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An appraisal on the sustainability payback of additively manufactured molds with conformal cooling

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ABSTRACT

The use of Additive Manufacturing (AM) in the production of tooling for injection molding has led to the introduction of conformal cooling as an effective way to lower the cycle time of the process. As the cooling cycle is responsible for a large portion of the energy consumed during the injection molding process, conformal cooling allows increasing the energy efficiency. However, AM could create a large upfront cost of energy for the manufacturing phase. This paper investigates a case study where a cradle-to-grave life-cycle assessment is used to evaluate the cumulative energy demand of conventional or conformal cooling molds.

1. Introduction

Injection molding represents a considerable portion of the contemporary plastics manufacturing industry (Mianehrow and Abbasian 2017). The plastic pellets/granules used as feedstock material are fed through a hopper into a heated barrel containing the reciprocating screw, melted, and injected into the mold cavity under high pressure. Following the injection phase, the plastic is cooled and allowed to solidify. The part is then ejected from the core, and the cycle is repeated. The injection molding process can produce high quality parts at a low cost to manufacturers and at a large enough volume to meet the increasing demand for polymer products. During the injection molding process, the cooling phase takes up a substantial amount of time and energy. In order to quickly cool the part after injection, coolant is cycled through channels inside of the mold. A study by Meekers et al. (2018) showed that the cooling phase accounted for one third of the energy consumed during a full cycle on a hydraulic injection molding machine. Being one of the main contributors to the energy consumption of the injection molding process, increasing the efficiency of the cooling cycle can be targeted as an effective way to lower the total energy usage. In traditional molds, linear cooling channels are created by drilling holes to allow coolant to flow through and lower the temperature of the mold. The effectiveness of the cooling cycle can be increased by positioning the cooling channels as close to the surface of the part as possible. ‘Conformal cooling’ is the term used in such cases as the channels ideally run conformal to the surface of the part being molded (Jahan et al., 2019). Conformal cooling can efficiently cool parts, reduce variance in the surface temperature of the part, and reduce wasted heat transfer. These changes result in an injection molding process that produces parts faster with fewer defects (Lu et al., 2019, Evens et al., 2019). Also, by increasing the efficiency of injection molding, conformal cooling has the potential to reduce the energy consumption and create a more sustainable process. However, conventional manufacturing using CNC milling has limitations due to the cutting tool geometries when creating conformal cooling channels. To address this problem, other approaches were proposed (Kuo et al., 2019). In addition, Additive Manufacturing (AM) has given mold designers new tools for implementing conformal cooling. For instance, Direct Metal Laser Sintering (DMLS) is an AM technique that uses a laser to melt metal powder. Complex shapes can be created layer after layer (Baumers et al., 2013). With no limitations on the complexity of the part being produced, conformal cooling channels can be designed nearby the surface of the mold cavity while maintaining a constant distance regardless of the geometry. This paper deals with the sustainability implications resulting from the adoption of AM to manufacture conformal cooling molds. A case study, which is described in Section 2, was considered. Beginning with the component to be produced by means of injection molding, (*i*) a standard cooling mold and (*ii*) a conformal cooling mold were designed. The first one can be manufactured by ma-

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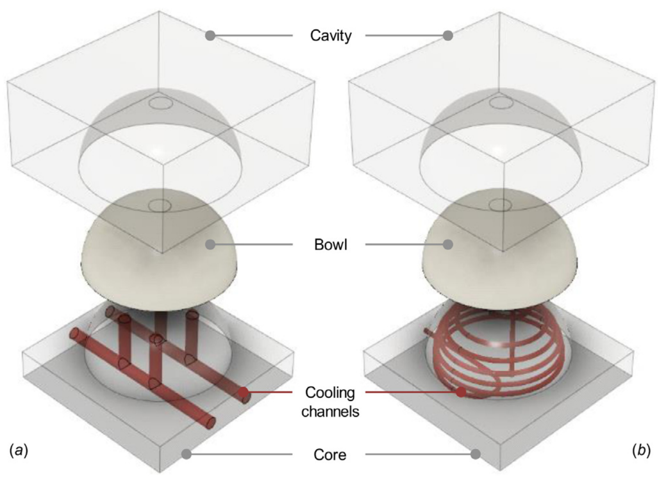

