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ABSTRACT

This study is a life-cycle assessment (LCA) comparing two types of a powertrain structural component: one made of diecast primary aluminum and another hypothetical part made of semi-solid injection molded primary magnesium (Thixomolded®). The LCA provides an indication of the potential environmental burdens throughout the life-cycles of both parts, ranging from raw material acquisition to product end-of-life. Preliminary results show high sensitivity to selection of primary vs. secondary metals, and to the SF_6 emission factor used in the model. Opportunities exist for reducing energy consumption using secondary instead of primary metals for both parts, although the use of such is influenced by market supply and demand

INTRODUCTION

Since the oil crisis of the 1970s, lightweight metals have been increasingly used in the automobile. Better fuel economy and vehicle emissions can be realized with lighter components. In particular, aluminum has been commonly used as a replacement for steel and iron castings. In some instances, substituting aluminum for steel can save 40-50% of a part's weight (Polmear, 1996). According to the American Automobile Manufacturers Association (AAMA), the typical family vehicle in 1978 had 51 kg aluminum. In 1996, this figure increased to 89 kg aluminum (AAMA, 1996). Steel use and the total weight of the vehicle dropped correspondingly. The steel industry has responded with its Ultralight Steel Auto Body project.

Magnesium is another lightweighting metal that has been emerging in the automotive industry. In 1978, the typical family vehicle had 0.45 kg magnesium castings. In 1996, the Mg castings weight increased to 2.5 kg magnesium (AAMA, 1996). Because magnesium is about two-thirds the density of aluminum, it represents a competitive alternative for further vehicular lightweighting.

Although magnesium can realize clear advantages in the use phase of the vehicle, these benefits may be offset by environmental burdens upstream (e.g., raw material acquisition and part manufacture) or downstream (part retirement and disposal). Questions regarding the energy and environmental burdens associated with other phases of a product's life-cycle need to be accounted for. These phases include raw material acquisition, product manufacture and product end-of-life. It is the purpose of life-cycle assessments (LCAs) to address all major environmental burdens of a product from its inception to its retirement.

One life-cycle assessment of particular relevance to this study was developed by Reppe et al. (1997). Reppe conducted an LCA comparing transmission cases produced from diecast aluminum and diecast magnesium. Results showed significantly lower use phase air emissions and energy consumption associated with the magnesium case, primarily due to its lower weight. However, there were greater environmental burdens outside the use phase of the magnesium case. In the raw material acquisition and product fabrication phases, results indicated a high potential for emission of a highly potent greenhouse gas. Sulfur hexafluoride (SF_6), a gas that has a global warming potential 23,900 times greater than carbon dioxide, is used as a cover gas in magnesium production and casting processes (IPCC, 1995). Although variability of its use is high, sulfur hexafluoride from the magnesium industry represents a potentially high environmental burden to the global climate. It should be noted that there is a current trend in the diecast magnesium industry toward the use of much lower concentrations of SF_6 than in the past.

It is the purpose of this study to determine the environmental impacts of using an alternative magnesium casting process, which does not use SF_6. Thixomolding® is a semi-solid metal injection molding process that derives its name from the "thixotropy", a slurry-like property that results from mechanical shearing and heating of a solid. The technology is licensed by Thixomat, Inc. (Ann Arbor, Michigan), from which much of the information is provided. Thixotech, Inc. (Calgary, Alberta), one of its licensees, provided a significant portion of quantitative data on the process for this study.

Several mechanical properties inherent to semi-solid magnesium molding have been found to be comparable, if not better, than conventional diecast magnesium. Studies conducted by Thixomat, Inc. and Thixotech, Inc. have shown that the magnesium semi-solid slurry has a higher apparent viscosity and can be molded to near net shaped parts with mechanical properties superior to diecast parts (Ghosh, 1994). Lower porosity, for example, is one such property improvement. The higher viscosity of the semi-solid metal slurry allows for more laminar flow and reduces the volume of entrapped gases in the slurry. Other improvements include increased corrosion resistance, increased ductility and reduced shrinkage (LeBeau, 1997). Because of these stronger mechanical properties, semi-solid magnesium molded parts can typically be designed with thinner cross sections, lower draft angles and closer tolerances. Depending on the part Thixomolded®, there may be potential to design the part with less volume than diecasting.

