LIFE CYCLE ANALYSIS OF CONVENTIONAL MANUFACTURING TECHNIQUES: DIE CASTING

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ABSTRACT

A system-level environmental analysis of die casting based on aggregate national data and representative machine characteristics could be applied to design and manufacturing decisions where environmental impact is accounted for. By examining the life cycle of a process, it is possible to consider the environmental impact of the metal forming process as well as the impact of associated processes such as metal preparation and die preparation. The emphasis on aluminum high-pressure die casting reflects the current state of the industry and its environmental footprint. An energy analysis exposes the clear and significant environmental benefits of the use of secondary aluminum. Analysis of material byproducts gives less straightforward solutions, where improvement on one field comes at the cost of another.

INTRODUCTION

Die casting is a manufacturing process used to produce a part in near-net shape with high dimensional accuracy and a good surface finish in a short cycle time. Molten metal, most commonly aluminum, is forced into the cavity of a reusable steel mold (the die) under high pressure. The metal is driven through the feed system while air escapes through vents. There must be enough metal to overflow the cavity, such that a complete part will be cast. Once full, the pressure on the mold is increased during solidification. The die halves are separated and the part released.

Auxiliary functions of the manufacturing process that must be included in the life cycle analysis include mold (die) preparation, metal preparation, and finishing (Figure 1). Die preparation involves the machining of the die and its preparation for each casting. Though a die can be reused for many castings, between castings it must be relubricated to facilitate release. Meanwhile, the charge metal is melted and any oxidized metal is removed to scrap. Once the part is released after casting, some machining and cleaning has to be done to, at least, remove the traces of the feed system and any flashing. A variety of other treatments can be done to meet specifications.

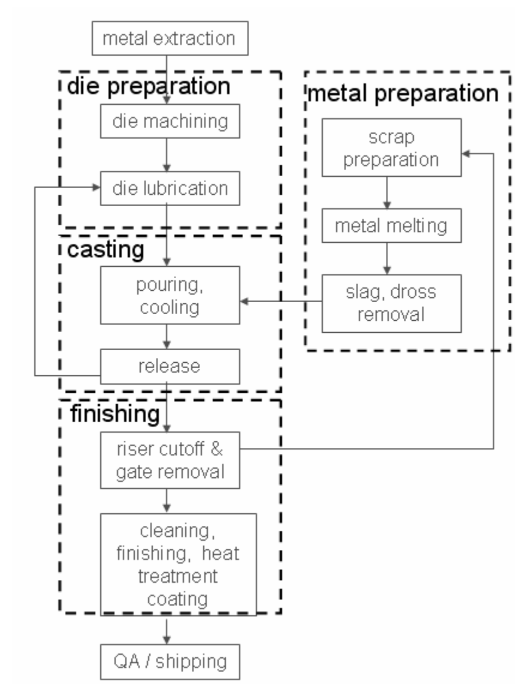

Figure 1. Major functions within the die casting process.

As part of a life cycle inventory of the manufacturing process, the energy and material flows through the foundry must be accounted (Figure 2). Die casting uses significant quantities of energy, as well as materials like oil-based lubricants and cooling water.

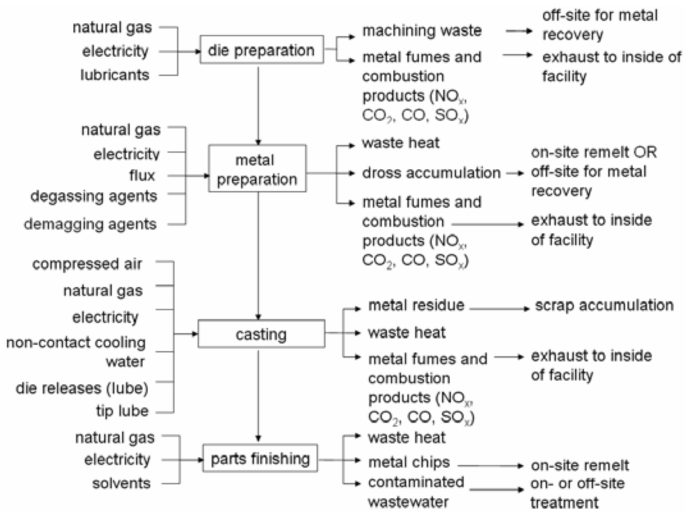

Figure 2. Profile of major flows at a die casting foundry.