Fig. 1. Standard (*a*) and conformal cooling (*b*) molds.

chining, the second can be obtained using an additive-subtractive integrated manufacturing approach (Priarone and Ingarao, 2017). A methodology for quantifying the cradle-to-grave cumulative energy demand of each mold design is proposed in Section 3. All the energies required for raw material production, pre-manufacturing stages, mold manufacturing, transportation, use and disposal were assessed. The assumptions regarding the Life Cycle Inventory are detailed in Section 4. The achieved results are presented and discussed in Section 5. In particular, since AM is expected to require a higher energy demand than the conventional mold manufacturing techniques, a sustainability payback period with respect to the total energy consumption was determined. Conclusions and research outlooks are given in Section 6. Overall, this paper aims to contribute to the development of decision-support criteria for the mold design when accounting for the cradle-to-grave energy efficiency.

2. Case study

A bowl made of Acrylonitrile Butadiene Styrene (ABS) was the component to be produced by means of injection molding. The bowl shape is particularly suitable to highlight the limitations of conventional cooling channels, and ABS is a material commonly used for several applications (e.g., Hovorun et al., 2017). The bowl had a height of 7.5 cm with a base diameter of 17.5 cm. Guidelines for the part design were taken from the manual 'Part and Mold Design' published by Bayer (2000). A constant wall thickness of 2.5 mm was chosen to allow for rigidity without excessive weight and to foster even flow during injection without gas entrapment. The mass of the bowl was 0.128 kg.

2.1. Molds and cooling channels

The molds included two halves (a core insert and a cavity insert) having all the features to fulfill the geometrical component specifications. A coherent simplified mockup was studied for the purpose of the methodological application here discussed. The material chosen for the tooling was stainless steel, which is commonly used for high volume injection molds. The designed cooling channels are highlighted in Fig. 1. The Standard Cooling (SC) mold had a linear design of the cooling channels to allow for machining. The Conformal Cooling (CC) mold had a helical design of the cooling channels, according to the guidelines published in Autodesk (2016), Marques et al. (2015). The channels had a constant pitch and were uniformly spaced from the surface of the part to allow even cooling.

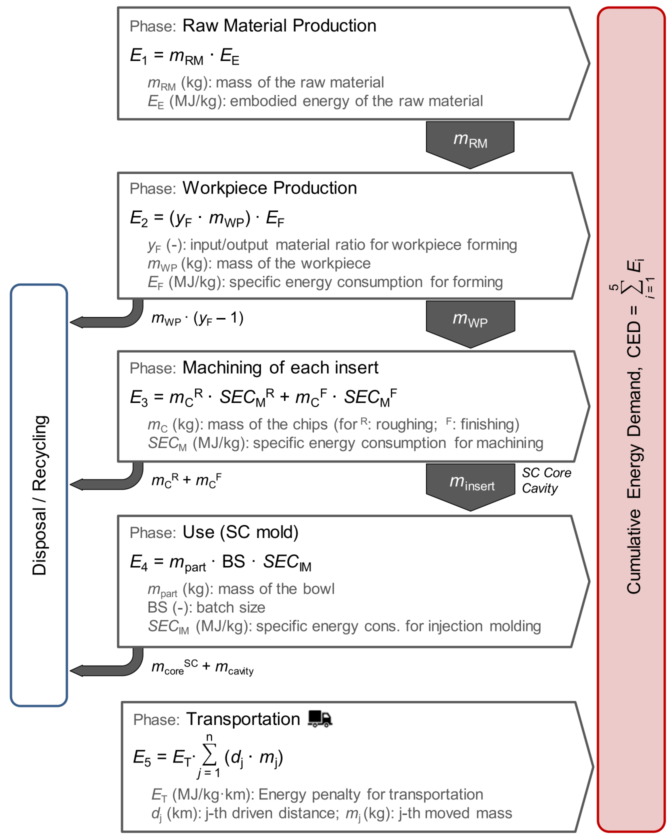

Fig. 2. Flowchart highlighting the machining approach.

