EVALUATING ENVIRONMENTAL IMPACTS OF SAND CAST PRODUCTS USING LIFE CYCLE ASSESSMENT

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Global casting production is estimated to be over 100mT by the end of 2010. Sand casting is the most widely used process and accounts for 90% of all castings produced of which 95% belong to three materials — cast iron, aluminium and steel [1]. Sand casting is known to be resource intensive and environmental impacting manufacturing process.

The total environmental impact of sand cast products depends on part design, material, choice of melting furnace, percentage of secondary (recycled) material, and usage of cast product. Process parameters as pouring temperature, core making, mould making, and casting yield also influence the environmental impact. Above all energy model causes variations in these environmental impacts for various regions. Life Cycle Assessment (LCA) is performed considering above employing EDIP (Environmental Design of Industrial Products) methodology. System boundary includes raw material mining and extraction, manufacturing, transportation, use, and end of life. LCA of sand cast product can thus be useful in quantitative evaluation of the total environmental impact resulting from a cast product in lieu of traditional way of comparing the emission during manufacturing alone.

Keywords: Life cycle assessment (LCA), Environmental impact analysis, Metal casting.

1. INTRODUCTION

Metal casting is a primary manufacturing process for producing intricate parts in any metal that can be melted. Both ferrous as well as non-ferrous foundries are considered to be the major sources of hazardous air pollutants (HAP's) from processes such as melting, pouring, cooling, and shakeout [2]. Emissions in foundries have been identified, investigated and documented by various environmental protection agencies as well as by researchers. These emissions are traditionally evaluated and compared by the amount of various pollutants emitted per ton of melt. Apart from emissions to air there are considerable liquid and solid wastes due to the casting production. Each emission has a different impact on the environment, and it is necessary to quantitatively evaluate their potential impact (damage) to human health and ecology. In addition to emissions from the manufacturing (casting) process, adverse impacts on the environment occurring from the other life cycle stages such as mining, raw material extraction, distribution, use, and disposal (or recycle) along with emissions due to usage of energy at every step must be considered for the complete evaluation of the environmental impacts from the production and consumption of the cast product [3].

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Life Cycle Assessment (LCA) methodology encompasses the entire 'life cycle' of a product or process, expanding the alternatives as: land-filling, incineration, recycling, re-using, etc. [3]. Complete environmental impact analysis on local, regional and global level of various emissions during all life cycle phases of cast product can be performed employing LCA. This can help in identification of environmental hot spots in the product LCA which can be then focused for minimization. The purpose of this work is to evaluate the environmental impacts considering (1) commonly used cast metals – cast iron, aluminium and steel. (2) the choice of melting furnace (3) process parameters as pouring temperature, core making, mould making, metal to sand ratio, and casting yield (4) proportion of secondary material (5) usage of cast product and (6) energy model.

1.1. Goal

The goal of applying LCA is to examine the environmental impact of a sand casting process for three major cast materials – cast iron, aluminium and steel. LCA of cast products, require (1) determining the system boundaries (2) collecting energy and emission data as per the system boundaries (3) inventory classification and characterization as per LCA method and (4) interpretation of results.

1.2. System Boundaries

The overall system boundary for life cycle evaluation of sand castings is described in Figure 1. This is extension to those suggested by Dalquist and Gutowski, 2004 [4]. To incorporate cradle to grave analysis, the LCA of casting must track the environmental impact of the cast metal as well as mould material from mining phase, extraction phase, during casting process and its recycling or end of life phase.

