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LIFECYCLE ANALYSIS FOR ENVIRONMENTALLY CONSCIOUS SOLID FREEFORM MANUFACTURING[1]

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ABSTRACT

A lifecycle based process model for analyzing environmental performance of SFM processes and SFM based rapid tooling processes is presented for analyzing SFM based Rapid Tooling (RT) processes in this paper. The process environmental performance assessment model considers material, energy, and disposal scenarios. The material use, process parameters (e.g. scanning speed) and power use can affect the environmental consequence of a process when material resource, energy, human health and environmental damage are taken into account. The presented method is applied to the SLA process and two SLA based rapid tooling processes. The method can be used to compare different Rapid Prototyping (RP) and RT processes in terms of their environmental friendliness and for further multi-objective decision making.

I. INTRODUCTION

Solid Freeform Manufacturing (SFM), or often referred to as Rapid Prototyping/Manufacturing (RPM), can be used not only to generate rapid prototypes for design optimization and verification but also to create production tools or directly fabricate products. This new manufacturing technology has been experiencing tremendous development and growth since its introduction a little over one decade ago. SFM has been widely adopted in aerospace and automotive industries, and is quickly becoming an important production process in electronics industry.

In view of the fast growth and wide adoption of various SFM processes, it is important to study the lifecycle performance of SFM processes, including consumption of natural resources and energy, and impact on human health and the environment, together with other process attributes such as cost, accuracy, productivity, and functionality, so that the SFM technology can become more sustainable. SFM processes have many good environmental characteristics. The material utilization rate is much more higher (almost 100%) in material additive process adopted in SFM than in material removal process used in machining process. The waste streams are less in SFM processes than in conventional manufacturing processes such as machining. Worn tools and scraps seldom occur in SFM processes and equipment. Cutting fluids, which are the major source of hazard in machining [5-7], are not used in SFM processes. Comparing with conventional manufacturing processes, SFM processes have distinguishing features in process mechanisms, materials, energy use, etc. It is essential to look into these processes, investigating how the process variables influence the environmental consequences, and apply a systematic method to assess the process environmental performance so that these processes can be optimized with consideration of their environmental properties.

In [14], we reported some preliminary results of our research towards a systematic approach that we developed for SFM processes based on lifecycle concept. In this paper, we extend the previous method to assess SFM based rapid tooling processes. The method holistically incorporates the entire process lifecycle, including material extraction, pattern fabrication, shape replication, post processing, and material disposal. The environmental performance is evaluated, based on Lifecycle Assessment (LCA) principle [1-3] and with an environmental impact index called the Eco-indicator [8]. Details of this method and an example illustrating its use will be given.

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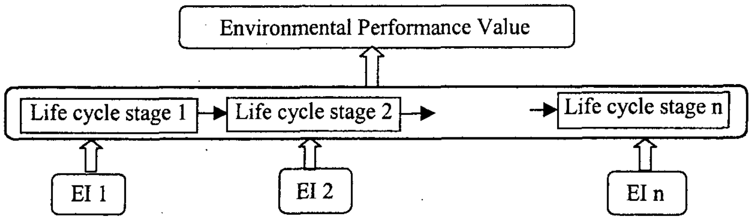

EI: Environmental Impact

Figure 1. Lifecycle environmental performance model

II. LIFECYCLE ENVIRONMENTAL PERFORMANCE OF SOLID FREEFORM MANUFACTURING PROCESSES

LCA has been found useful for examining the design of products and processes to reduce the impact upon human health and the environment and to achieve sustainable industrial development. From the lifecycle point of view, a part produced with a SFM process generally goes through the following stages: (a) inputting the building material into the system, (b) building the part layer by layer, (c) shape replication and sintering or burning (for tooling processes) and (d) post-processing. When the user finishes using the part fabricated by SFM, the part goes to the disposal stage: to be landfilled, incinerated, or recycled. While the material, part usage and part disposal are not exactly part of a process, their inclusion provides a holistic view of the environmental performance of an SFM process. Thus, factors taken into account in process environmental performance should include the material extraction stage, energy consumption and process wastes in the fabrication and replication stages, and the disposal stage.