It is not uncommon for furnaces and die casting machines to last for decades, allowing the manufacturing of the machine to be considered negligible for each cast part. Dies can be used on the order of 10^5 or 10^6 castings, depending on the melting temperature of the cast alloy. The environmental effects of equipment manufacture can then be amortized over the many years of service.

This analysis focuses on the activities which occur within an aluminum foundry doing high-pressure die casting. Sometimes, die making and finishing are outsourced away from the foundry, but they are included in the analysis because of their importance in defining the process and the finished product.

DIE MANUFACTURING AND PREPARATION

Dies are typically machined from tool steel. Dies last between 15,000 and 500,000 castings, depending on the casting temperature of the alloy (Boothroyd, et al., 1994). Dies for aluminum, a moderate-temperature alloy, have an expected lifetime of 100,000 castings.

Dies are a large capital investment, especially for small firms, and their cost must be distributed over a long use phase. Similarly, the environmental investment in die-making can be amortized over the 100,000 casting lifetime. A die for 170 cm^3 of casting requires a shot size of 370 cm^3, including overflow wells and feed system (Boothroyd, et al., 1994). Removing that much metal from 800 cm^3 of stock requires 4300 kJ (Dahmus and Gutowski, 2004). Steel typically has a high recycled content, upwards of 80% (US EPA, 2002), which is carefully sorted to control alloy specifications. The die then has an embodied energy content of 84 MJ, which represents 9 MJ per kilogram of recycled steel (collection, processing, etc.) and 31 MJ per kilogram of virgin steel (extraction, refining, etc.) (Chapman, 1983) or 0.043 kilojoules per casting.

Lubricants are used both in making the die and preparing the die for each casting. Oil-based cutting fluids are the most popular for machining, such as when making steel dies for casting (Dahmus and Gutowski, 2004). They frequently include naphtha, and, despite being diluted to 95% v/v with water, release more volatile organic compounds than their water-based counterparts. To make the representative die considered above would require 0.04 L soluble oil cutting fluid and 0.8 L water diluent.

Both oil-based and water-based lubricants are commonly applied to the die and plunger tip before casting. On the die, lubricants act as releasing agents. The sample cast part requires about 0.13 liters die lube and 0.002 liters of tip lube (Roberts, 2003a). Despite the seemingly small volumes, oil-based lubricants are a major source of air releases from die casting facilities, as reflected in the Environmental Protection Agency's Toxics Release Inventory (EPA TRI) for aluminum die casting, standard industrial code (SIC) 3363 (Figure 3). Actual emissions vary with the composition of the lubricant, but typically volatile organic compound (VOC) emissions are associated with oil-based lubricants. Products containing alkylbenzene sulfonate, 1,2-epoxypropane, alkylether, and poly(oxyethylene) nonyl phenyl ether are commonly used (SCE, 2001). Water-based lubricants have lower VOC emissions, but may be associated with increased hazardous airborne particle (HAP) emissions (US EPA, 1996). Cumulative VOC emissions are around 1 kg per tonne of produced casting (Roberts, 2003).

Throughout the die casting process, because of the proprietary nature of the input compounds and the wide variety of reactions that can occur, the exact composition of VOCs is not as closely monitored or regulated as the total emission of VOCs. VOCs include any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions (US GPO, 2003).

