Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE 2013
August 4-7, 2013, Portland, Oregon, USA

DETC2013-12634

SUSTAINABILITY CHARACTERIZATION FOR DIE CASTING PROCESS

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ABSTRACT

The manufacturing sector accounts for approximately one-third of the total energy consumption in the United States. Today, sustainable manufacturing has become an area of increasing interest, as companies look to reduce their manufacturing footprint and become more environmentally friendly. A science-based methodology, known as sustainability characterization, has the potential for providing companies a way to measure the sustainability of their manufacturing processes. In this paper, the sustainability characterization methodology was used to evaluate the sustainability of die casting unit manufacturing process. More specifically, a way to theoretically model sustainability, based on energy use, was investigated. Using the fundamentals of die casting processes, corresponding input-outputs were first mapped in terms of sustainability parameters and later equations to theoretically calculate the energy used in a die casting machine were identified/formulated. The theoretical energy equations provide a baseline for creating an information model that will eventually lead to creating a science-based methodology standard for sustainability characterization of unit manufacturing processes.

Keywords: sustainable manufacturing, manufacturing performance, characterization, assessment methodology

1. INTRODUCTION

Sustainability is a common word used today. The desire to protect the environment and reduce the use of natural resources is at the forefront of the minds of many, including those of manufacturing companies. The manufacturing sector is a key part of the U.S. economy, accounting for approximately one-third of U.S. energy consumption [1, 2]. Reducing energy consumption and associated energy costs through increased energy efficiency measures helps strengthen the economic vitality of U.S. manufacturers while also helping to protect our environment. Energy efficiency, as well as the cost and availability of energy, consequently have a substantial impact on the competitiveness and economic health of U.S. manufacturers [3]. Energy efficiency varies dramatically across industries and manufacturing processes, and even between plants manufacturing the same products [4]. Improved efficiency can also reduce the use of feedstock energy through greater yields, which means more products can be manufactured for the same amount of energy [3]. According to a McKinsey report, producers that take steps to increase resource productivity could reduce the amount of energy they use in production by 20 to 30 percent [5]. Increasing the efficiency of energy use could potentially benefit both industry and the nation.

Manufacturing plays a significant role in the U.S. economy and hence it is crucial to ensure that it is sustainable. The

Department of Commerce defines sustainable manufacturing as the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound [6]. Currently, manufacturing companies lack the knowledge and tools to effectively *measure* sustainability. Generally, the performance of manufacturing processes, in terms of sustainability, is measured based on the difference between the current performance and the desired performance. Unfortunately, the sheer complexity of the thousands of processes used in the manufacturing sector makes performance measurement a daunting task. There are, however, significant opportunities to address energy efficiency through well-founded science-based methods.

A science-based methodology, known as sustainability characterization will give companies a way to measure their sustainability [7, 8]. By modeling sustainability performance of a manufacturing process in this fashion, manufacturing companies transform their practices from ones based on human experience to science-based practices. Although human experience has taken the manufacturing industry far in the production of goods, science-based modeling will take manufacturing to the next level. Indicators, such as energy use, water use, and air emissions, are used to indicate the performance of a process by condensing large amounts of data into an easy to understand format. They can be used to set goals and monitor progress [9]. Performance indicators provide a foundation from which a model to measure sustainability can be built.

In this study, sustainability characterization was used as a guideline to analyze the die casting process in terms of sustainability. The inputs and outputs of a die casting process were studied in terms of sustainability and matched to corresponding performance indicators. Particularly, energy use as a performance indicator was examined in more detail. Existing energy models were researched. Finally, a theoretical energy model for a die casting process was created, using existing models as a baseline.

2. LITERATURE REVIEW

In recent years, sustainability analyses of manufacturing processes have become more prevalent. Various researchers have conducted life cycle analysis for particular manufacturing processes, and a few have reported theoretical energy models. A brief overview of the relevant papers studied as part of this research is presented.

A life cycle analysis of a die casting process was presented by Dalquist & Gutowski [10]. They specifically looked into the environmental impact of aluminum die casting. The life cycle aspects of die casting were broken down into four main parts: metal preparation, die preparation, casting, and finishing. The flow of energy and materials was presented in detail.

Similarly, Roberts [11] created a modified life cycle inventory (LCI) of aluminum die casting. His work looked to improve the existing life cycle inventory by adding manufacturing and other “costs.” This life cycle inventory went more in depth to include not only the major functions of the die casting process, but also small processes, such as transport of materials around the manufacturing plant. The life cycle inventory was represented in a way that is more meaningful to industry; in terms of cost. Using a Cost-Usage model to evaluate manufactured parts the research work determined that the life cycle assessment (LCA) has large inaccuracies due to variations in data, as well as process variations.

