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Energy performance evaluation and improvement of unit-manufacturing processes: injection molding case study

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ABSTRACT

In an effort to make more sustainable decisions, industry seeks reliable methods to assess and compare sustainability for manufacturing. Sustainability characterization is intended to provide such a reliable method to access and track sustainability information. As a step towards developing a standard reference for sustainability characterization of unit-manufacturing processes, in this paper, we focus on injection molding with energy as a sustainability indicator. This paper proposes a science-based guideline for energy: (i) prediction, (ii) benchmarking and performance evaluation, and (iii) improvement, for unit-manufacturing processes, which unlike the previous methods does not require a physical benchmark. We discuss in detail the steps of the proposed guideline for the injection molding process. The guideline considers different influencing factors such as part geometry, material-related physical and processing properties, and the manufacturing equipment information. The guideline is implemented by developing a user friendly system, and is demonstrated by a case study. We expect this work to contribute to the development of a standard reference methodology to help further sustainability in the manufacturing sector.

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1. Introduction

With the increasing cost and scarcity of energy resources, saving energy is getting more attention of the policy planners. The major energy consuming sectors in the world are: industrial, transportation, residential and commercial, their combined total energy consumption being over 500 EJ[3] (EIA, 2014). Nearly one third of the total global energy demand and resulting CO_2 emissions are attributable to the industrial sector in which manufacturing is a major part. Energy intensity is one of the important indicators for assessing sustainability performance of manufacturing (OECD, 2011).

Manufacturing enterprises need to consider and initiate the implementation of energy assessment and energy quota practices to improve both their economic benefit and environmental performance (Wang et al., 2013). Unfortunately, methods and tools to support such energy performance evaluation and improvement are not available. Today's industry employs life cycle assessment (LCA) tools to assess the sustainability performance (including energy performance) of a product's life cycle. Such a sustainability assessment is predominantly based on the weight of a product's constituting material, ignoring the manufacturing factors, such as part design, manufacturing equipment used, and processing conditions. Despite the application of LCA tools to assess and compare energy footprints of alternative product designs, their usefulness to compare energy performance of alternative manufacturing scenarios is limited.

To help the U.S. industry, it is pertinent to develop the needed measurement science methodologies and related standards to evaluate and improve sustainability of manufacturing processes (Mani et al., 2014). Focusing on energy alone, the U.S. industrial sector consumes about 31 % of the total energy (EIA, 2014; Elliott, 2007). The work presented in this paper is a step towards improving the energy competitiveness.

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[3] EJ = 10^{18} J.

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Nomenclature

Symbol	
A_{part}	projected area of the part, cm^2
A_{total}	projected area of all the cavities, cm^2
C_p	heat capacity of the polymer, J/kg K
D	diameter of the injection screw, mm
d	depth of the part, cm
E_{cy_theo}	theoretical energy required for an injection molding cycle, J
E_i	energy required for the *i*th sub-process, J
E_{part}	per part energy consumption for the injection molding UMP, J
F_{sep}	separating force, kN
f_{i_k}	fraction of the energy of *i*th sub-process supplied by *k*th sub-system
H_f	polymer heat of fusion (zero for amorphous polymers), J/K kg
h_{max}	maximum wall thickness of the part, mm
L_s	maximum clamp stroke of the machine, cm
m	number of sub-processes in a UMP
n	number of cavities in the die
P_{inj}	machine injection power, kW
P_{basic}	power required for basic energy consuming units of the machine, W
P_{idle}	machine idle power, W
l	number of sub-systems of the manufacturing equipment
S	length of injection stroke[2], mm
T_{pol}	polymer temperature at the time of loading in the injection molding machine, K
T_{ej}	part ejection temperature, K
T_{pol}	temperature of the polymer at the time of its loading in the machine, K
T_m	mold temperature, K
T_{inj}	polymer injection temperature, K
T_{dry}	polymer drying temperature, K
t_d	dry cycle time of the machine, s
t_{cycle}	injection molding cycle time, s
t_{idle}	idle time of the machine for each cycle, s
t_r	mold resetting time, s
V_{inj_cap}	injection capacity, cm^3
V_{att}	practically attainable injection volume, cm^3
V_{part}	volume of the injection molding part, cm^3
V_{shot}	shot volume, cm^3
α	coefficient of thermal expansion of the plastic material, m/m K
λ	thermal conductivity, W/m
ρ	specific density of the polymer, g/cm^3
Δ	fraction of the part volume used in the gating system
ε	change in volume/unit volume of the polymer for a given decrease in temperature, m^3/m^3
γ	thermal diffusivity of the material, mm^2/s
η_k	efficiency of the sub-system *k*
$\eta_{machine}$	overall efficiency of the machine

Manufacturing a product or a component usually requires the integration of a number of unit-processes. *Unit-manufacturing processes* (UMPs) are the individual steps required to produce finished goods by transforming raw material and adding value to the work-piece as it becomes a finished product (National Research Committee, 1995). An effective science-based energy performance evaluation and improvement methodology for manufacturing must therefore consider the energy requirements at the unit-process level.

The scope of this paper is to develop a science-based guideline to estimate the energy consumption of UMPs, with the objectives of benchmarking, evaluation and improvement.

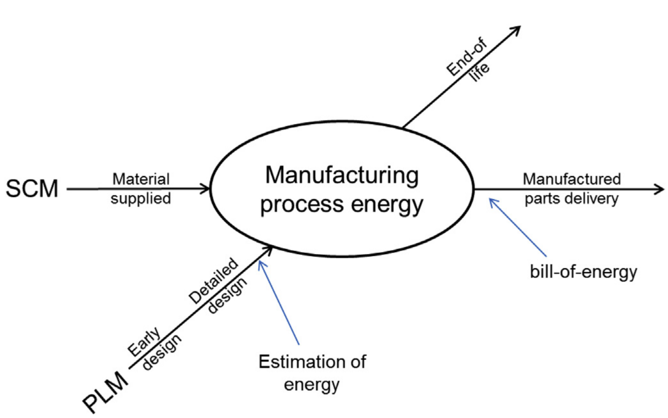

Fig. 1. A schematic showing manufacturing energy information use in design and manufacturing.

Estimating and evaluating energy consumption for manufacturing is useful: at early stages of the product development for decision support, to generate bill-of-energy, and to plan for energy performance improvement. As shown in Fig. 1, both early estimation and bill-of-energy of manufacturing process energy are useful for decision support in the product life cycle management (PLM), and for the supply chain management (SCM), respectively. With industry focus to integrate sustainability information in agile manufacturing systems (Calvo et al., 2008), the energy information at the process level has become more desirable.

We initially focus on the injection molding process to demonstrate the approach for energy performance evaluation and improvement, which will eventually contribute towards developing a standard reference methodology for UMPs. We selected the injection molding process for this study primarily because of its wide application in the consumer, automotive and industrial products. Another major reason is that the proposed guideline, with minor modifications can be used for other near net-shape manufacturing processes, such as casting, plastic fabrication processes and die-casting, which have great similarities with the injection molding process. Further, the extent of energy use in the injection molding process is well recognized (Gutowski et al., 2006), and it consists of a number of identifiable and controllable steps, required for energy performance evaluation and improvement. If we look at the cradle-to-gate energy

[2] The optimum value of the feeding stroke *S* is generally taken between 1D and 2D to ensure good quality parts. The maximum utilizable shot weight corresponds to feeding stroke of 3D.