This study is a life-cycle assessment comparing a structural powertrain component currently diecast in aluminum with a hypothetical semi-solid molded magnesium prototype. This LCA comparison provides an indication of the potential environmental advantages or disadvantages inherent with this alternative technique. More information could be gained from quantification of the environmental burdens associated with a magnesium Thixomolded® part in production which would provide a more precise comparison to the diecast aluminum. Analysis is performed over four life-cycle phases:

- Raw material acquisition phase: mining, refinement and alloying of metals.
- Product fabrication phase: semi-solid injection molded magnesium or diecast aluminum.
- Use phase: use of the part over the service life of the vehicle. A large-sized light duty truck platform was the vehicle system being investigated.
- End-of-life phase: retirement of vehicle and part.

In addition, transportation of the part throughout its life-cycle is also inventoried. The machining phase was not compared in this study since the Thixomolded® part is considered hypothetical and therefore optimization designing and corresponding performance testing would need to be performed to be able to determine what level, if any, machining would be required.

To illustrate the differences in environmental burdens between diecast aluminum and semi-solid injection molded magnesium parts, data is compiled into four metrics: energy consumption, water use, air emissions, global warming potential and acidification potential. Each are described in more detail in the Results section.

The results of this study are intended to be used twofold:

- To provide automotive manufacturers and suppliers interested in vehicular lightweighting with a first level environmental evaluation of an alternative magnesium manufacturing process in relation to a conventional process
- To provide a comparison of the environmental burdens associated with the product fabrication phase of the semi-solid injection molded magnesium part in relation to the other life-cycle phases of the component.

It should be emphasized that performance and cost requirements must be satisfied in product design analysis in addition to environmental considerations. These parameters were not fully evaluated in the hypothetical Thixomolded® magnesium part and were therefore not addressed in this study.

METHODOLOGY

PRODUCT SYSTEM

Part Description – The part modeled is a powertrain structural component for a light-duty truck. Depending on the metal market, the part may be made either from aluminum or magnesium.

The mass of the aluminum part, which is currently in production, is 1.85 kg. The mass of the Thixomolded® part was determined using an estimate for a diecast magnesium equivalent part. The mass of the diecast magnesium component was assumed to be 1.25 kg, which reflects the density difference of the two metals. Using the magnesium diecast mass to represent the Thixomolded® part mass is an upper mass limit. In general, Thixomolded® parts have been found to be made more thin and lighter than conventional diecast parts (Decker, 1999).

Thixomolding® Process Description – The Thixomolding® process resembles the plastic injection molding process, both of which require the use of an injection molding machine. The most prominent difference between the two is the design of the injection unit. The barrel and screw of the Thixomolding® machine are designed for the high temperatures and abrasion associated with processing magnesium. The heater bands for the barrel are also of a significantly higher wattage than those used for plastics. Injection pressures, however, do not exceed those in plastic injection molders.

The feedstock for the Thixomolding® process consists of magnesium chips that are conveyed to the Thixomolding® machine hopper using a vacuum conveying system. The magnesium chips are metered into the barrel feed throat using a volumetric auger feeder. A blanket of argon gas is applied at the feed throat opening to displace ambient air, protecting the metal from high temperature oxidation. Sulfur hexafluoride is not required.

Energy from the barrel heater bands and shear from the reciprocating screw heat the magnesium to 560°C – 590°C. The combination of heat and shear forces result in a slurry of magnesium consisting of nearly spherical solid particles suspended in a liquid matrix. The magnesium is then injected into the mold that is held closed using a mechanical toggle clamp. The mold is heated by pumping hot oil through it, in order to prevent any metal from solidifying in the mold passages. Cooling water is required for the hydraulic system of the Thixomolding® machine. Unlike most plastic molding processes, Thixomolding® does not require cooling water for the mold (Rinella, 1998).

When the part cools sufficiently, the clamp opens, and the part is removed by a mechanical robot and placed on a cooling conveyor. The sprues and runners are then removed from the Thixomolded® parts and the parts are deburred in a fluidized bed of Al beads.

LCA MODEL – The LCA model was developed using LCAdvantage™, a software program designed by Battelle Memorial Institute. Much of the data for the production of ancillary and some primary materials were provided by DEAM™, an LCA database compiled by Ecobalance (Rockville, Maryland). Ecobalance also provided information on the fossil fuel usage of regional electrical grids.