Brevick [12] looked more specifically into energy consumption as a performance indicator for die casting. In this research work, a survey was conducted with the members of the North American Die Casting Association (NADCA), to determine the amount of data available in the die casting industry and the quality of that data. It was concluded that the amount of available data is minimal. This research also created two computer-based models, iThink and TEAM, that can be used to determine the factors of manufacturing that affect energy consumption.

Thiriez & Gutowski [13] looked into the energy consumption of an injection molding process, using a theoretical approach. They analyzed the energy consumption trends of three different types of injection molding machines; hydraulic, hybrid, and all-electric. They created a model to represent the specific energy consumption trends exhibited by each of the machines. They also expanded slightly upon a theoretical energy model originally presented by Mattis et al. [14]. Mattis et al. created an energy-based process model that included the theoretical energy to melt the plastic and to inject the plastic into the mold. The model excluded the energy consumed during the packing, clamping, and ejecting stages because together they account for less than 25% of the total energy consumption.

These papers provided an understanding of the die casting process as a whole, the energy and material flows that occur throughout the process, and the areas of major energy consumption. An introduction to theoretical energy modeling was also presented, which provided a baseline for the theoretical energy model created in this study.

3. SUSTAINABILITY CHARACTERIZATION METHODOLOGY

In today’s competitive global market, production companies are being forced to create and deliver quality products while decreasing their environmental impact [15]. The transformation of manufacturing companies from environmental practices based on human experience to science-based practices can be achieved through a methodology known as sustainability characterization [8]. This characterization will include information for various performance indicators, which will be crucial in the determination of the sustainability of a manufacturing process. Specifically, this methodology will be applied to unit manufacturing processes (UMPs). UMPs are the individual steps that transform raw material into a finished product by adding energy [16].

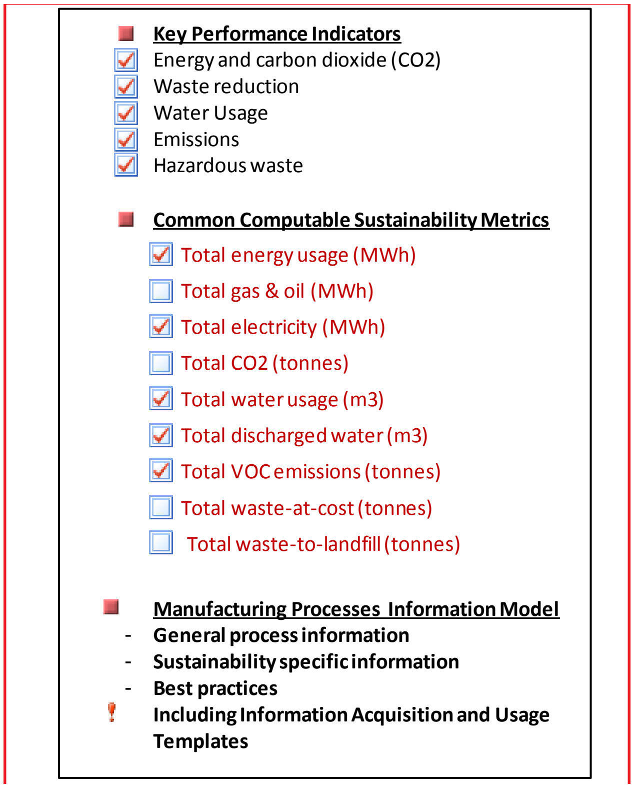

Figure 1. Sustainability Characterization components

The sustainability characterization methodology [8] primarily includes three main parts (See Fig. 1). The first part consists of defining the key performance indicators and their common computable metrics. Performance indicators can be broken down into two categories; input and output indicators. Examples of input indicators include water use, energy use, and material use. Examples of output indicators include product, solid waste, liquid waste, and air emissions [9]. The second part of the methodology involves determining analytics that can be used to calculate a UMP sustainability, and using the analytics to create an information model. The final part involves applying manufacturing process-specific data sets to provide evidence in support of the information models and enable execution of computable metrics.

An example of the methodology for die-casting can be seen as a logical model in Fig. 2 below.