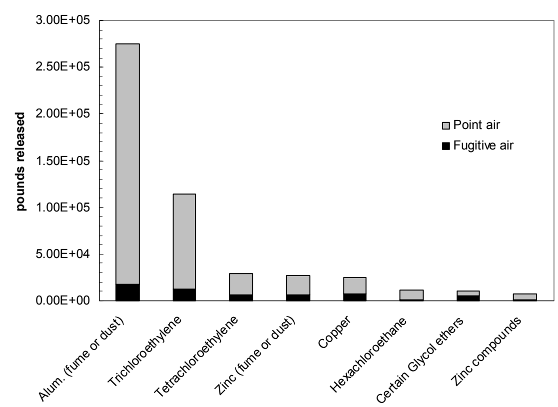

Figure 3. Top TRI air releases for aluminum die casting SIC show high contribution of VOCs. The top air releases are metal compounds, cleaning fluids (ethylenes) or lubricants (glycol ethers). Source: US EPA, 1998.

In some foundries, dies are preheated to reduce thermal stress and extend die life. This is most common in dealing with high-temperature copper and magnesium alloys (US DOE, 1999). Preheating can be done in a furnace, but is most commonly performed by applying a gas torch.

METAL PREPARATION

Aluminum is the most commonly die cast material in the US, followed by zinc and magnesium (Figure 4). In 2002, 570,000 tons of aluminum alone were die cast (US Census

Bureau, 2003). Small amounts of copper, tin, and lead are also die cast (US DOE, 1999). Die cast aluminum parts are in demand by many industries, and its relatively low cost and light weight ensure that it will be the dominant metal in the field for years to come.

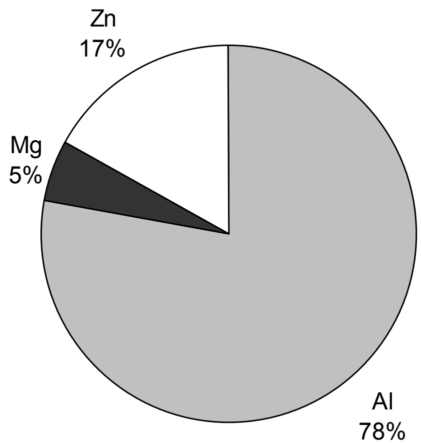

Figure 4. Metal distribution of US die casting in 2003. The total amount of die cast metal was 2.03 million tons. Source: Schifo and Radia, 2004.

A representative aluminum die caster uses bout 28% scrap metal by mass. The remainder, based on US Census Bureau data (US Census Bureau, 2003), is new material. Higher quantities of new metal allow greater control over alloy contents and reduce the metal loss due to dross formation. Scrap metal is prone to increased dross formation because the scrap is predisposed to being contaminated with lubricants which burn off, creating an oxidizing environment in the furnace around the lubricant and flux. As much as 80% of dross comes from the melting of scrap metal. Additional metal loss occurs when raking dross from the top of a furnace, for a total direct metal loss around 5% (Roberts, 2003a).

Reverberatory furnaces are the most common type of furnace used in aluminum die casting foundries. Reverberatory furnaces use wall mounted burners to radiate heat from the refractory wall to the metal inside. Though typically fired by natural gas, electric reverberatory furnaces are available, and are primarily used as holding furnaces. Many foundries have more than one furnace – one used for melting metal and another for holding molten metal. The same types of furnace can be used for both purposes, but furnaces that are designed for efficient melting are less efficient at holding molten metal (Upton, 1982). Other techniques allow optimization of furnaces for the two functions. For example, it is recommended to keep melt furnaces at near capacity for efficiency.

Energy requirements for holding furnaces are typically much lower than for melting furnaces, simply due to the high energy requirements of melting metals. An average melting furnace like that in Table 1 has an efficiency around 40%, requiring 2.5 times more than the theoretical minimum to melt the metal (Dalquist and Gutowski, 2004). This is in agreement with other published gas-fired furnace efficiencies for melting aluminum (Broadbent, 1991).