Any time a process produced two or more usable outputs, environmental and energy burdens were proportionally allocated to each based on mass. A second model, in addition to this one, was done such that all burdens were allocated to the powertrain component. Comparisons between the two models did not yield any major differences.

As a cautionary note, uncertainties are expected to be higher for air emission results relative to energy . Previous comparisons of material production databases indicated that significant differences exist for air emissions (Keoleian and McDaniel, 1997).

MAGNESIUM LIFE-CYCLE – The life-cycle of the powertrain structural component is summarized in Figure 1.

<u>Raw Material Acquisition</u> – Two methods of producing magnesium are used commercially throughout the world: the ferrosilicon and electrolytic methods. The ferrosilicon processes, including Magnetherm and Pidgeon, use dolomite as the source of magnesium oxide. A briquetted mixture of dolime and ferrosilicon is heated to 1200°C – 1600°C under a high vacuum. The resulting magnesium vapor is then condensed, re-melted, refined and cast into ingots (Kroschwitz, 1995).

In the United States, a significant fraction of its magnesium is produced using the electrolytic process, which uses seawater or brine as the raw material. Anhydrous magnesium chloride, which is produced in a variety of methods, is the feed material to the electrolytic process. The major outputs are magnesium and chlorine gas.

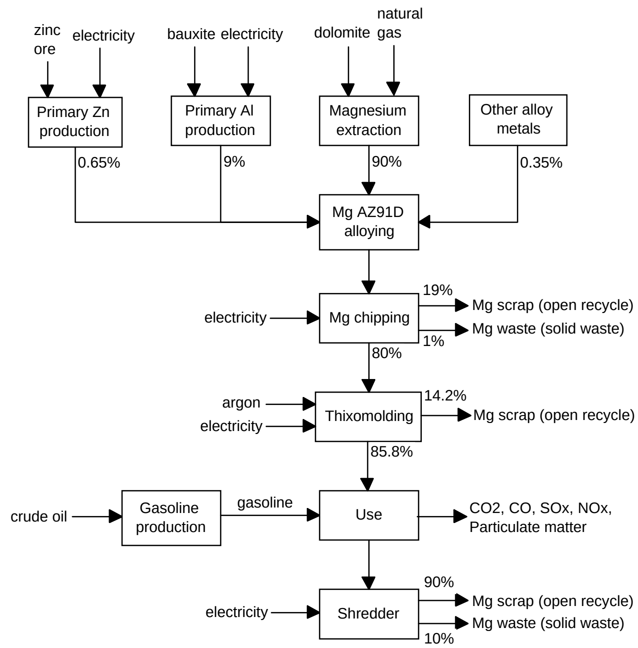

Figure 1. Life-cycle of Thixomolded (Mg) powertrain structural component.

Several sources of magnesium raw material acquisition data were considered for this study. Thixotech, Inc. purchased AZ91D magnesium alloy produced electrolytically by Dow Chemical in Freeport, Texas (which has closed down operations during the research phase of this study). However, because limited data was available, alternative surrogates were considered. Ecobalance provided a complete LCA data set on the Magnetherm process. This was compared to data from a Norsk Hydro electrolytic facility compiled by Reppe (1997). Although the Norsk Hydro data more closely represents the Dow facility (both are electrolytic), the Magnetherm data set was chosen as the surrogate because it was more comprehensive. Results are reported for both the Magnetherm and electrolytic processes. Comparisons between the two data sets indicated similarities in some environmental burdens and differences in others. Table 1 below shows comparisons for selected burdens. Primary energy consumption and CO_2 emissions were similar, though other air emissions differed.

Table 1. Inventory datasets for the production of 1 kg of magnesium using the Magnetherm and Norsk Hydro (electrolytic) processes.

Environmental Burden	**Magnetherm**	**Norsk Hydro**
Energy consumption	115 MJ	150 MJ
CO_2 emissions (air)	7.34 kg	6.0 kg
HCl emissions (air)	0.137 g	1.96 kg
SO_x emissions (air)	7.16 g	2.98 kg

The environmental burdens from the production of the AZ91D alloying elements, including aluminum (8.5-9.5%), zinc (0.5-0.9%), copper (0.01% max) and iron (0.004% max), are also modeled using data from Ecobalance. Silicon (0.02% max) is modeled using LCA information provided by Elkem. Manganese (0.17-0.32%) and nickel (0.001% max) were not modeled. In addition, it was assumed that the energy required to combine alloying materials was insignificant compared to the energy requirement for the production of the individual metals.