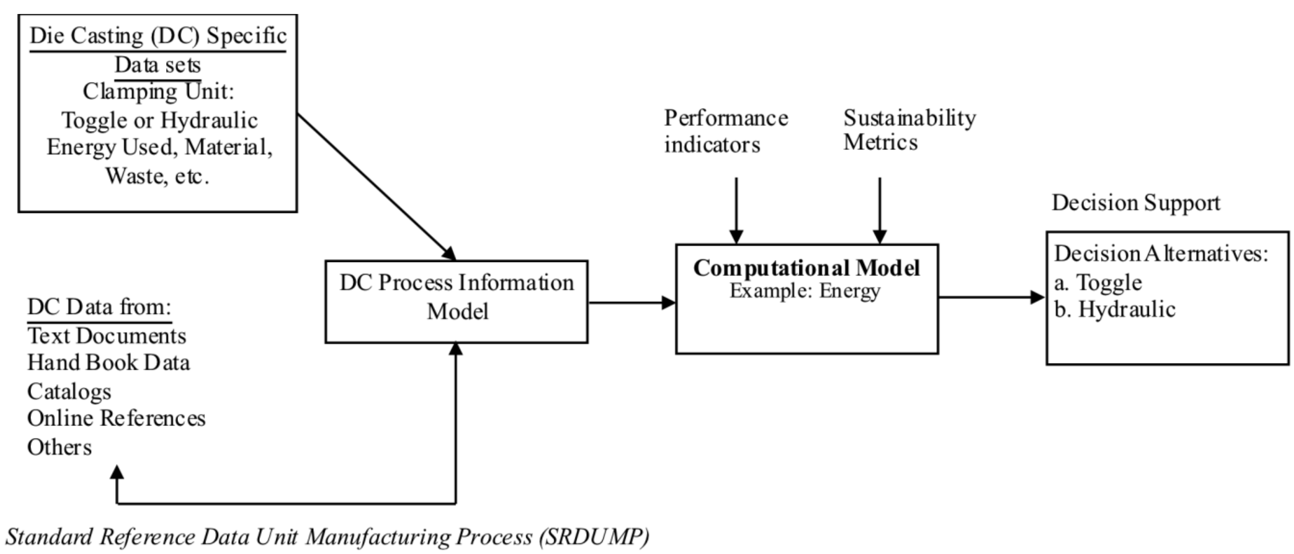

Figure 2. Example sustainability characterization for die casting

Nomenclature for Die casting

Q_s – Heat energy to heat alloy from ambient to solidus temperature
Q_f – Heat energy to heat alloy from solidus to liquidus temperature
Q_{sh} – Heat energy to heat alloy from liquidus to superheat temperature
V_{inject} – Volume of shot
H_s – Specific heat of alloy
H_f – Latent heat of fusion of alloy
T_a -- Ambient room temperature
T_s – Solidus temperature of alloy
T_l – Liquidus temperature of alloy
T_{sh} -- Superheat temperature
P_{inject} – Injection pressure
P_1 – Accumulator pressure
A_1 – Area of shot piston at inlet
P_2 – Exhaust pressure
A_2 – Area of rod end at outlet
A_t – Area of plunger tip
F_{close} – Force to close the die
F_{clamp} – Force to clamp the die
F_{open} – Force to open the die
F_{eject} – Force to eject the solidified part
d_{move} – Displacement of the die during closing/opening
d_{clamp} – Displacement of the die during clamping
$P_{cyl,1}$ – Average hydraulic system pressure (1)
$A_{cyl,1}$ – Cross-sectional area of clamping cylinder (1)
M – Mechanical advantage of toggles (if applicable)
$P_{cyl,2}$ – Average hydraulic system pressure (2)
$A_{cyl,2}$ – Cross-sectional area of ejection hydraulic cylinder (2)
d_{eject} – Displacement of ejector system

4. DIE CASTING UNIT MANUFACTURING PROCESS

Die casting is the process of injecting molten metal into a reusable mold, called a die. Die casting is used to produce parts with complex shapes and fine detail, as well as fastening holes. Die castings can be found in thousands of industrial, consumer, and commercial products [17]. The most commonly cast metals are aluminum, zinc, and magnesium [10].

Fundamentals of Die Casting
There are two types of high pressure die casting machines: cold chamber and hot chamber. Cold chamber machines are used to cast parts made of metal alloys with high melting temperatures, such as aluminum, brass, and some magnesium alloys. On the other hand, hot chamber machines are used to cast parts made of low melting temperature metals alloys, such as zinc, tin, and some magnesium alloys [18]. Hot chamber machines have a shorter cycle time than cold chamber machines. This is partly due to the fact that the time for the part to solidify is less because the metal is at a lower initial temperature [19]. In terms of machine functionality, the two machines use the same general process, the only difference existing in the injection system. Both machines can be broken down into three main components: the injection system, the clamping system, and the die assembly. Figures 3 and 4 show, respectively, a diagram of the cold chamber and hot chamber machines.