In both cases, the cavity (i.e., the mold half on the top of Fig. 1) can be manufactured using CNC milling together with the core of the standard cooling mold. In the conformal cooling mold, the core can be produced using an integrated additive-subtractive manufacturing approach in which: (*i*) the core is additively manufactured with a given allowance using Selective Laser Melting (SLM), and (*ii*) the allowance is then machined off during a finishing machining operation to address the surface roughness constraints presented with SLM.

3. Methodology

The here applied methodology to measure the Cumulative Energy Demand (CED) of both the standard cooling mold and the conformal cooling mold was adapted to the specific case study from the recent literature (Priarone and Ingarao, 2017, Priarone et al., 2018, Ingarao et al., 2018, Priarone et al., 2019). The functional unit is the single mold. Cradle-to-grave boundaries, including the feedstock material production, mold manufacturing, use phase, disposal and the main transportation-related impacts, were considered for the analysis. Flowcharts highlighting the unit processes and qualitative material flows for the machining approach and the integrated SLM-subtractive approach are shown in Fig. 2 and Fig. 3, respectively, where the equations used to model each contribution to the CED are specified. Primary energy was selected as the performance metric to sum up, at the same energy level, the different shares due to the resource/material flows and the electric energy flows (Frischknecht et al., 2015). A primary-to-secondary energy conversion factor of 0.38 was generally assumed to account for the energy losses that occur at the various steps during the production of electricity. According to the hypotheses mentioned above, the framework detailed in Fig. 2 was applied to model the cradle-to-gate impact of (*i*) the cavity inserts (which are equal for

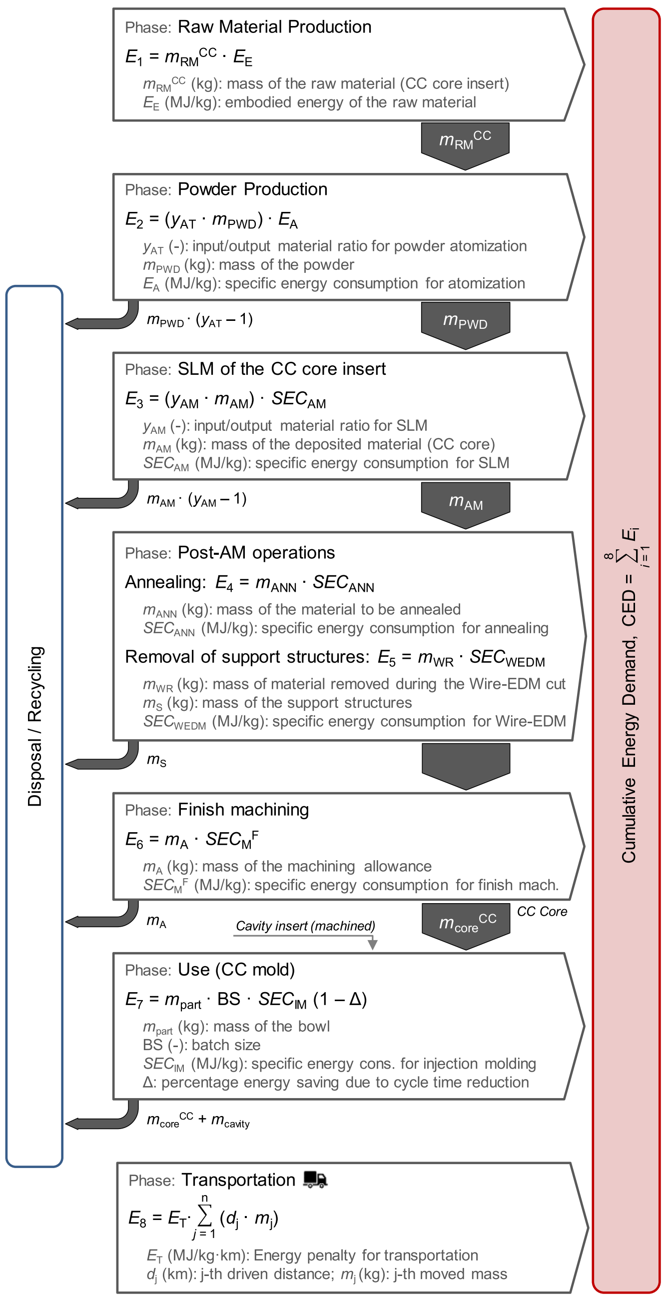

Fig. 3. Flowchart highlighting the integrated SLM-subtractive approach.

both the designed molds shown in Fig. 1) and (*ii*) the core insert of the SC mold. On the other hand, the flowchart as planned in Fig. 3 was used to model the cradle-to-gate impact of the core insert of the CC mold.