Transportation within the raw material acquisition phase was assumed to be modeled in the Ecobalance data sets. Freeport, Texas was chosen as the site of origin of the primary magnesium.

Product Fabrication

Chipping Process – The AZ91D ingots are shipped to a facility in the northeastern United States to be reduced to a granular feedstock (up to 4 mesh) for Thixomolding®. Due to confidentiality issues, availability of data on the chipping process was limited. Estimates of energy consumption were based on a known production rate and estimations suggested by Thixotech, Inc. The estimated specifications for the chipping equipment are summarized below in Table 2.

It was estimated that 80-85% of the chips produced were within the specifications required for the Thixomolding® process. The out-of-spec chips (14-19%) were classified as recyclable co-products because they are used as desulphurizers in the steel industry. Magnesium fines (1%) collected in filters are classified as solid waste (Decker, 1998).

Data on energy usage and emissions, other than that which is shown above, were not available and therefore not included in this study. Transportation calculations were based on an assumption that the chipping facility was located in Pittsburgh, Pennsylvania.

Table 2. Chipping specifications

Specification	Value	Reference
Power	22.4 kW (30 hp)	7
Chipping Rate	227 kg/hr	7
Yield to Thixomolding®	170.25 kg/hr	7
Yield to Steel Industry	54.48 kg/hr	7
Solid Waste	2.27 kg/hr	7

Thixomolding® – After the magnesium is chipped, it was assumed to be sent to Thixotech, Inc. to mold. It should be noted that Thixotech, Inc. is a relatively new organization that is only now beginning to manufacture products on a full production scale. The data provided from the company corresponds to an earlier period when production runs were shorter. These short runs produce more solid waste (mostly start-up scrap) than in full-scale production facilities. Energy consumption may also be higher because the barrel of the Thixomolding® machine is continuously heated, even when the machine is idle. At the end of a day, it is a common practice to continue to heat the barrel through the night, though at a lower temperature (Decker, 1996).

The energy input was based on total electrical and natural gas consumption for the Thixotech, Inc. facility in 1997. Energy consumption was allocated to the part according to Equation 1.

$$E_{part} = \frac{E_{tot} \times \left(\frac{C_{Thix}}{C_{plt}}\right)}{\frac{M_{tot} \times \left(\frac{C_{Thix}}{C_{plt}}\right)}{M_{shot}} \times R_{good}} \qquad (1)$$

where: E_{tot} = Total 1997 electricity consumption (kWh)
E_{part} = Electricity consumption for part (kWh)
M_{tot} = Total mass of Mg used in 1997 (kg)
M_{shot} = Part shot weight (kg)
R_{good} = Rate of hypothetical good part production (.98)
C_{Thix} = Thixomolding® capacity of machine (ton)
C_{plt} = Thixomolding® capacity of plant (ton)

The electricity used to produce the part was estimated from the total electrical consumption of the facility (E_{tot}), prorated according to the capacity of the injection molding machines. C_{Thix}/C_{plt} is the ratio of die clamping force of the machine that produces the part (400 ton) to the total clamping force of all machines. This factor is multiplied by E_{tot} to estimate the electricity consumed by the 400 ton machine in 1997. This value includes overhead electrical costs such as lighting.

This adjusted electrical consumption value is then divided by the 1997 rate at which good parts are made (Eqn. 1 denominator) in order to estimate the electricity consumed per part. Because the part was never in production, estimations were required. The production rate for the part was estimated by multiplying the total 1997 facility magnesium consumption (M_{tot}) by the capacity ratio (C_{Thix}/C_{plt}) and dividing by the shot weight of the part (M_{shot}). Scrap rate was accounted for by multiplying by R_{good}, the rate at which good parts are produced. However, since the part magnesium part modeled was not in production, and is therefore considered hypothetical, an actual scrap rate cannot accurately be defined.