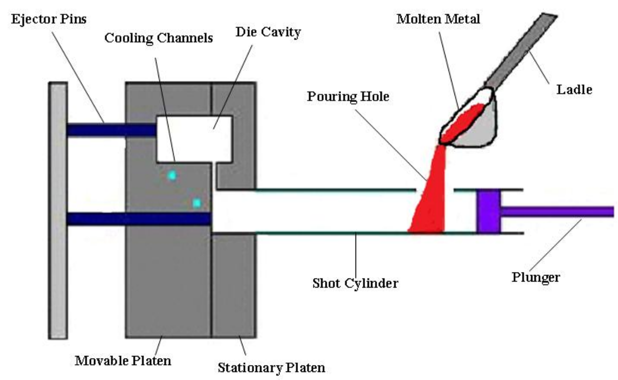

Figure 3. Cold chamber die casting machine

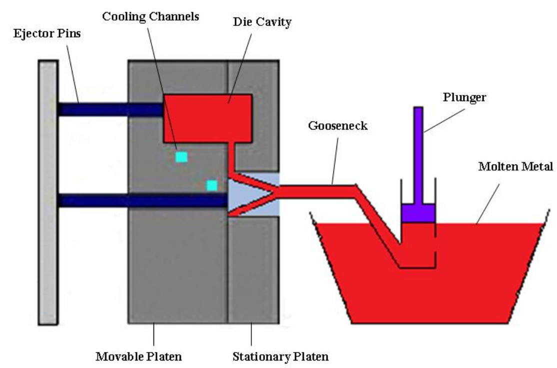

Figure 4. Hot chamber die casting machine

The general process for both machines involves the injection of molten metal into the die cavity via a shot cylinder. A hydraulically or pneumatically controlled plunger forces the molten metal into the die. The molten metal enters the die through a sprue, which is connected to a runner system to allow molten metal to flow to multiple cavities in the die. The molten metal remains in the die cavity until the metal has solidified. Cooling channels are built into the die, through which a cooling fluid, usually water, runs, to help cool the metal. Once the metal has solidified, the die is opened by the clamping unit, which is hydraulically controlled. An ejector system is initiated during die opening, either mechanically or hydraulically. The ejector system consists of ejector pins, which force the cast part out of the die as they move forward. Once the part is ejected, a lubricant is sprayed on the surface of the die for ease of removal of the next casting. The cast part removed from the machine is then transferred to a trim press.

Sustainability Aspects

Die casting is a highly energy intensive process. Approximately 25% of the total cost for die cast products is associated to energy consumption [12]. Of the total energy consumed at a die casting plant, approximately 50% corresponds to the melting of the metal in furnaces. This large energy consumption by the furnaces is due to the fact that furnaces run 24 hours a day and that reverberatory furnaces (most common furnaces used in die casting) have energy efficiencies between 15 and 40 percent [20].

In this study, the die casting UMP was examined in terms of environmental factors, such as energy consumption. The die casting process was subdivided into three main sub processes: melting, casting, and trimming. Each process was examined in terms of energy and material flows into and out of the process. The inputs and outputs flow were mapped as shown in Fig. 5.

For the purposes of this study, the casting process was of main interest. Therefore, the casting process was further subdivided into five operations: die preparation, clamping, injection, cooling, and ejection. Another version of the input-output diagram was created, separating the flows into the different operations. The expanded input-output diagram can be seen in Fig. 6.

The large box in Fig. 6 represents the system boundary of the casting process. A more thorough description of each process follows in the subsequent sections.

Melting

The *melting* process consists of the heating of the metal from ambient temperature to the superheat temperature by a furnace. Here it is assumed that a gas furnace is used, rather than an electric furnace, since gas furnaces are still more prevalent in die casting foundries [10]. As a result of using a gas furnace, combustion products are released inside the foundry. The melting process also includes the addition of flux to the molten metal to prevent oxides from forming on the surface of the melt, as well as the addition of "demagging" and "degassing" agents, which are used for removing magnesium and gas from certain metal alloys. Although flux is used, some dross (solid impurities on the surface of the metal due to oxidation) still forms and must be removed from the melt.