	MJ/kg	m^3 natural gas/kg
Melting furnace	2.465	0.08
Holding furnace	0.493	0.02

Table 1. Natural gas use per kilogram aluminum cast for a typical melting and holding reverberatory furnace in an aluminum die casting foundry. Source: Bergerson, 2001.

Overall, natural gas fired furnaces are much more common than electric furnaces in die casting foundries. Despite lower efficiency at the plant (Broadbent, 1991), variable costs for natural gas are markedly lower than for electricity (EIA, 2002). 2002 energy use in aluminum die-casting foundries topped 10 million MWh, 85% of which was consumed as natural gas at the plant (Census Bureau, 2003). The remainder was consumed as electricity produced off-site (does not include losses in electricity generation and distribution). Much of that electricity was not even used in melting, but rather in other parts of the process with smaller tools and in auxiliary functions like administration.

The consumption of raw energy for melting causes emissions to the environment. Though gas-fired emissions are released at the foundry (Table 2), it is cleaner than electric-fired melting from the national grid when compared at the life-cycle scale.

	Fuel-fired	Electric
CO2	147 – 294	495
SOx	0.001 – 0.0015	2
NOx	0.175 – 0.35	1
VOCs	0.005 – 0.015	unknown
Particulate	0.0	unknown

Table 2. Emission factors for gas-fired and electric melting furnaces in kg/tonne. Electric emissions are based off the proportion of different energy sources on the US grid. Gas-fired emissions are based on data from US DOE, 1999.

Electric-fired furnaces would have to be penalized for electricity losses at the plant, such that the 2,958 kJ for melting and holding 1 kg of aluminum would require approximately 9,000 kJ at the plant (EIA, 2001). Emissions would vary by the source of the electricity, but based on the distribution of US energy generation (EIA, 2000), a MJ of electricity is accompanied by the generation of 167 g of CO_2, 0.7 g of SO_2, and 0.3 g of NO_x (EIA, 2002). Therefore, the melting and holding of 1 kilogram of metal for casting would result in the emissions of 495 g CO_2, 2 g SO_2, and 1 g NO_x.

CASTING

The high-pressure die casting process can be done in two different types of machines, known as hot-chamber and cold-chamber. Cold-chamber machines (Figure 5) are typically used for high-temperature metals such as aluminum and magnesium alloys. The die halves are first locked into the machine and the plunger retracted, as the molten metal is ladled into the shot chamber by way of a pouring hole. The plunger is moved back into the chamber, forcing the metal into the cavity. It remains in place and under pressure for the duration of the "dwell time" required to solidify the metal. After the metal solidifies, the die is opened and plunger returned to its initial position.

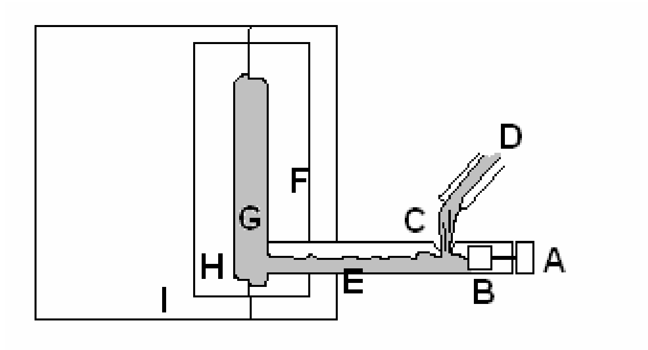

Figure 5. A typical cold-chamber die casting machine and its major elements.

A	Hydraulic cylinder	E	Shot sleeve
B	Plunger	F	Stationary die half
C	Pouring hole	G	Cavity
D	Ladle	H	Ejector die half
		I	Ejector platen

Adapted from Heine, 1967.

The hot-chamber machine (Figure 6) is typically used for alloys with low melting temperatures (Boothroyd, et al, 1994), such as zinc-, lead-, and tin-based alloys (DOE, 1999). In the hot-chamber machine, the plunger and cylinder do not get submerged in the metal.