Thixomat, Inc. also provided separate data on electricity consumption of a sample 400 ton machine. As above, the machine molded parts during the day and was heated during non-operating hours. Because this data only includes electricity consumption for the molding operation, the overhead at the Thixotech, Inc. facility can be estimated by subtracting this consumption by the total facility consumption calculated by the above process.

Scrap magnesium was classified as a co-product because it is often sold to the steel industry as a desulphurizer. Energy consumption and emissions were allocated to the scrap magnesium on a mass basis.

Natural gas consumption is modeled slightly differently from electricity. As with the previous two parameters, natural gas was allocated to the part from the total gas usage in 1997. Instead of modeling the number of parts produced based on the magnesium consumed in 1997 (denominator of Equations 1), however, a theoretical production rate based on the cycle time of the machine was used.

Water use was based on estimates of water used for cooling of the hydraulics of the Thixomolding® machine. Values for water use were assumed to be similar to that of a plastic injection molding machine (Husky, 1980).

The consumption and emission of the cover gas argon was based on the quantity of argon Thixotech, Inc. purchased in a 6-month period in 1998.

Remaining Automotive Assembly – The assembly of the magnesium powertrain structural component and automobile is assumed to be similar to the aluminum part. Consequently, assembly-related environmental burdens were not modeled. Environmental burdens associated with transportation within the assembly stage were not modeled.

<u>Use Phase</u> – In the use phase of the powertrain component the environmental burdens of the part were estimated over a 200,000 km vehicle service life. The main processes modeled were gasoline consumption, gasoline production and emissions.

Fuel Consumption – The fuel economy of a large-sized light-duty truck is 5.1 km/L (12 mpg) (city) and 6.8 km/L (16 mpg) (highway). Combined fuel economy is given in Eqn 2, which is calculated to be 5.7 km/L (13.5 mpg).

$$FE_{comb} = \frac{1}{\left(\frac{0.55}{FE_{city}}\right) + \left(\frac{0.45}{FE_{hwy}}\right)} \qquad (2)$$

where: Fe_{comb} = combined fuel economy (km/L)
Fe_{city} = city fuel economy (km/L)
FE_{hwy} = highway fuel economy (km/L)

To prorate fuel consumption to the powertrain component, the following correlation was used:

$$F_{part} = FE_{comb} \times L_{part} \times \left(\frac{M_{part}}{M_v}\right) \times \left(\frac{\Delta f}{\Delta M}\right) \qquad (3)$$

where: F_{part} = fuel used over part life (L)
FE_{comb} = combined fuel economy (km/L)
L_{part} = life of part (km)
M_{part} = mass of part (kg)
M_v = test weight of vehicle (2426 kg or 5350 lbs)
$\Delta f/\Delta M$ = fuel-mass correlation (0.315)

The vehicle fuel economy (FE_{comb}) is multiplied by the estimated lifetime driving distance (L_{part}) to obtain the fuel consumption of the entire vehicle. This value is multiplied by the weight fraction of the powertrain component and a fuel-mass correlation (0.315) derived from an internal Ford study.

Emissions – Emissions from the operation of the vehicle are derived from US EPA emission factors and off-cycle and malfunction emissions (Ross, 1995).

A simple mass balance was done to estimate the carbon dioxide emissions, since this is not tested by EPA. The emissions were estimated by taking the carbon content of the fuel and subtracting the other carbon-based emissions based on the EPA emission factors and the malfunction and off-cycle emissions.

Emissions are prorated to the powertrain component based on the fuel consumption allocated to the part, the EPA emission factors, the off-cycle and malfunction emissions and fuel economy.

The lifetime fuel consumption allocated to the part (F_{part}) was calculated using Eqn 3. The powertrain component contribution to vehicle emissions was obtained by assuming that emissions are proportional to the total vehicle fuel consumption allocated to the powertrain component. This allocation is straight-forward for CO2, but for other emissions the relationship is non-linear. Non-CO2 emissions were allocated assuming a linear relationship as these emissions are a direct result of fuel use.

Additional assumptions inherent with this phase include:

- Replacement of the part during the service life of the vehicle was not accounted for in this model since there is no data to predict the replacement rate of the hypothetical part
- Maintenance, including fluid and part changes, are assumed to be the same for both aluminum and magnesium parts and not modeled in the study.
- Potential secondary lightweighting benefits by the lighter magnesium part, such as the decreasing of engine power and size, are not modeled.