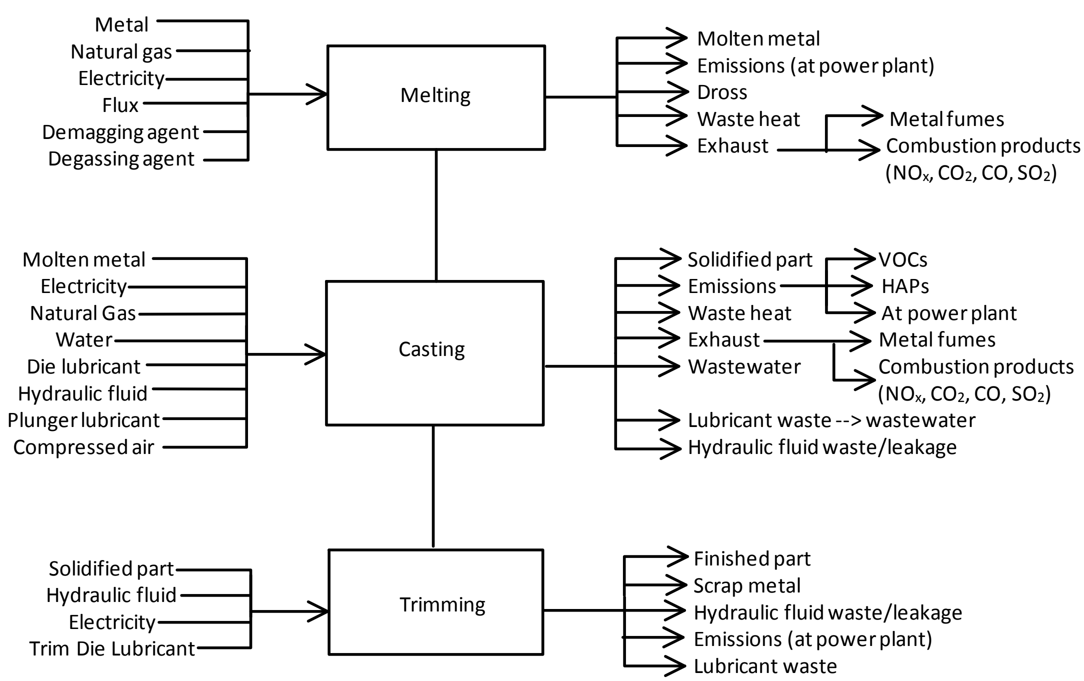

Figure 5. Input-output diagram

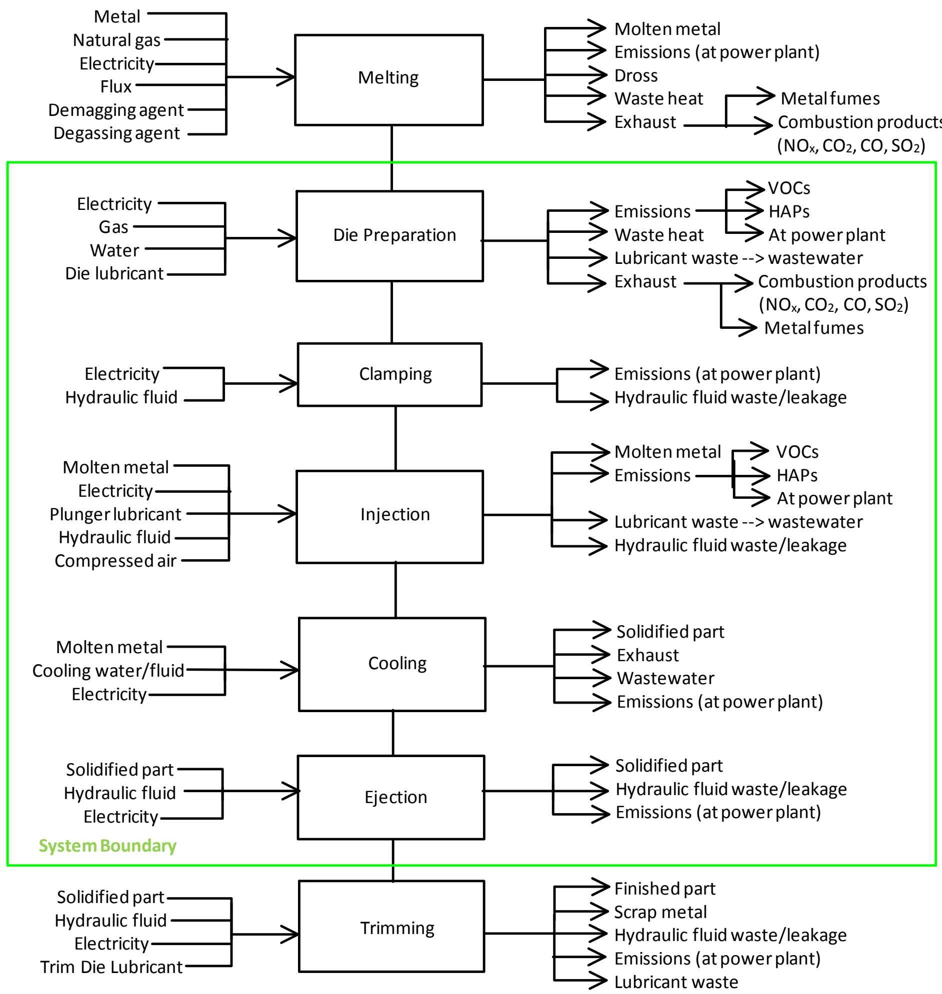

Figure 6. Expanded input-output diagram

Die Preparation

The *die preparation* operation consists of the cooling and lubrication of the die at the beginning of each cycle. Die lubricants only stick to the die in a particular temperature range; therefore, cooling water is sprayed on the die after a casting is removed, to cool the die. The use of lubricants has various environmental impacts. An electric pump is used to power the water and lubricant sprayer, which results in emissions at the national grid as a result of the use of electricity. Approximately 30% of the die lubricant used makes it onto the die surface, while the rest goes to waste [11]. Excess lubricant and cooling water is removed in wastewater. Finally, the decomposition of lubricants due to the heat of the die causes the release of emissions to the air, in the form of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). The amount and composition of each depends on the make-up of the lubricant [10].

Preheating of the die also takes place during this phase, when necessary. It is most commonly performed in magnesium and copper die casting. Preheating of the die can either be done in a furnace or with a gas torch; however the torch is more commonly used [10]. Once again, as a result of burning gas, combustion products are released into the die casting foundry.

Clamping

There are two parts to the *clamping* operation: the closing of the die and the application of the clamping force. Both parts, however, use the same system. Two main types of clamping units are employed in die casting machines: one uses a toggle mechanism, which is powered by a hydraulic cylinder, and the other is purely hydraulic, with the hydraulic cylinder connecting directly to the moveable/ejector die [21]. In terms of environmental aspects, both units have very few factors. Electricity is used to power both units, resulting once again in emissions at the national grid. The difference between the two systems is in the amount of electricity used. Besides energy, material usage is the only other significant sustainability factor.

Injection