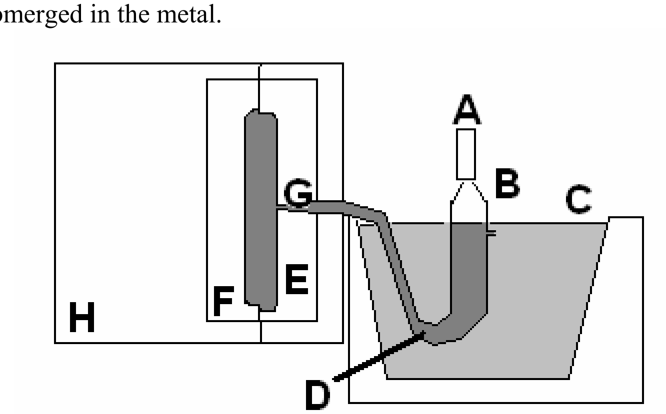

Figure 6. A typical hot-chamber die casting machine and its major elements.

A	Hydraulic cylinder	E	Cover die half
B	Plunger	F	Ejector die half
C	Molten metal	G	Nozzle
D	Gooseneck	H	Ejector platen

Adapted from Heine, 1967.

The machine itself typically runs on a 40 hp electric motor (Upton, 1982). Assuming one 8-hour shift a day for 250 days a year and 85 tonnes of material handled in a year (Upton, 1982), the representative casting machine uses around 2.5 MJ/kg of metal cast. This is on the same order of magnitude as the estimate made by Roberts, et al., (2003) of 1.8 MJ/kg.

The die casting machine is connected to an auxiliary system which provides cooling water used to maintain constant operating temperatures. One typical foundry uses two 90 kW pumps for water circulation, which consumes 0.75 liters per casting (Roberts, et al., 2003). The system increases the foundry energy needs by 0.65 MJ/kg of saleable casting.

Because the casting machine is powered by electricity generated off-site, the total energy consumption must include energy losses from production and distribution on the order of 6.5 MJ (EIA, 2001), for a total consumption of 9.7 MJ. Based on the national grid, this results in the emission of 418 g CO_2, 2 g SO_2, and 1 g NO_x (EIA, 2002).

Once solidified, the platen moves to allow ejection of the semi-finished part. The cast runner system must be removed before the part can be considered complete.

FINISHING

The part, once released from the die, is still attached to flashing and the extra cast bits of the feed system. It is typical to finish the casting by trimming the runner and overflows, then grinding away the sharp edges and any remaining flashing.
The product at this stage and the treatments still needed are similar to those performed after sand casting. The energy requirement for the finishing stage is around 1.2 MJ/kg (US DOE, 1999). Finishing by band saw and cutoff wheels can create dust and metallic particulates. Emissions can be controlled with hoods and ducts which pass the particulates into scrubbers. Cleaning the product can involve the use of abrasives or pressurized water, and is sometimes followed by the application of protective coatings. Although particle, HAP, and effluent pollutants are created in this stage, they are largely contained by filters.

RECYCLING AND WASTE

Part of the measure of the environmental burden created by die casting as a manufacturing process includes its use of recycled materials, recyclability of products at end-of-life, and the waste byproducts created during the process. In considering environmental factors in manufacturing design decisions, the process must be appropriately credited (or penalized) for its environmental burden.

The inclusion of 28% scrap metal in die cast metal input greatly reduces the environmental footprint of aluminum die casting. Preparation of secondary aluminum for a manufacturing process requires much less energy than the preparation of virgin aluminum (16 MJ/kg and 270 MJ/kg, respectively) (Chapman, 1983).

For the most part, die cast products are also highly recyclable, and there is a strong market for scrap aluminum (OIT, 2000). Additionally, the large quantity of cast parts sold to the automotive industry increases the likelihood that the material will actually be recycled at end-of-life.