3.1. Material flows

The raw material production accounted for the extraction or recycling of the material and its transformation into an in-stock form (i.e., an ingot). The embodied energy (E_E), which is intended as the primary energy consumed to produce a unit mass of the in-stock material, was computed according to the equations proposed by Hammond and Jones (2010). Different scenarios were chosen: (*i*: the worst case) where there was no material recycling; (*ii*) where the energy credits were due to the up-stream flow of recycled materials, and E_E was obtained by using the 'recycled content approach'; (*iii*: the best case) where the energy credits were due to the down-stream flow of recyclable materials, and E_E was calculated by means of the 'substitution method'. Afterwards, the ingot was formed into the workpiece used for milling or underwent atomization to create the powder for the SLM process. Input/output material ratios ($y_F = 1.176$ and $y_{AT} = 1.053$) were assumed to account for the material waste of these steps. As far as the machining approach is concerned, the bounding box of each insert was considered with the addition of a fixed allowance to machine the exterior of the mold to size. For the standard cooling mold, the workpiece of the core is rough machined with an allowance of 0.38 mm left on the internal surfaces to be machined off using finishing machining parameters.

Table 1
Cavity insert, standard/conformal cooling mold: material flows.

Mass (with reference to Figure 2)		kg
Mass of the cavity insert	m_{cavity}	29.7
Mass of the chips to be machined off	$m_C^R + m_C^F$	17.8
Mass of the workpiece	m_{WP}	47.5
Mass of waste when workpiece forming	m_{WP}•(y_F-1)	8.4
Mass of the raw material	m_{RM}^{cavity}	55.9

As far as the integrated additive-subtractive approach is concerned, the core of the conformal cooling mold was first additively manufactured via SLM. Second, the obtained part was annealed and the support structures were removed using Wire-EDM. Third, the inner cavity of the mold was milled and the allowance was machined off. According to Fig. 3, the mass of powder (m_{PWD}) was obtained by adding the masses of the core (m_{core}^{CC}), the machining allowance (m_A), the support structures (m_S) and all the material wastes of each manufacturing unit process. An input/output material ratio ($y_{AM} = 1.005$) was assumed for SLM. In addition, m_{WR} quantified the unrecoverable material losses due to the Wire-EDM cut. The material flows for the production of the cavity insert (by means of machining) and the core insert (by means of the two manufacturing approaches) are summarized in Tables 1 to 3.

4. Life Cycle Inventory

The main eco-properties concerning the feedstock material production and the pre-manufacturing unit processes are listed in Table 4. Average values of the energies for primary material production (i.e., the production of the raw material from virgin sources) as well as the energy to recycle were obtained from the CES Selector database (2017). The 'recycled content approach' and the 'substitution method' were used to quantify the recycling benefit awarding (Hammond and Jones, 2010). The recycled content and the end-of-life recyclability of both process wastes and bulk materials were fixed to 0.58 CES Selector database, 2017) and 0.90 (Priarone and Ingarao 2017), respectively.

The SEC (Specific Energy Consumption) approach, which allocates the primary energy consumed to each unit mass of transformed material, was followed in this paper for the ease of implementation. The data for the pre-manufacturing phases were extracted from (Priarone and Ingarao, 2017, CES Selector database, 2017). The specific energy demand of SLM was obtained from Priarone and Ingarao [8, and references therein] and was fixed at $SEC_{AM} = 244.1$ MJ/kg of deposited material. The SEC values for rough and finish milling (equal to $SEC_M{}^R = 11.4$ and $SEC_M{}^F = 245.5$ MJ/kg of removed material) were calculated from the SEC (kJ/cm^3) = 2.953 + 2.019 / MRR (cm^3/s) model proposed by Kara and Li, 2011 to characterize the electric energy consumption of wet cutting by means of a Mori Seiki milling machine. Process parameters adequate to mold manufacturing were assumed. The here-considered SEC for finish machining appears to be higher