The *injection* operation includes the lubrication of the plunger (for the cold chamber process) and the injection of the molten metal into the die cavity. Similar to the die lubricant, the plunger lubricant results in the release of VOCs and HAPs, the amounts depending on the composition of the lubricant [10]. Excess lubricant is removed to wastewater, along with any potential hydraulic fluid leakage. Electricity is used to power the plunger lubricant sprayer, as well as the hydraulic or pneumatic system that controls the plunger.

Cooling
The *cooling* operation involves the solidification of the molten metal within the die, through the circulation of cooling water. Cooling water is continuously pumped around the foundry in a closed loop, resulting in the constant use of electricity. "Dirty" cooling water is disposed of in wastewater [11].

The air flow out of vents machined into the die is also included in the cooling operation. Exhaust is released from the die as air trapped within the die casting machine is forced out by molten metal. Air occupying the die cavity and shot sleeve before the injection of the molten metal must be removed, along with the gas created by the decomposition of the lubricant upon contact with the hot die [19].

Ejection
There are two components to the *ejection* operation: the opening of the die and the ejection of the solidified part. The opening of the die is performed by the same means used in the *clamping* operation to close the die. Therefore, electricity is used again to power the clamping unit, and hydraulic fluid leakage may be disposed of in the wastewater system of the foundry.

Unlike the *clamping* operation, however, the *ejection* operation also includes an ejector system. The ejector system can either be hydraulically controlled or mechanically actuated [22]. In the latter, the ejector system is initiated during the die opening. During the opening, the die rams into a stationary ejector bar that is connected to a rear platen. This, in turn, drives the ejector system forward, pushing the solidified part out of the die. This ejection system has no environmental impacts. On the other hand, the hydraulic system simply uses another hydraulic cylinder to control the movement of the ejector system. The environmental impacts are the same as those for the closing and opening of the die.