Most emissions in die casting come from electricity generation or from the combustion of fuels used for furnaces. The emissions from electricity are based on the power source used at the plant. Use of natural gas allows trade-offs in emissions creation based on such characteristics as the combustion air temperature (higher combustion air temperature increases combustion efficiency, but also increases NO_x emissions) and the air-to-fuel ratio (a high ratio will reduce CO emissions, but lead to high NO_x emissions) (Bergerson, 2001).

Other releases come from the decomposition of lubricants under heat and the disposal of lubricants with wastewater. It is well-established that lubricants are beneficial to the process as releasing agents. Both oil-based and water-based lubricants pose environmental hazards. Both generate emissions of VOCs and particulate matter, though water-based lubricants have lower emissions levels of VOCs (US EPA, 1998). However, reducing VOC emissions alone does not necessarily indicate lower total emissions – water-based lubricants have also been associated with greater HAP emissions, which are related to the additives used to replace the solvents found in oil-based lubricants (US DOE, 1999).

In addition, small amounts of material are emitted to air during metal preparation. Excess sulfur hexafluoride from fluxing is sometimes emitted. Demagging agents can react to form aluminum chloride ($AlCl_3$). In the atmosphere, this can react to form aluminum oxide and hydrochloric acid (US EPA, 1996).

Decisions incorporating environmental factors will often end up considering trade-offs, rather than clear-cut solutions. The preferred resolution will also have to be compatible with local regulations, local pollution prevention priorities, and economic sense.

INDUSTRY TRENDS

Die casting is becoming increasingly important worldwide. Aluminum shipments for the year 2003 totaled 1.6 million tons (Schifo and Radia, 2004), a 5% growth from 2002. Increases in demand for die castings come from internal combustion engines and valve and fitting applications.

US Aluminum die casting facilities shipped $4.8 billion of product in 2002, a sharp increase over the $3.8 billion shipped in 2001 (US Census Bureau, 2003). Despite growth in sales, the US trends in die casting mirrors general downward trends in employment, as seen in other manufacturing fields (Figure 7).

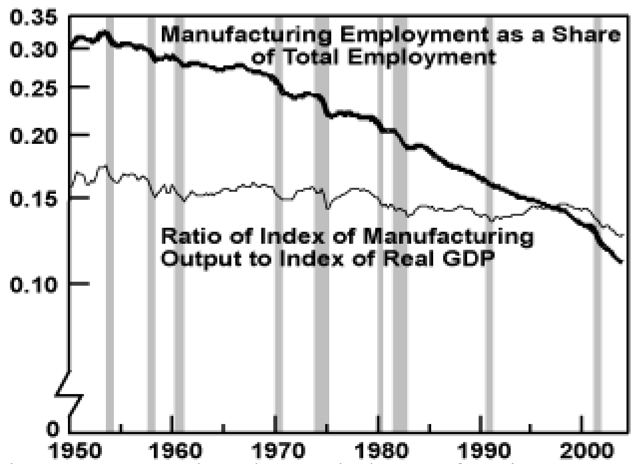

Figure 7. Output and Employment in the Manufacturing Sector. Source: US Congressional Budget Office, 2004.

The die casting industry in the US is increasingly threatened by overseas production facilities. Offshore production has forced the closure or consolidation of smaller companies. The total number of foundries decreases while the proportion of large foundries increases. This is apparent from US census data (Figure 8) (US Census Bureau, 2003).

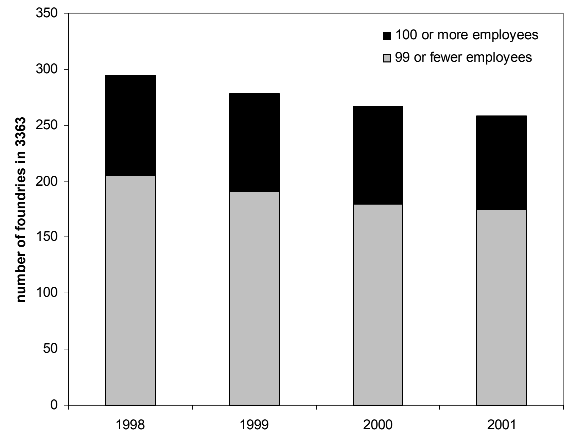

Figure 8. The number of small foundries has been decreasing at a greater rate than the number of large foundries, which have become a greater proportion of the US die casting industry.

