABS	PE-LD
weight of 4 parts	2.00 g	1.60 g
weight of waste	2.72 g	2.28 g
total weight	4.72 g	3.88 g

Table 3. Weight of 4 produced parts and residual material of the IM process that was not used in the final parts for 1 shot.

It was chosen to use GWP in CO₂ equivalent as well as HT in kg1,4 – DB equivalent, as indicators for the life cycle impact of the investigated inserts and parts.

3 Results

It was shown that the GWP increased at increasing CF content whereas the contributions to HT decreased. An increase in GWP of approximately 5 % and a reduction of HT by less than 1 % is reached when adding 1 % CF to the AM insert compared to an insert without CF.

Brass leads to a significantly higher impact on HT as shown in Table 4 where influencing factors of 1 kg of the materials are listed. ABS has a higher impact on the LCA as compared to PE-LD with an accelerated impact due to its chemical composition and its production chain.

	VP 0 %	VP 5 %	VP 10 %	aluminum	brass	steel	carbon fibers
GWP in kgCO ₂ eq	3.118	3.769	4.419	18.971	5.045	1.744	16.127
HT in kg1,4 – DBeq	621.790	596.313	570.835	269.738	4772.948	85.757	112.236

Table 4. LCA data for 1 kg of the inserts' materials.

	ABS	PE-LD
GWP in kgCO ₂ eq	3.995	1.896
HT in kg1,4 – DBeq	7.057	2.486

Table 5. LCA data for 1 kg of the parts' materials.

Waste is responsible for 60 % of the necessary injected polymer and makes up for up to 33 % of the contributions for 1 shot as shown in Table 6 for 1 shot. The factors were calculated as ratio of impact of waste to overall impact of necessary parts and waste. ABS can be considered more influential in both factors with a high impact on the LCA.

When neglecting the contributions of the polymer waste, CFs have a strong impact on the LCA of the IM process. Even at higher shot numbers, the GWP

	VP 0 %	VP 5 %	VP 10 %	aluminum	brass	steel
GWP ratio of ABS	0.3301	0.2857	0.2508	0.0159	0.0194	0.0569
HT ratio of ABS	0.0043	0.0044	0.0046	0.0020	0.0000	0.0022
GWP ratio of PE-LD	0.1576	0.1318	0.1128	0.0061	0.0075	0.0224
HT ratio of PE-LD	0.0012	0.0013	0.0013	0.0006	0.0000	0.0006

Table 6. Ratios of waste material as compared to the total of GWP and HT impacts for 1 shot.

contributions to the 4 inserts VP 10 % in the IM machine remains significantly below the GWP of the metal materials and VP 5 % competes with steel at higher shot numbers as can be seen in Fig. 3.

Fig. 3. Cumulative GWP impact neglecting the polymer waste.

Due to the high effects of the photopolymer on HT, the AM inserts remain between aluminum and steel below and brass exceeding the impact. Still, smaller production numbers below 5000 shots favor the AM inserts as suitable alternatives for prototyping applications as shown in Fig. 4.

It is moreover noticeable that the GWP of both ABS as well as LD-PE waste remains high compared to the inserts' materials. The contributions of the waste component of the IM process overrules the contributions of the insert material on the GWP as shown in Fig. 5 and Fig. 6. At higher shot numbers, the ratio converges to 1 meaning that the inserts' materials have negligible contribution to the global impact.

Fig. 4. Cumulative HT impact neglecting the polymer waste.

Fig. 5. Ratio of GWP impact of ABS waste material as compared to the total impact on the LCA.

Fig. 6. Ratio of GWP impact of PE-LD waste material as compared to the total impact on the LCA.

Due to the poor performance of brass in terms of HT, the contributions of waste ABS and PE-LD remains at 20 % for brass in terms of ABS waste (Fig. 7) and 10 % for brass in terms of PE-LD waste (Fig. 8). Production of VP 0 % inserts is influenced up to 63 % in terms of ABS waste and up to 40 % in terms of PE-LD waste. Better performance of FRPs in the AM inserts in terms of lifetime results in a higher contribution of the waste material.

4 Conclusion

As a conclusion, the IM manufacturing process needs revision in terms of produced polymer waste that does not contribute to the part or the mold. Production of ABS and PE-LD parts was not dominated by the difference in the insert material, but by the environmental impact of ABS and PE-LD parts and waste production.

CFs have a significant influence on the performance of AM inserts in the LCA. Concerning GWP contributions, AM inserts with a ratio of 10 %_{wt} have a preferable performance than metal inserts.

AM inserts are most suitable for smaller production volumes in terms of their environmental impact, manufacturing costs and time as well as feature accuracy.

Due to the lower lifetime of AM inserts in the IM process, metal inserts are preferred for series production of high part volumes whereas AM inserts are preferred in all key aspects for prototyping of low to medium volume production.

Fig. 7. Ratio of HT impact of ABS waste material as compared to the total impact on the LCA.

Fig. 8. Ratio of HT impact of PE-LD waste material as compared to the total impact on the LCA.

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