Trimming
The *trimming* process involves trimming off any flash (molten metal that seeped out of the die cavity during casting), the runners, and the sprue from the solidified part. For the purposes of this study, a trim press is assumed to be used. The trim press operates similar to the die, in that it is divided into two halves, is hydraulically controlled, and a lubricant is applied to the press prior to the trimming. As a result, emissions from electricity use are released and hydraulic fluid and lubricant waste are removed in the wastewater system.

5. THEORETICAL ENERGY ANALYSIS
One way to *measure* the sustainability of a die casting process is by comparing the theoretical energy consumption of the die casting machine to the actual energy consumed. The theoretical energy consumed during the melting and casting processes was therefore examined in this study.

The theoretical energy model for total energy consumption originally proposed by Mattis et al. [14] was used as a baseline for the analysis. This model, which is used to represent the energy consumed by an injection molding process, is represented by Eq. (1).

$$E_{total} = E_{melt} + E_{fill} + E_{pack} + E_{clamp} + E_{eject} \quad (1)$$

Here, E_{total} represents the total energy consumed, E_{melt} represents the energy to melt the plastic, E_{fill} represents the energy to fill the die cavity, E_{pack} represents the energy required during the packing stage, E_{clamp} represents the energy to clamp the die, and E_{eject} represents the energy required to eject the finished part from the die. Since die casting and injection molding exhibit similar processes, this model could be appropriately used to model die casting, with the exception of the packing energy because there is no packing stage in the die casting process. The die casting energy model is represented by Eq. (2).

$$E_{total} = E_{melt} + E_{fill} + E_{clamp} + E_{eject} \quad (2)$$

Here, E_{melt} represents the energy to melt the metal in the furnace. Each term in Eq. (2) was analyzed separately to determine equations that can be used to calculate the theoretical energy of each sub-process.

Melting Energy
The energy to melt the metal for one casting from the ambient temperature to the superheat temperature is based on thermodynamics and the concept of enthalpy. The equations, originally proposed by Andresen [19] are shown below in Eq. (3-6).

$$E_{melt} = Q_s + Q_f + Q_{sh} \quad (3)$$

$$Q_s = V_{inject} H_s (T_s - T_a) \quad (4)$$

$$Q_f = V_{inject} H_s (T_l - T_s) + H_f V_{inject} \quad (5)$$

$$Q_{sh} = V_{inject} H_s (T_{sh} - T_l) \quad (6)$$

Here, Q_s represents the heat energy to heat the alloy from the ambient temperature to the solidus temperature, Q_f represents the heat energy to heat the alloy from the solidus temperature to the liquidus temperature, Q_{sh} represents the heat energy to heat the alloy from the liquidus temperature to the superheated temperature, and V_{inject} represents the shot (total amount of metal injected into the die) volume. The specific heat (H_s), latent heat of fusion (H_f), solidus temperature (T_s), and liquidus temperature (T_l) are all given for a particular metal alloy, while the ambient room temperature (T_a) can be determined using a simple temperature measuring device such as a thermostat. The superheat temperature (T_{sh}), on the other hand, must be determined by the manufacturer based on the desired gate injection temperature [19].

Filling Energy

The energy to inject the molten metal into the die cavity is dependent on the shape of the cavity itself. Mattis et al. [14] proposed an equation for calculating the energy consumed during the filling of a die cavity for a flat plate. However, there are so many possible mold designs that a simplified model was used for this study. This model uses a simple work equation based on the average injection pressure and the volume of the shot. The resulting model is given by Eq. (7).

$$E_{fill} = P_{inject}V_{inject} \tag{7}$$

P_{inject} represents the injection pressure. The average injection pressure is determined based on the average pressure applied to the piston in the hydraulic cylinder [19]. Figure 7 shows a schematic of the hydraulic piston/plunger setup. The following Eq. (8) is used to calculate the average injection pressure.

$$P_{inject} = \frac{P_1A_1 - P_2A_2}{A_t} \tag{8}$$

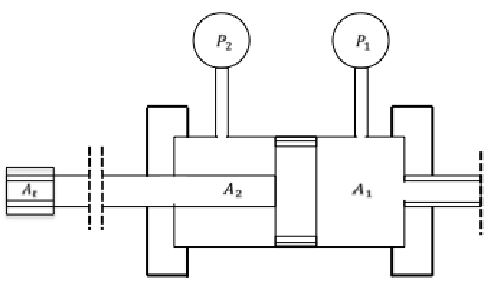

Figure 7. Piston/plunger schematic

P_1 represents the accumulator pressure, P_2 represents the exhaust pressure, A_1 represents the area of the shot piston at the inlet, A_2 represents the area of the piston minus the area of the rod, and A_t represents the area of the plunger tip. The accumulator and exhaust pressures of the hydraulic cylinder can be determined by placing pressure transducers in the feed lines, while the shot volume is predetermined by the manufacturer [19].