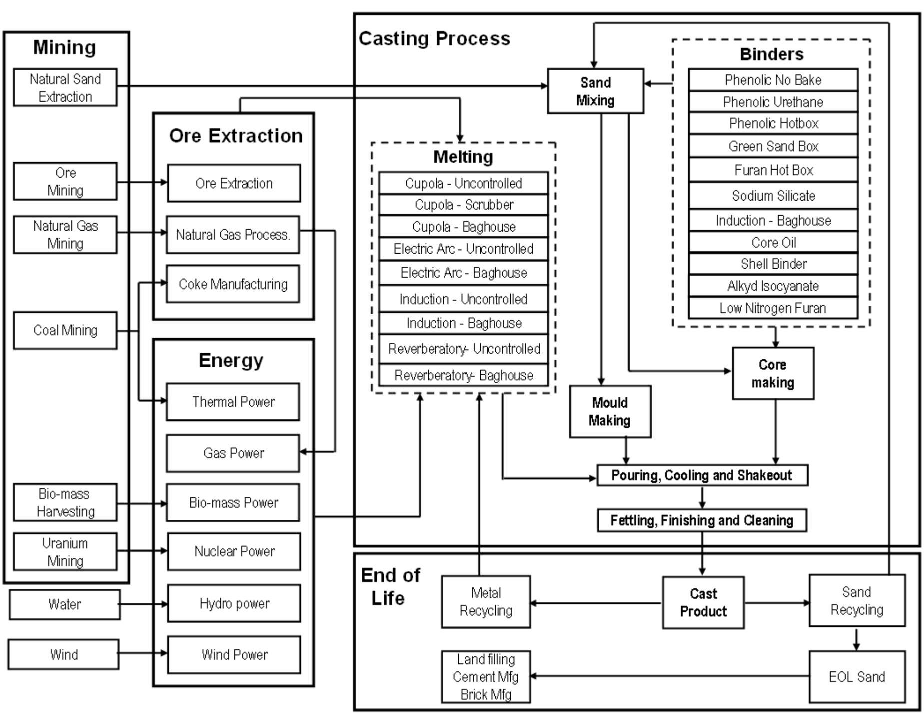

Figure 1. System boundaries for LCA of castings.

1.3. Method

Raw materials which are required for the extraction of cast iron, steel and aluminium are identified and all the possible material input, energy input, air emission, water emission and solid waste related to these materials are obtained from various sources. During this phase emissions are generated mainly by combustion of fuel by mine site vehicles and machines and particulate matters due to excavation work. The production process of sand casting consists of sand preparation, binder mixing, mould/core preparation, metal melting, pouring, cooling, shakeout, fettling, and finishing. Proportion of primary and secondary material, type of binder system, melting furnace and casting yield have significant effect on foundry emissions. Binders are chemicals that are added during mould/core sand preparation for getting the desired properties such as green strength, permeability and collapsibility. We have considered common binder types and melting furnaces as shown in system boundary and as well as percentage of primary/secondary material and casting yield. Various binders have varying emissions during pouring, cooling and shakeout of casting, hence it become imperative to consider the environmental impact of these binder systems, however upstream binder manufacturing and its associated environmental impact analysis is not considered due to considerably low proportion (1%-3%). During the use phase it is assumed that the cast product is to be used as an automobile component. In this phase emissions are mainly due to combustion of fuel and these are assigned to the components on the basis of mass contribution to the whole mass of the vehicle. Emission due to transportation of finished castings is also considered in the use phase. Vehicle life, weight and its mileage are important parameters that affect the environmental impacts. Casting at the end of its useful life is recycled i.e. collected, transported and re-melted in the furnace as secondary material. Waste sand can be used for making concrete pavement blocks, bricks, asphalt road, portland cement rather than land filling. In the former case it remains rather passive in nature and does not affect environment significantly. In the later case it affects the ground water quality, however this aspect is not considered in the present study.

1.4. Functional Unit and Assumptions

Functional unit is a hypothetical sand castings having volume equal to 144.00 cubic centimeters; equivalent to 1 kg cast iron castings. The density difference for aluminium and cast iron respectively is almost 300% (2.70 and 7.86 g/cm^{3}respectively). Backhouse C J *et al.* [5] assumed mass of 3.5 kg in aluminium alloy equivalent to 5 kg of cast iron, considering the mechanical properties of the two metal alloy systems. For present study also, we assumed a weight ratio of aluminium and cast iron to be 1:0.7 as per the Backhouse C J *et al.* [5]. However the weight ratio of cast iron to steel has been taken corresponding to their density ratio. Following are the assumptions of this study:

- Additives less than 2% of charge are excluded from the system boundary
- A genric composition is considered for aluminium, cast iron and steel. Effect of alloying elements not considered.
- Euro-II emission norms are taken for vehicle emissions, generally common in India.
- Automobile emissions are assumed linearly proportional to weight of the vehicle
- Construction of mine site vehicles and equipments are not included in the system boundary.