The domestic environmental consequences are two-fold. More larger companies will result in increased transparency by way of requiring more foundries to report their environmental footprint. Secondly, the growing foundries may replace older equipment to reflect increased capacity, purchasing new machines designed with efficiency and environmental regulation in mind.

International environmental consequences are not so positive. Die casting is following assembly overseas, where both industries benefit from the significantly lower environmental standards than the United States. The myth of lower labor costs does not match reality. In one industry source in the US, labor is 14% of sales. The savings in labor in Asia are offset by higher material costs in China, where scrap prices are at least 20% higher than in the US, and material is often imported.

The increased demand for die cast parts is directly connected to the increase of the total environmental burden of die casting. Regulation, economic advantage, or environmental factors may drive these businesses to more benign practices throughout the manufacturing process.

Energy savings can begin even before reaching the foundry. In Europe, for example, it is common to ship molten aluminum to foundries from the aluminum supplier. This replaces the molding, solidifying, and re-melting of incoming aluminum, reducing energy requirements and subsequent emissions by 35% (Bergerson, 2001). It can also reduce labor, maintenance, and capital costs.

For continued holding and melting at the foundry, increased attention is being paid to heat recovery. Adding recovery units to concentrate waste heat for preheating metal is considered a good way to increase efficiency, but is not commonly done (Rogers, 2003a). Increased efficiency can be gained by monitoring charge weight, melting time, metered oxygen levels, and high temperature insulation (Broadbent, 1991). Redirecting this energy towards die-preheating can reduce total energy consumption at the foundry.

Volatile organic compound emissions may be released by replacing oil-based tip and die lubricants with water-based lubricants. Such substitution could make wastewater treatment easier, cheaper, and less energy intensive, but it may also increase emissions of (HAPs).

CONCLUSIONS

Within the foundry, the different major functions of the die casting process consume about 8 MJ of energy per kilogram (Table 3), and also release another kilogram of greenhouse gases from the foundry.

	Die Prep	Metal Prep	Casting	Finishing	Total
Energy (MJ)	~0.5	3.0	3.2	1.2	7.9
Including loss (MJ)	1.5	-	9.7	3.7	14.9
CO_2 (g)	85	147 – 294	418	200	850 – 997
SO_x (g)	0.35	0.001	2	1	3.35
NO_x (g)	0.15	0.25	1	0.4	1.8

Table 3. Energy, energy including losses in generation and distribution, and emissions per one kilogram of cast final product.

Given the current and rising demand for die cast parts, the environmental burden of the process must be understood in order to make sensible manufacturing choices for the future. The absolute numbers portray the current state of the industry, but are more valuable when considering the process in comparison with other manufacturing options. Analyzing the findings for one component can lead to improvements in the process and in design decision making with respect to environmental factors.

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REFERENCES

Bergerson, J. 2001. *Greenhouse Gas Emissions Inventory of Toronto Area Aluminum Billet Casting/Extrusion Facility*. University of Toronto: Toronto, Ontario, Canada.

Boothroyd, G., , Dewhurst, P., and Knight, W. 1994. *Product Design for Manufacturing and Assembly*. Marcel Dekker: New York, New York.

Broadbent, K. "Furnace Efficiency: A User's Guide." *1991 Joint Conference of the Australian Die Casting Association and the Australasian Institute of Metal Finishing*, 21-25 October 1991, Sydney, NSW.

Chapman, P.F. and Roberts, F. 1983. *Metal Resources and Energy*. Butterworth and Co., Ltd: Thetford, Norfolk, England.