To evaluate the environmental performance, we propose a process model based on lifecycle concept. The steps of an SFM process can be viewed as the process lifecycle stages, and thus the environmental impact factors in all process stages can be included in this model. The model is then extended for assessment of SFM based Rapid Tooling (RT) processes.

The environmental performance process model is shown in Figure 1. Figure 2 is an extension of this model for RT processes. In the process model, the overall environmental performance value is the sum of the environmental performance values of the various life stages, each of which has one or more corresponding environmental impacts. The environmental performance of a process is evaluated by defining the lifecycle stages of the process, identifying the individual environmental impact factors, obtaining the environmental impact values, and summing these values.

Figure 1 shows that the lifecycle of a process can be divided into n stages. For SFM process, there are generally four lifecycle stages: 1) material preparation, 2) part build, 3) part use, and 4) part disposal. Environmental impacts that occur in each lifecycle stage are identified as follows. In the material preparation stage, the environmental impact is material extraction & production. During the part building stage, the main environmental impact is energy consumption. Process residues, such as cutting fluids, which exist and have severe environmental consequences in the part cutting stage of machining process, are rare in most of SFM processes, and can be ignored in evaluation. Material toxicity may cause negative impact to human health in the part use stage. Finally in the disposal stage, the part can be landfilled, incinerated or recycled. Different disposal methods have different environmental impacts.

The model presented above is the basic process model for SFM processes. It can be extended to SFM based RT processes. Here we consider indirect RT processes, in these processes, a few additional steps are needed to duplicate the shape of the pattern made by SFM, and then sintering or burning the duplicate part is needed to get the tool. These steps are needed for the mold creation, and they can be seen in, for example, 3D Keltool and the rapid tooling process that integrates SFM with electroforming. The extended process model for indirect RT processes is shown in Figure 2. The environmental impacts corresponding to every lifecycle stage need to be identified. In the figure 2, EI1 is for material extraction & production. EI2 is for energy consumption. EI3 includes material consumption, energy consumption and process residue. And EI4 results from the tool disposal stage where the tool can be landfilled, incinerated or recycled.

The environmental performance value obtained should provide an unambiguous measure for the combined environmental impact of material, process, energy, etc. This kind of data quantifies the impact of the process to the environment. It should be noted that there is no database of this kind available today. For performing the quantitative assessment, we use the Eco-indicator index [8] that was made available by PréConsultants of the Netherlands. The provided database contains 100 indicators for commonly used materials and processes. The higher the indicator, the greater the negative environmental impact.

To summarize, our process model deals with the process complexity by dividing a process into several life stages. The environmental impact index provides a quantitative measure of environmental impact for each stage of the process. The implementation of this evaluation method can be carried out as follows. First, every process stage and the elements of its associated environmental impact factors are identified. Then, the value of eco-indicator is obtained for each environmental impact factor. Finally, the environmental index values for all process stages are summed up to generate the total environmental performance value.

III. EXAMPLE: ASSESSMENT OF SLA PROCESS AND RAPID TOOLING PROCESS

This example considers the StereoLithography (SLA) process and two rapid tooling processes that utilize SLA to build patterns: 3D System's Keltool process [14] and an SFM based electroforming process [13]. SLA is one of the most widely used SFM processes today. It is a fabrication process that builds a part by controlling a laser beam to selectively cure liquid photo-polymer layer by layer. 3DKeltool and electroforming tooling processes are two rapid tooling processes that utilize SLA to quickly create highly detailed and accurate patterns.

For the SLA process, the process parameters that influence the environmental performance are identified as follows: M: Material used (cm^3), V: Scanning speed (mm/sec), W: Line width (mm), T: Layer thickness (mm), P: Power rate of the equipment (kW), k: Process time delay between layers.