End-of-Life (EOL) – The end-of-life phase is defined as the life-cycle period after the service life of the vehicle. This phase includes dismantling, remanufacturing and shredding. For the purposes of this study, it is assumed that retired parts are shredded. Estimations from a prominent shredding company show that the energy required for shredding is 97 kJ/kg (42 BTU/lb) metal (Keoleian, 1997).

Because the secondary magnesium market is as of yet relatively undeveloped, little information on magnesium recovery is available. For simplification, magnesium is assumed to have the same recycling rate as aluminum, on the basis that magnesium is separated with aluminum and other non-ferrous material during and after the shredding process. According to the Aluminum Association, 85-90% of all automotive aluminum is recycled (Aluminum Association, 1997). A value of ninety percent was used in the model.

Packaging and Transportation – Transportation through the life-cycle of the part was modeled using MJ/kg-km factors for various modes of transport. Transport of ancillary materials is not considered.

Packaging material used to transport parts from facility to facility predominantly consists of reusable metal containers. Because of their relatively long lifetimes and little maintenance requirements, these containers are not factored into the model.

ALUMINUM LIFE-CYCLE – The life-cycle of the aluminum part is summarized in Figure 2.

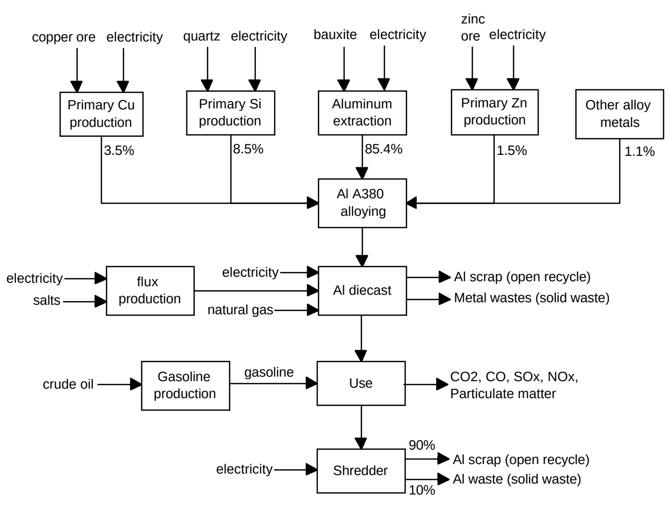

Figure 2. Life-cycle of diecast aluminum powertrain structural component.

Raw Material Acquisition – The aluminum part is made from primary A380 aluminum. Although many aluminum automotive parts are cast with secondary aluminum, at the time of this study, market supply and demand were such that the part modeled was made of primary metal. Primary aluminum is conventionally extracted and processed through the Bayer process, which involves the extraction of alumina (aluminum oxide) from bauxite ore. The alumina is sent to a smelter and subjected to electrolytic reduction via the Hall and Heroult process. This step requires large amounts of electricity to separate the strong bonds between aluminum and oxygen. The oxygen is picked up by a carbon reducing agent and forms carbon dioxide (CO_2) and carbon monoxide (CO).

Energy, material inputs and emissions data for the production of primary aluminum are provided by Ecobalance. The environmental burdens from the production of A380 aluminum alloying metals, including iron (up to 2%), copper (3-4%) and zinc (up to 3%), are also modeled using data sets from Ecobalance. Silicon, an alloying element that makes up a significant fraction in A380 (7.5-9.5%), is modeled using information provided by Elkem, one of the leading producers of the metal.

Primary energy consumption for the production of a kilogram of primary aluminum is cited as 207.0 MJ/kg by Ecobalance. This value is slightly higher than some other citations, as shown by Table 3, but was chosen because the complete material production inventory data set was available.

Table 3. Comparison of primary aluminum production primary energy requirements.

Citation	Primary Energy Consumption (MJ/kg)
Ecobalance	207.0
University of Stuttgart Germany (Eyerer, 1992)	163.73
ALCOA, USA (ALCOA, 1994)	188.40
SFOEFL, Switzerland (SFOEFL, 1991)	171.20
Intl Iron and Steel Institute, Belgium (IISI, 1994)	170.00
Sullivan and Hu, USA (1995), SAE Paper	196.3

It should be noted that due to confidentiality constraints, the location of the true supplier of primary aluminum was not provided. As a conservative estimate, the primary aluminum production facility nearest to the diecast plant was used to model transportation.