For the purpose of computation associated data was taken as following: (1) coal, ore and crude oil are assumed to be transported 500 km using locomotive trains (2) pig iron, scrap, coke and limestone are assumed to be transported to a distance of 300 km using trucks (3) fresh core/ mould sand, waste sand and finished castings are assumed to be transported to a distance of 100 km. using trucks, and (4) casting is considered to be used in Heavy Commercial Vehicle (HCV) of an average life of 5,00,000 km, weighing 8 tons and with mileage 4 km/l of diesel.

1.5. Data Sources

The emission and energy data has been collected from CERP reports, NREL Database, Environmental Protection Agency, USA and some other sources. Casting Emission Reduction Program (CERP) has

Table 1. Data sources three cast metals – Aluminium, Cast iron and Steel.

Cast Iron	Iron Ore mining [14], Ore transportation, Coal mining, Coal to coke oven transportation [16] Mining of crude oil, Crude oil transportation, Processing of oil Limestone mining [7] Limestone transportation [16] Coke manufacturing [17] Coke transportation [16] Sintering/palletizing [14] Blast furnace [14] Electricity generation [7, 18]
Aluminium	Bauxite mining, Bauxite transportation, Alumina refining, Ingot casting, Anode production, Aluminium smelting, Crude oil mining, Crude oil transportation Processing of oil [7] Electricity generation [7, 18]
Steel	Iron Ore mining [14] Ore transportation, Coal mining [7] Coal to coke oven transportation [16] Mining of crude oil [7] Crude oil transportation [8] Processing of oil [7] Limestone mining [8] Limestone transportation [16] Coke manufacturing [17] Coke transportation [16] Sintering/palletizing [14] Steel billet manufacturing [14] Electricity generation [7, 18]

been initiated from 1994 with an objective to document and evaluate the impact on air emissions (HAP's, VOC's, POM's and others) of materials, equipment, and processes during production of metal sand castings [6]. The National Renewable Energy Laboratory (NREL) is the United States' primary laboratory for renewable energy and energy efficiency research and development (R&D) and its partners have created the U. S. Life-Cycle Inventory (LCI) database to help life-cycle assessment (LCA) experts with data compilation [7]. This database provides a cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly. A comprehensive list of criteria and toxic pollutant emission factors, for sources commonly found in iron foundries, has been provided by the Environmental Protection Agency, USA [8]. The environment impact of casting and its sub-processes have also been presented in Emission Estimation Technique Manual [9] and Emission Calculation Fact Sheet [10]. Data sources for mining and raw material extraction is presented in Table 1. Data sources for casting process are taken from following source: sand system [11]; cupola /oil fired/induction furnace [2, 10]; pouring, cooling and shakeout [11]; fettling, finishing, cleaning [10]; core making, baking and storage [12, 13]; mould mixing/making, storage [15]; ore, scrap, and sand transportation [16]; and part transportation [16].

For evaluating equivalent emissions in different impact categories, all the emission data collected previously are converted according to the requirement of functional unit.

The energy consumption and emissions in mould-making, core-making, melting (with cupola, electric arc, induction, reverberatory, open hearth and fuel-fired furnace), refining, pouring, cooling, cleaning and finishing operations of sand casting have been documented in energy and environmental profile of the US metal casting industry [2].

1.6. Inventory Classification and Characterization

Classification of emission data to various impact categories is performed using Environmental Design of Industrial Products (EDIP). Characterization factors for various emissions are taken from Simapro software [19]. It should be noted that one emission can affect more than one impact categories. For instance, NO_X can affect not only acidification but also eutrophication and even smog formation. There are four cases where multiple impacts occur from a single inventory parameter. They are parallel impacts, serial impacts, indirect impacts, and combined impacts. In parallel impacts, a single inventory parameter causes more than two distinctively different impacts. It is customary to assign the total amount of inventory parameter to all types of impact category in the parallel impact case [20]. After assigning to respective categories, parameters are multiplied by characterization factors in order to arrive at equivalent emissions for each sub-process. Finally all the equivalent emissions are added up to obtain gross equivalent emission for a particular impact category.