The scanning speed can be estimated using the following equation [4]:

$$V = \sqrt{\frac{2}{\pi}}\left[\frac{P_L}{W_0 E_c}\right]\exp\left[-\frac{T}{D}\right] \qquad (1)$$

in which P_L is the laser power, W_0 is the half line width, Ec is the critical laser exposure, and D is a material constant of the polymer. The Process Productivity (PP) and the Energy Consumption Rate (ECR) for each unit volume of material processed can be calculated as follows:

$$\text{PP}\ (cm^3/h) = V \times W \times T \times k \times 3600 / 10^3 \qquad (2)$$

and

$$\text{ECR}\ (kWh/cm^3) = P / PP \qquad (3)$$

The environmental performance of SLA process is evaluated according to the assessment method introduced in section 2.

A. Assessment of SLA Process

The building material in the SLA process is photopolymetric resin. The process is evaluated with three models of the equipment, SLA-250, SLA-3500, and SLA-5000. The manufacturer's recommended process parameter values are used in the assessment. First we need to obtain the environmental impact due to energy consumption in the process. Here we use equation (1) to calculate the process scanning speed V, then use equation (2) and (3) to estimate the process energy consumption rate (ECR). Finally we obtain the environmental impact of energy consumption. Table 1 shows the result representing the environmental impact of the energy used to process one cm^3 of epoxy resin. Because SLA-5000 has the highest laser power, resulting in the highest scanning speed, and the least ECR. While for SLA-3500 and SLA-250, the former one has higher scanning speed but also higher power rate of equipment than the later one. The result gives that the SLA-250 has less ECR than SLA-3500.

Table 2 shows the environmental indicators of the environmental impact occurring in each lifecycle stage of the process, and the environmental performance value representing the total environmental impact. As we discussed in section 2, the environmental impacts in various lifecycle stage are identified and the corresponding index values are obtained from the Eco-indicator database, and converted to the values representing effect of one cm^3 of specific material. Since there are usually two alternatives of disposal, two values are given for the disposal stage. The value before "/" is for disposal using landfill and the one after "/" is for disposal using incineration.

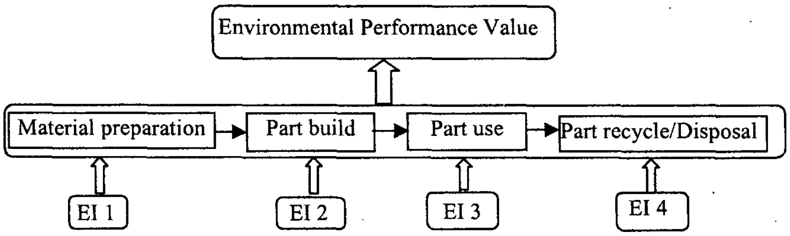

Figure 2. Lifecycle environmental performance model of indirect RT process

Table 1. Environmental Impact Due to Energy Use of SLA Process

	SLA-250	*SLA-3500*	*SLA-5000*
V (mm/sec)	*340*	*1000*	*2000*
W (mm)	*0.25*	*0.25*	*0.25*
T (mm)	*0.15*	*0.1*	*0.1*
k	*0.7*	*0.7*	*0.7*
P (kW)	*1.2*	*3*	*3*
PP (cm^3/h)	*32.13*	*63.00*	*126.00*
ECR (kWh/cm^3)	*0.037*	*0.048*	*0.024*
Eco-indicator (/kWh) [8]	*0.57*	*0.57*	*0.57*
Environmental Impact	*0.021*	*0.027*	*0.014*