Dahmus, J. and Gutowski, T., "An Environmental Analysis of Machining," *Proceedings of the 2004 ASME IMECE*, November 13-19, 2004, Anaheim, CA.

Dalquist, S. and Gutowski, T. "Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting," *Proceedings of the 2004 ASME IMECE*, November 13-19, 2004, Anaheim, CA.

EIA (Energy Information Administration). 2000. *The Changing Structure of the Electric Power Industry 2000: An Update*. Chapter 3.
eia.doe.gov/cneaf/electricity/chg_stru_update/update2000.pdf

EIA (Energy Information Administration). *1998 Manufacturing Energy Consumption Survey*. 2001.
www.eia.doe.gov/emeu/mecs/contents.html

EIA (Energy Information Administration). "Electricity InfoCard 2002," *EIA Home, EIA Brochures*. 2002.
www.eia.doe.gov/neic/brochure/elecinfocard.html

Heine, R.W., Loper, C.R., Jr., and Rosenthal, P.C. 1967. *Principles of Metal Casting*. McGraw-Hill Book Company: New York, New York.

OIT (Office of Industrial Technologies) Profiles and Partnerships. *Aluminum Industry Profile*. 2000.
www.oit.doe.gov/aluminum/pdfs/aluminum.pdf

Roberts, M.J. 2003a. *A Modified Life Cycle Inventory of Aluminum Die Casting*. Deakin University: Geelong, Victoria, Australia.

Roberts, M., Hu, E. and Nahavandi, S. 2003. "A Life Cycle Inventory of Aluminium Die Casting." *MACRO REVIEW Special Issue for The Review of Japan Macro-Engineers Society. Proceedings of the Asia-Pacific Conference on Sustainable Energy and Environmental Technologies*, pp. 256-260, Japan Macro-Engineers Society, Japan.

SCE (Society of Chemical Engineers). *Summary of Manuals for Estimating Quantities of Released and Transferred Chemical Substances.* March 2001.
www.prtr.nite.go.jp/english/pdf/summary1.pdf.

Schifo, J.F. and Radia, J.T. *Theoretical/Best Practice Energy Use in Metalcasting Operations.* Prepared under contract to the Advanced Technology Institute for the US DOE Industrial Technologies Program. May 2004.
www.eere.energy.gov/industry/
metalcasting/pdfs/doebestpractice_052804.pdf

Upton, B. 1982. *Pressure Diecasting Part 1: Metals – Machines – Furnaces*. Pergamon Press: Oxford, England.

US Census Bureau. *Statistics of U.S. Businesses: Aluminum die-casting foundries*. 16 December 2003.
www.census.gov/epcd/susb/1998/us/US331521.HTM .

US Congressional Budget Office. *Economic and Budget Issue Brief: What Accounts for the Decline in Manufacturing Employment?*

http://www.cbo.gov/showdoc.cfm?index=5078&sequence=0
18 February 2004.

US DOE (Department of Energy). *Energy and Environmental Profile of the U.S. Metalcasting Industry*. September 1999. www.resourcesaver.com/file/sectorstar/program_269.pdf

US EPA (Environmental Protection Agency). 1996. *Pollution Prevention Practices for the Die Casting Industry.* North American Die Casting Association: Rosemont, Illinois.

US EPA (Environmental Protection Agency). *EPA Office of Compliance Sector Notebook Project: Profile of the Metal Casting Industry*. US EPA Office of Compliance. 1998. www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/casting.html

US EPA (Environmental Protection Agency). *Economic Impact Analysis of the Final Integrated Iron and Steel NESHAP.* US EPA Office of Air Quality Planning and Standards. September 2002.
www.epa.gov/ttn/ecas/regdata/IPs/Iintegrated%20Iron%20and%20Steel_IP.pdf

US GPO (Government Printing Office). 2003. *Code of Federal* Regulations. 40 C.F.R. 51.100 (s).