2. RESULTS

Results of impact categorizations as per EDIP (Environmental Design for industrial products) LCA method are presented in this section in the following order (1) comparison of cast metals — aluminium, cast iron and steel (2) comparison of melting furnaces (3) effect of recycling or using secondary material (4) comparison of various binder systems (5) effect of process variables (6) comparison of energy models.

2.1. Comparison of Cast Metals — Aluminium, Cast Iron and Steel

Green sand mold and cold box no bake core is considered for this study. Charge is composed of 80% primary material and 20% secondary material. Typical casting yield for cast iron is taken as 70% whereas for steel and aluminium is taken as 65% and 60% respectively. Melting furnaces for cast iron, steel and aluminium are taken as Cupola, Induction furnace and Reverbatory furnace respectively. Sand to metal ratio is taken as 5. Binder to sand ratio for cast iron and steel is 1.75% whereas for aluminium 1.1%. Phenolic urethane binder is used for the comparative study. Table 2 and Figure 2 present the environmental performance of the three metals.

It is observed that steel is most whereas aluminium is least harmful in all the impact categories except solid waste category wherein results are just reversed i.e. aluminium is most and steel is

Table 2. Environmental Performance of three cast metals – Aluminium, Cast Iron (CI) and Steel

Mt.	Life Cycle Phases	GW	AC	EU	PS	ET	HT	SW
CI	Pre-Manufact.	2.41E+E	5.65E−03	1.7E−02	3.31E−E	1.51E+00	8.65E+05	3.59E+00
	Manufacturing	7.06E−01	2.52E−03	3.23E−03	4.13E−03	1.10E−01	7.85E+04	1.62E+00
	Use	1.36E+01	5.37E−01	1.04E+00	1.10E−01	0.00E+00	5.81E+05	1.64E−02
	End−of−Life	3.80E−01	7.11E−03	3.67E−03	1.03E−04	5.90E−02	4.69E+02	1.53E−05
	Total	1.71E+01	5.52E−01	1.06E+00	1.17E−01	1.68E+00	1.53E+06	5.22E+00
Steel	Pre− Manufact.	4.78E+00	2.97E−02	3.14E−02	5.25E−03	1.68E+00	9.59E+05	3.45E+00
	Manufacturing	6.32E−01	2.00E−02	7.46E−03	1.30E−03	9.51E−02	4.17E+03	1.76E+00
	Use	1.40E+01	5.55E−01	1.07E+00	1.13E−01	0.00E+00	6.01E+05	1.70E−02
	End−of−Life	3.93E−01	9.57E−03	3.80E−03	1.07E−04	6.10E−02	2.88E+02	5.10E−04
	Total	1.98E+01	6.14E−01	1.11E+00	1.20E−01	1.84E+00	1.56E+06	5.23E+00
Al	Pre− Manufact.	4.84E+00	6.67E−02	8.46E−03	5.72E−03	3.21E−01	6.29E+05	7.77E+00
	Manufacturing	7.13E−01	1.39E−02	2.71E−02	3.83E−03	1.03E−02	6.02E+03	1.29E+00
	Use	9.50E+00	3.76E−01	7.25E−01	5.94E−02	0.00E+00	4.12E+05	1.07E−05
	End−of−Life	2.77E−01	4.98E−03	2.57E−03	6.02E−04	4.13E−02	2.03E+01	3.45E−04
	Total	1.53E+01	4.61E−01	7.63E−01	6.95E−02	3.72E−01	1.05E+06	9.07E+00