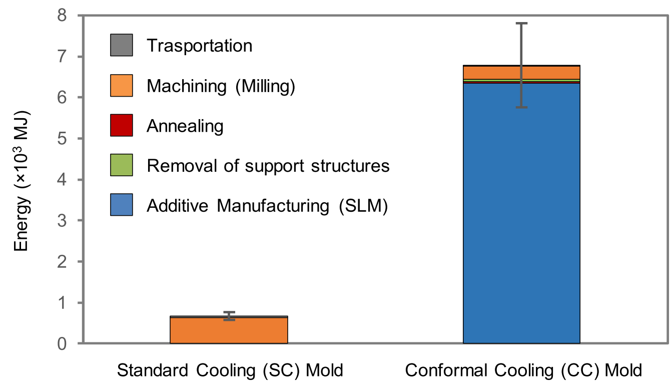

Fig. 4. Comparison of energy demand for manufacturing and transportation.

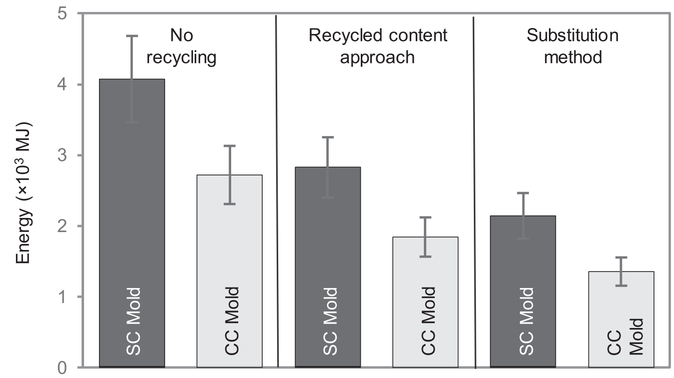

Fig. 5. Comparison of energy demand for feedstock material production.

than the values available in literature (e.g., (Priarone and Ingarao, 2017, CES Selector database, 2017). This is due to the choice of retaining a low feed rate to favor a better surface finish, resulting in an MRR of 2.8 mm^3/s. A residual stress annealing of the core insert after the SLM process was hypothesised, and a $SEC_{ANN} = 1.5$ MJ/kg of thermally treated material was adapted from the work of Kamps et al., 2018. As far as the energy for the removal of the support structures is concerned, a few values are available. A best estimate was extrapolated as suggested in Kara and Li (2015), and the specific energy consumption was referred to the unit mass of material that was cut (i.e., removed) by the wire. The energy in the use phase was calculated as a function of the specific energy demand of the injection molding machine ($SEC_{IM} = 6.8$ MJ/kg) and the total mass of the parts in ABS being produced. In the case of the conformal cooling mold, a reduction in energy usage of $\Delta = 15\%$ was assumed based on case studies with similar geometries whose cycle time reductions range from 6 – 70% Meekers et al. (2018). As far as the material transportations are concerned, the energy penalty per unit weight and travelled distance ($E_T = 0.71 \cdot 10^{-3}$ MJ/kg•km), considering a 55-t truck, was extracted from Ashby (2013). The transportations, (*i*) of the feedstock material from the material production plant to the manufacturing plant, (*ii*) of the brand new mold from the manufacturing plant to the point of sale, (*iii*) of the worn mold from the disposal site to the material recycling plant, and (*iv*) of all the recyclable process wastes from the manufacturing plant to the recycling plant, were included in the assessment. All these travelled distances were fixed at 200 km Priarone and Ingarao (2017). According to Ashby (2013) the precision of much eco-data could be low (some database values are known to be within 10%, others with much less certainty). Therefore, a ±15% range of variation for the input data was considered in order to ensure validity and reliability of the outcomes.

5. Results and discussion

The methodology presented in Section 3 was applied to the here-considered case study using the inventory data detailed in Section 4. The achieved results, which were obtained by implementing the models in the MATLAB® R2019a software, are presented in this Section.