Environmental Impact = ECR × Eco-indicator

Table 2. Environmental Impact of SLA Process

Process *SLA*	***Project*** *Environmental effect for 1* cm^3 *material processed*		
Equipment *SLA-250, SLA-3500, SLA-5000*	***Environmental impact index*** *Eco-indicator*		
	SLA-250	***SLA-3500***	***SLA-5000***
Material preparation			
SLA 5170 Epoxy resin	*0.0104*	*0.0104*	*0.0104*
Part build			
Energy use	*0.021*	*0.027*	*0.014*
Disposal			
Landfill/Incineration	*4.03e-5/0.0021*	*4.03e-5/0.0021*	*4.03e-5/0.0021*
Total Impact	*0.0314/0.0344*	*0.0374/0.0404*	*0.0244/0.0265*

B. Assessment of Two Rapid Tooling Processes

3D KelTool and the SFM based electroforming process are two indirect rapid tooling processes. Indirect tooling requires a master pattern built by SFM process. At least one intermediate step is needed. The intermediate steps may include shape replication and sintering or burning in the manufacture of the production tool.

3D Keltool process [14] can be used to rapidly create injection molds or die casting inserts. It begins with an SLA master pattern. The pattern is used to produce an RTV silicone rubber mold. Once the RTV mold is produced, it is then filled with a mix of tooling steel powder, tungsten carbide powder and epoxy binder. After this material has cured in the mold, this "green part" is sintered in a hydrogen-reduction furnace and the binder material is burning off. The final step is to infiltrate the sintered part with copper.

The SFM based electroforming process [13] can be used to produce EDM electrodes, molds and dies. First, an SLA pattern is fabricated. Then the pattern is metalized and electroformed in nickel or copper solution. When the desired thickness of metal shell is reached, the SLA pattern is removed by burning out. Finally, the metal shell is backed with other materials to form the production tool. Figure 3 illustrates the concepts of these two indirect tooling processes. When a cylindrical metal mold cavity is required to be manufactured, both 3D Keltool and SFM-Electroforming processes have this function, although they differ from each other in the type and amount of materials use and specific intermediate steps. If we are going to look into the environmental performance, the model introduced in section 2 can be used to assess them from the lifecycle viewpoint.

Unlike the assessment of SFM process in which only unit volume of material is considered, In evaluating indirect RT processes, the volume of final tool should be accounted in order to estimate the amount of intermediate material consumed. In the following assessment, the cylindrical mold cavity in figure 3 is used as an example with dimensions of diameter 50mm and height 60mm.

In the pattern building stage, we can use the assessment result for the SLA process and assume the two RT processes both use SLA 250 to fabricate the master pattern. The environmental impact for unit volume (cm^3) SLA material consumed is 0.0104. Since 3D Keltool uses the negative pattern and SFM-Electroforming uses positive pattern, different volumes of materials used yield different impact values for this stage. Here we assume the dimensions