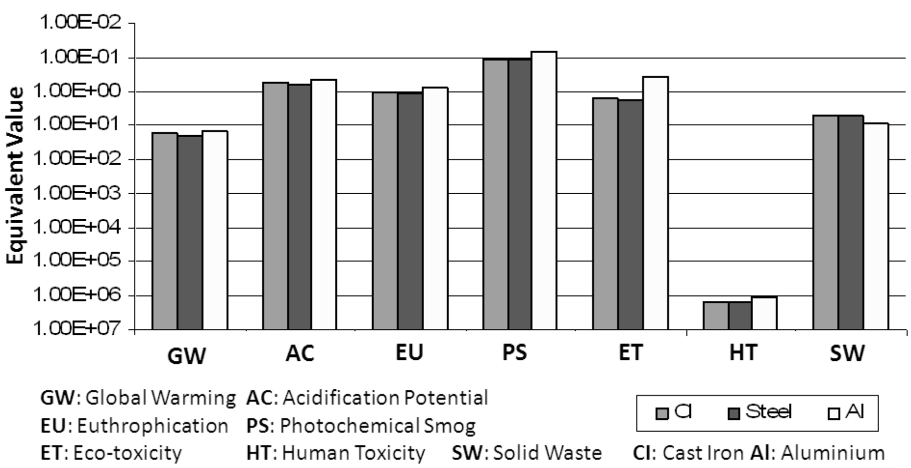

Figure 2. Performance of three cast metals –Aluminium, Cast Iron (CI) and Steel.

least harmful. It is mainly because solid waste from aluminium during pre-manufacturing phase is so high in comparison with cast iron and steel that even lesser waste in other lifecycle phases couldn't offset pre-manufacturing phase results. By phase-wise comparison aluminium proves to be biggest contributor to global warming potential during pre-manufacturing phase perhaps due to poor percentage of aluminium in bauxite ore leading towards more mining and vehicle use at mine site per unit casting. Steel has least global warming potential during manufacturing phase mainly because of use of induction furnace for melting, which is more environment friendly than cupola and oil fired reverberatory. In use and end-of-life phase aluminium is least harmful because lesser quantity is to be transported and melted during these phases. Steel is most harmful for all the phases for acidification except pre-manufacturing phase where aluminium is most harmful. Steel is most harmful from eutrophication point of view in all the four lifecycle phases. Oxides of nitrogen play a major role in acidification and eutrophication. NO_x is mainly emitted during fuel combustion in transportation. Steel is least harmful from photochemical smog point of view during manufacturing phase due to less emission by induction furnace whereas aluminium is most harmful during pre-manufacturing phase due to poor percentage of aluminium in bauxite ore. Eco-toxicity and human toxicity impacts are maximum for steel and least for aluminium for all lifecycle phases except manufacturing phase wherein cast iron is most harmful perhaps because of more emission of oxides of sulphurs, carbon monoxide and other HAPs from cupola furnace.

2.2. Comparison of Melting Furnaces

Melting contributes to more than 50% of energy required in castings and thus dominates the environmental impacts during manufacturing phase. In this section we present the comparison of melting with cupola, electric arc furnace, electric induction furnace and reverberatory furnace, for one kg of gray cast iron melting. The comparison using EDIP method illustrates that cupola melting causes the highest global warming potential (due to high CO_2 emission), photochemical smog potential and human toxicity (due to lead emission). Electric arc furnace causes highest acidification potential (due to high SO_2 and NO_2 emissions). Reverberatory furnace is more harmful than electric arc and induction furnace and less harmful than cupola furnace (except acidification potential) in all categories.

2.3. Effect of Recycling or Using Secondary Materials

Use of recycled castings eliminates the mining and extraction phases and thus has considerable scope for reduction of environmental impacts. Higher the amount of secondary material lower is the environmental impacts. 100% primary material casting in aluminium results in global warming than cast iron, but when 60% secondary material the impact is lower than that of cast iron with 80% primary and 20% secondary material.

2.4. Comparison of Various Core Making Process (Binder Systems)

In this section, comparison for eleven generally used binder systems for various impact categories is presented (Figure 1). It is observed that all the binders have some Global Warming Potential (GWP). Shell core is most harmful for environment for GWP. Most of the binders also contribute to photochemical smog category but seem to have little impact as far as eutrophication and acidification is concerned except hot box furan, hotbox phenolic and shell core. Hot box furan has greatest impact among all binder systems in eutrophication and acidification category.