5.1. Mold manufacturing

Fig. 4 allows the comparison of the primary energies needed to produce core and cavity inserts of (*i*) the standard cooling (SC) mold, by means of the machining approach, and (*ii*) the conventionally cooling (CC) mold by using the integrated additive-subtractive approach for the core insert. The imposed variability of ± 15% in the input data concerning the specific energies caused a variability in the results, which is highlighted in the graphs through error bars. Even where the energy demand for the CC mold is at its lowest and the one for the SC mold is at its highest, a difference of approximately 5000 MJ was outlined. Moreover, as far as the CC mold is concerned, the contribution to additively manufacture (SLM) the massive core insert was the largest of all, requiring 94% of the total energy (as discussed in Ingarao et al., 2018). Comparing the energy spent during CNC milling only, the CC mold required 49% as much energy as the SC mold. This is because, in both cases, the cavity insert was manufactured using the milling process. In addition to this, after support removal, the core insert must undergo a finish machining operation. This latter operation accounted for a considerable amount of energy due to the low MRR which was chosen (Kara and Li, 2011). It is worth remarking that the surface roughness of the cooling channels affects the cooling performance (Liu et al., 2018). Other post-processes, such as the Abrasive Flow Machining, could be needed to finish the CC-mold channels (Bouland et al., 2019). If, for instance, (*i*) a mixture made of 60% of boron carbide (with an embodied energy of 170 MJ/kg CES Selector database, 2017) is flushed inside the cooling channels for 2 h (Bouland et al., 2019) by means of a pump demanding a constant electric power of 4 kW (Kenda et al., 2014), and (*ii*) typical industrial consumption ratios for the abrasive medium are assumed, the contribution of this manufacturing step to the CED results to be far lower than that of the AM process itself. Therefore, it was overlooked in the present assessment.

5.2. Material production and recycling-related issues

Fig. 5 compares, for both the manufacturing approaches, the energy required to produce the feedstock materials (i.e., the workpiece and the metal powder), while recycling benefit awarding was either neglected or included in the assessment. The highest energy consumption for both the approaches was when no recycling took place and all the materials were produced from their virgin sources. The environmental benefit of the future end-of-life recyclability, which was here fixed at 90%, allowed the best results to be achieved. On the other hand, the recycled content approach, which accounts for the impacts of recycling on the present climate (Hammond and Jones, 2010), provided intermediate results (Priarone et al., 2018). In Fig. 5, the energy consumption for producing the material of which the CC mold is made is lower than that of the SC mold in each recycling scenario. This evidence is due to the fact that AM required less raw material, as it can be noticed from the comparison between Table 2 and Table 3.

5.3. Payback period

The integrated additive-subtractive approach appears to be highly energy-demanding in comparison to the machining one.

Table 2
Core insert, standard cooling mold: material flows.

Mass (with reference to Figure 2)		kg
Mass of the core insert	m_{core}^{SC}	23.4
Mass of the chips to be machined off	$m_C^R + m_C^F$	29.1
Mass of the workpiece	m_{WP}	52.5
Mass of waste when workpiece forming	$m_{WP}\cdot(y_F - 1)$	9.2
Mass of the raw material	m_{RM}^{SC}	61.7

Table 3
Core insert, conformal cooling mold: material flows.

Mass (with reference to Figure 3)		kg
Mass of the core insert	m_{core}^{CC}	23.7
Mass of the machining allowance	m_A	0.4
Mass of waste when removing the supports	$m_S + m_{WR}$	1.9
Mass of waste when SLM	$m_{AM}\cdot(y_{AM} - 1)$	0.1
Mass of the powder	m_{PWD}	26.1
Mass of waste when powder atomization	$m_{PWD}\cdot(y_{AT}-1)$	1.4
Mass of the raw material	m_{RM}^{CC}	27.5

Table 4
Eco-properties for material production and pre-manufacturing.