Clamping Energy

According to Mattis et al. [14] the packing, clamping, and ejecting energy account for less than 25 percent of the total energy consumed in the injection molding process. Models of these energy components were therefore neglected from their study. Furthermore, no other existing models for the theoretical energy consumption were found. Therefore, equations for the clamping and ejecting energy were formulated using similar principles to those already mentioned.

The energy necessary to clamp the die is broken into the same two parts as in the *clamping* operation. A simple work equation is used to represent the energy to close and clamp the die, which is represented by Eq. (9).

$$E_{clamp} = F_{close}d_{move} + F_{clamp}d_{clamp} \tag{9}$$

Here, F_{close} represents the force to close the die, F_{clamp} represents the force to clamp the die, d_{move} represents the displacement of the die during closing/opening, and d_{clamp} represents the displacement of the die during clamping. For both parts, the force is based on the hydraulic pressure applied by the clamping unit. In the case of the toggle clamp, the mechanical advantage provided by the linkages is accounted for with an extra variable, M [23]. Equation (10) represents the clamping unit forces.

$$F_{close} = F_{clamp} = P_{cyl,1}A_{cyl,1}M \tag{10}$$

Here, $P_{cyl,1}$ represents the average hydraulic pressure of cylinder 1, $A_{cyl,1}$ represents the cross-sectional area of hydraulic cylinder 1, and M represents the mechanical advantage of the toggles. Note that although the clamping and closing forces use the same equation, the hydraulic pressures are different because they refer to the pressure at different times. Also note that the pressure is an average pressure. Once again, a pressure transducer can be used to determine the hydraulic pressure. Linear displacement detectors can be used to measure the displacement of the die during closing, while a strain gauge placed on a tie bar (bar connecting the moveable platen to the rear platen) can be used to measure the displacement during clamping.

Ejection Energy

Similar to the clamping energy, the ejection energy is broken down into the two same parts as in the *ejection* operation. Once again, a simplified work equation is used to represent the energy to open the die and eject the part. This is represented by Eq. (11).

$$E_{eject} = F_{open}d_{move} + F_{eject}d_{eject} \tag{11}$$

F_{open} represents the force to open the die, F_{eject} represents the force to eject the part, and d_{eject} represents the displacement of the ejector system. In this case, however, the force to open the die is different from the force to eject the part because two different hydraulic cylinders are used. This model assumes that a hydraulic ejection system is used. The opening and ejection forces are represented by Eq. (12) and (13).

$$F_{open} = P_{cyl,1}A_{cyl,1}M \quad (12)$$

$$F_{eject} = P_{cyl,2}A_{cyl,2} \quad (13)$$

Here, $P_{cyl,2}$ represents the average hydraulic pressure of cylinder 2 and $A_{cyl,2}$ represents the cross-sectional area of hydraulic cylinder 2. A pressure transducer can once again be used to determine the hydraulic pressure. The ejection distance is predetermined and set before the machine is used. As a rough estimate, the ejection distance is equal to the maximum depth of the ejection die plus $^1/_8$" to ¼" [24].

Combining all of the above energy equations, the total theoretical energy consumed by a die casting UMP can be determined and used to measure the sustainability of the process.

6. CONCLUSION

The ability to measure the sustainability of a manufacturing process is becoming more important today. A science-based methodology, known as sustainability characterization, can be used to measure the sustainability. There are three parts to the methodology, including determining key sustainability performance indicators and their corresponding computable metrics, developing information models using analytics to measure the performance indicators, and using process-specific data sets to instantiate the information models. This methodology was used as a foundation for this study, which looked to examine the key performance indicators of a die casting process and determine analytics that can be used to calculate the energy consumption of a die casting machine. The energy and material flows were mapped to the sub-processes of the die casting process and theoretical energy equations were identified and formulated for the process. Future work should include performing a case study to verify the validity of the proposed energy equations, besides demonstrating sustainability assessment. The theoretical energy equations compiled in this study provide a baseline for creating an information model for a sustainable die casting unit manufacturing process.

DISCLAIMER

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