2.5. Effect of Process Variables

Increase in pouring temperature is sometimes desired during casting for increasing the fluidity of molten metal in the mould, however it has to be realized that 10% increase in pouring temperature causes 11% increase in energy requirement. Casting yield should be maximized not only from the prospective of cost but also for reducing the environmental impacts. It has been observed that a 10% increase in casting yield results in 8% decrease in global warming potential for cast iron.

2.6. Effect of Electricity Generation

Energy is required in upstream as well as in various sub-processes of casting as melting, sand preparation, core and mould making, fettling and cleaning etc. Every region uses a mix of various types of energy, and so the environmental impact of energy use is different regions is different. Comparison of two different electricity models Model-I: coal-56%, hydro-26%, biomass-03%, natural gas-10%, nuclear-3%, Others-2%; and model-II: coal-55%, nuclear-29%, natural-16% for steel revealed that model-I results in 4% more global warming as compared to model-II.

3. DISCUSSIONS

Main goal of this life cycle assessment is to identify scope for minimizing the environmental effects during the life of a sand casting. Because of the plethora of parameters under consideration in this assessment, no one phase can be expected to exercise general dominance for all parameters. Use phase is dominating phase in global warming, acidification, eutrophication, photochemical smog, energy consumption and natural resource categories whereas pre-manufacturing phase dominates eco-toxicity, human-toxicity, and solid waste impact categories. It is interesting to see that manufacturing phase, which we generally consider very crucial, do not dominates even a single category. However for some categories eco-toxicity and solid wastes manufacturing phase is second most dominating phase ahead of use phase. Cast iron, despite being lighter than steel, is more harmful than steel during manufacturing phase for global warming, eco-toxicity and human toxicity. In totality (combined impact of all phases) in all categories, steel is most harmful in all the categories except solid waste category. Cast iron is slightly less harmful than steel but considerable more harmful than aluminium except solid waste category. Aluminium, even being most harmful during pre-manufacturing in global warming, solid waste, energy resource and resource categories emerges overall least harmful casting for environment except solid waste category. During manufacturing phase melting furnace, composition of charge, binder system, process variables and electricity model play pivotal role. During use phase all the emissions come from fuel consumption. Hence reduction in the weight of vehicle will require less fuel for same life of the vehicle, resulting in significant reduction in environmental impacts. There are two ways for reducing the weight of casting: dematerialization and material substitution. By dematerialization we mean a reduction in the mass of the component by improved design (constrained by design limitations). In materials substitution we seek to reduce the mass of a component by choosing a material of lower density. Such iterations can be evaluated as above to realize the possible benefits in environmental impacts. LCA methodology can thus help in identifying environmental hot spots in material and process selection for subsequently reducing the environmental burdens.

4. CONCLUSIONS

In this study steel, cast iron and aluminium, the three major cast metals were analyzed for their impact on environment. The use of LCA method EDIP illustrates quantification of environment impacts that can be further evaluated for finding ways to reduce the environmental impacts. Environmental Impact of sand cast products is affected by all phases i.e. upstream, manufacturing, use and disposal or recycling. Impurities in raw material require more energy and result in more emissions. Environmental impacts are also influenced by manufacturing process parameters as selection of melting furnace, casting yield, pouring temperature, mould making and core making methods. Automotive castings though are passive element of automobile affect emissions by its weight. Castings are 100% recyclable and their usage as secondary material help in reducing the environmental impacts. These conclusions are based on currently available data from various sources, and there may be some differences in results for specific foundries and geographic regions.

5. RECOMMENDATIONS AND PERSPECTIVES

LCA of sand cast product can help in evaluating the total environmental impact resulting from a cast product early during design stage. In lieu of traditional way of comparing the emission during manufacturing alone, such analysis provides quantitative yet comprehensive feedback on the application of specific material process combination. This can help the product designer to choose material with minimum impact to environment early during product development. Further it can also help the process planner to design eco-friendly process for a given material. Consistent data sources and documentation of liquid and solid emissions of casting process can enhance the perspective of LCA. Further scope also lies in applying LCA to other cast materials and processes.

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