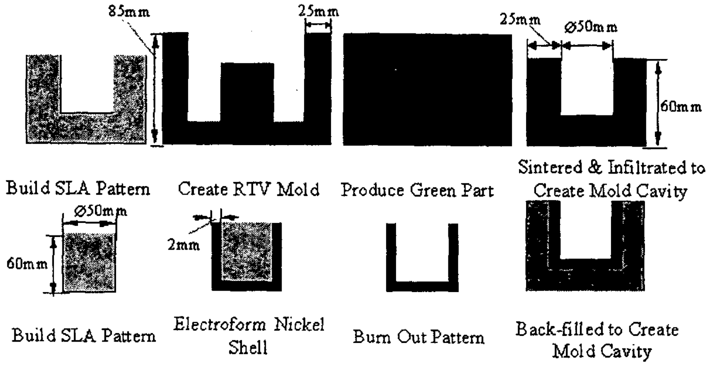

Figure 3. Indirect Tooling Process

of the mold is 100mm diameter and 90mm height. The volume of material used by the 3D Keltool process to build the pattern is 589.4cm^3 and that used by the SFM-Electroforming process is 117.2cm^3 In the mold creation stage, material consumption, and energy consumption during the sintering or burning step should be considered. In this stage, 3D Keltool typically consumes silicone rubber to build an RTV mold, uses mixed steel powder and epoxy binder to create the green part, and uses copper infiltration to create the final solid mold. The environmental indices for unit volume (cm^3) of silicone rubber, mixed steel, epoxy binder and copper are 0.0101, 0.133, 0.0104 and 0.757 respectively. The volumes of RTV mold can be calculated. The volumes of steel and epoxy binder are 70% of 30% of the mold volume respectively. Since the void volume of mold after sintering is 30% [13], the volume of infiltrated copper should be 30% of the mold volume. Therefore the material consumption impact in this stage can be estimated based on eco-indicators and the volume of materials used in this stage. Similarly, the SFM-Electroforming process usually uses nickel to electroplate certain thickness of metal shell, and then backfilles the shell with aluminum. For unit volume (cm^3) of nickel and aluminum, the environmental indices are 0.757 and 0.0486, respectively. The nickel shell thickness is typically 2mm. So the volume of nickel and aluminum used also can be calculated. Hence we can get the material consumption impact in this stage for SFM-Electroforming process. The results can be seen in table 4. Sintering & infiltration in the 3D Keltool process and burning off in the electroforming tooling process require energy. The energy consumption is estimated based on the melting point or burning point, the specific heat and the assumed furnace efficiency.

In the disposal stage, the 3D Keltool process produces wastes such as SLA material and silicone. The SFM-electroforming tooling process only has residue of SLA material. If the process residues are all disposed to landfill, the environmental impact can be assessed by considering the impact indices and the volume disposed. The results are shown in table 4. In addition, we expect that the disposed tools can be recycled by material recovering. The mixed metal of the tool made by 3D Keltool is less preferable than laminated nickel and aluminum used in the electroforming tooling process. The impact indices for recycling unit volume (cm^3) of mixed steel, nickel, and aluminum are -0.0226, -0.312, and -0.035 respectively. Table 3 shows the assessment results for the above two indirect RT processes.

From the above assessment, we can see that the environmental performance of a rapid tooling process depends on several factors. First, the selection of the base SFM process is an important factor. It is desirable to select an SFM process that has good environmental performance Secondly, the tooling materials, and process residues can further impact on the environmental performance due to the use of natural resources and possible generation of process residues. Finally, the method of disposal or recovery of tool material will also influence the total environmental performance of a process.

VI. CONCLUSION

A lifecycle based process model for analyzing environmental performance of SFM processes and SFM based rapid tooling processes is extended for analyzing SFM based RT processes. The process environmental performance assessment model considers material, energy, and disposal scenarios. The material use, process parameters (e.g. scanning speed) and power use can affect the environmental consequence of a process when material resource, energy, human health and environmental damage are taken into account. The presented method is applied to the SLA process and two SLA based rapid tooling processes. The method can be used to compare different RP and RT processes in terms of their environmental friendliness.

Table 3. Environmental Performance of RT Process

Process 3D KelTool SFF based Electroforming Tooling	**Project** Environmental effect for RT processes	
Base SFF process SLA	**Environmental impact index** Eco-indicator	
	3D KelTool	SFF-Electroforming
Pattern build		
• Material use	6.13 (epoxy resin)	1.22 (epoxy resin)
• Energy use	12.38 (energy used in pattern building)	2.46 (energy used in pattern building)
Mold creation		
• Material use	193.7 (silicon rubber + mixed steel powder + epoxy binder + infiltrated copper)	46.21 (nickel + aluminum)
• Energy use	0.707 (energy used in sintering and infiltration processes)	0.0191(energy used in burning off process)
Disposal		
• Process residues landfill	0.088 (epoxy resin + silicon rubber)	0.033 (epoxy resin)
• Material recovery	-64.49 (mixed steel + copper)	-26.67 (nickel + aluminum)
Total impact	148.52	23.24

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