Variable	MJ/kg
Energy for primary (raw) material production	25.7
Energy for material recycling	7.5
Embodied energy, E_E (MJ/kg), no recycling	25.7
Embodied energy, E_E (MJ/kg), Recycled Content Approach	15.2
Embodied energy, E_E (MJ/kg), Substitution Method	9.3
Specific Energy Consumption for forming, E_F	8.9
Specific Energy Consumption for atomization, E_A	2.9

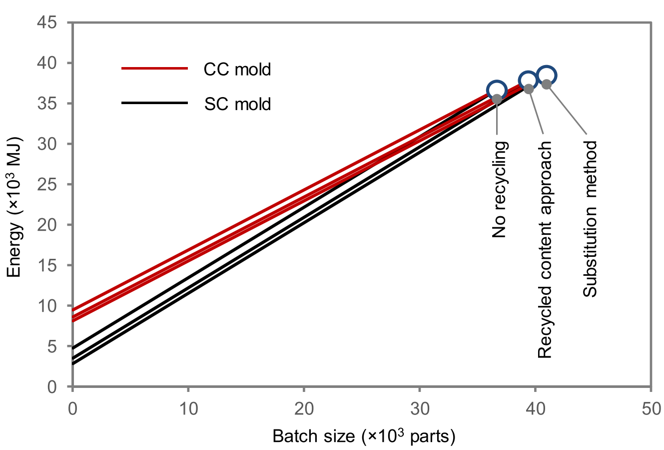

Fig. 6. Payback periods as a function of the material recycling scenario.

However, a higher energy efficiency due to the better cooling action is expected during the use phase of the CC mold. A payback period was therefore defined as the number of plastic parts required to be created during the mold lifetime to offset the initial extra energy cost of the integrated additive-subtractive manufacturing. After the breakeven point, the conformal cooling mold becomes the sustainable option. Starting at a batch size of 1, the cradle-to-grave Cumulative Energy Demand (CED) was calculated. This was repeated until the CED for the CC mold was less than that of the SC mold. A simulation was set in MATLAB® and run for all the three recycling scenarios. The results are plotted in Fig. 6. In this case study, the 'no recycling' scenario yielded the smallest payback period (or batch size). This result is affected by the differences in energy demand due to the material production and manufacturing phases.

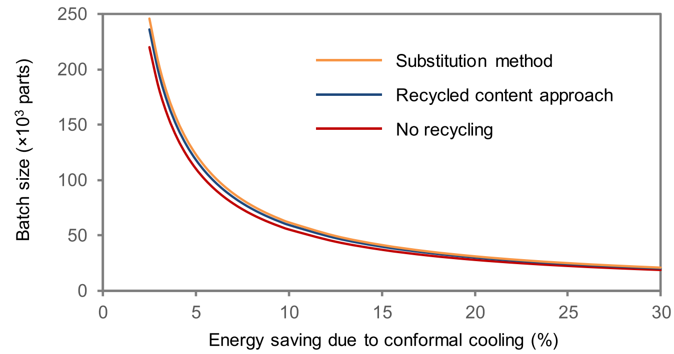

Fig. 7. Correlation between energy savings from conformal cooling and breakeven points.

Moreover, to investigate the impact of the savings offered from conformal cooling, the calculation was repeated at savings of 30% to 2.5% (Fig. 7). The required breakeven batch size increased as the energy savings offered from conformal cooling were reduced. Therefore, the effectiveness of the conformal cooling plays a key role in the payback period. The impact of the recycling scenario only accounted for a variance of around 4300 units when the saving was 15%, as the largest difference in CED between the SC mold and the CC mold was the energy for manufacturing.

6. Conclusions

The cooling cycle is responsible for a large share of the energy consumed during injection molding, and conformal cooling has been identified as a viable solution to improve the efficiency of the process. The making of conformal channels could be a complex operation with traditional manufacturing processes, while it can be straightforwardly achieved with Additive Manufacturing. However, AM requires to plan an integrated additive-subtractive manufacturing approach, since machining cannot be disregarded due to the surface finish requirements imposed by the final application. A methodology for the cradle-to-grave assessment of the life cycle of an additively manufactured conformal cooling mold was proposed in the paper, while considering a conventionally manufactured standard cooling mold as a benchmark. The here-developed empirical models were applied to a simplified case study. The results showed that, although the cumulative energy demand for the creation of the conformal cooling mold could be considerably higher (due to the massive geometry of the core insert), a positive energy balance is possible after a quantifiable payback period, which essentially depends on the increase in energy efficiency of the injection molding process.

Declaration of Conflict Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

William Davis: Investigation, Formal analysis. **Vincenzo Lunetto:** Investigation, Formal analysis. **Paolo C. Priarone:** Conceptualization, Methodology. **Dan Centea:** Supervision. **Luca Settineri:** Supervision.

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