Product Fabrication

Diecasting Facility – Once alloyed, the A380 aluminum is shipped to a diecasting plant in Ontario. Because of strict proprietary regulations, limited information was available from the site. As a substitute, data from the 1997 Reppe study comparing diecast aluminum and magnesium transmission cases were used. Aluminum diecasting information from that study is based on 1995 data from a Ford supplier of diecast aluminum transmission cases. Information on total facility emissions, electricity and natural gas usage were provided by the facility. These quantities were divided by the total aluminum mass output to prorate each to a kilogram of part produced.

Three major assumptions are relevant for this life-cycle phase:

- Die lubricants used in Thixomolding® and aluminum diecasting are assumed to have the same composition and used in the same quantities. They were not included in the inventory model.
- Drossing flux usage, though not included in the Reppe data, was added to the model based on published literature sources. From a paper by Cochran (1992), a reasonable value for correct flux usage is 0.1% by weight of the aluminum melted. A commonly used flux consists of 44% KCl and 56% NaCl by weight. These values were included in the model. Ecobalance provided the data on the production of both salts.
- Cleaning fluxes and purge gases are not considered to be significant in this study.

Use Phase – The use phase is modeled using the same method described in the magnesium methodology section. However, the part weight is greater than the Thixomolded® part. Consequently, higher fuel consumption and emissions were allocated to the aluminum part.

End-of-Life (EOL) – The end-of-life phase for aluminum is similar to magnesium. As stated in the magnesium methodology section, the aluminum part is assumed to be shredded after its useful life, ninety percent (90%) of which is assumed to be recycled and sent to the secondary aluminum market.

Packaging and Transportation – Packaging and transportation are modeled the same way as the magnesium part. However, it should be noted that no information on the location of the aluminum primary production facility was found. As a conservative estimate, the nearest one to the diecasting facility was used as a surrogate (Coldwater, Michigan).

RESULTS AND DISCUSSION

ENERGY CONSUMPTION – Overall energy consumption, measured by summing the heating content of all primary energy sources consumed, is greater in the aluminum part than in magnesium as shown in Figure 3. The main differences are present in the raw material acquisition and use phases. However, these differences are highly sensitive to changes in secondary metal content and part mass. Although at the time of this study the aluminum part was manufactured with primary aluminum, this changes with market supply and demand, as secondary aluminum parts are commonly found throughout the automobile. Should the part have been made with secondary metal the energy consumption in the raw material acquisition phase would have been significantly lower, as illustrated by the downward arrow in Figure 3. Similar benefits can be afforded by using secondary magnesium although this market is less robust.

In the product fabrication phase, energy consumption is slightly higher for the magnesium part. Because of differences in part weight and manufacturing processes, this was not expected. With aluminum and magnesium having similar heats of fusion, it was expected that the aluminum part would have the higher energy consumption due to its higher weight. Three possible factors are responsible. First, Thixomolding® uses electricity for melting, whereas natural gas is used at the aluminum diecasting facility. The average efficiency to convert primary energy sources to electricity is about 30% (US). Direct use of natural gas has no such conversion losses. Second, the electricity consumption of the Thixomolded® part may be overestimated. The data provided by Thixotech, Inc. corresponded to a period when the facility was not in production. As a result, the facility may have had higher overhead energy use. Lastly, the melting efficiencies of each process are not known and most likely will vary. Further investigation of this parameter is necessary.

Energy consumption in the use phase is predominantly dependent on the mass of the part. Because the magnesium part is lighter, less consumption of energy is allocated to it.

WATER USE – The most significant differences in water use are in the raw material acquisition and product fabrication phases, as shown by Figure 4. However, it should be noted that the electrolytic magnesium production process utilizes high volumes of seawater from which magnesium is produced. Norsk Hydro estimates that 400 kg water per kg Mg produced is used. However, because this water is immediately returned to the ocean after extraction it is not included in the model. During the product fabrication phase, water use is roughly proportional to the mass of the parts.

GLOBAL WARMING POTENTIAL – Global warming potential (GWP) is a measure of the relative effectiveness of a greenhouse gas to trap the Earth's heat. GWP is measured in equivalents of kg CO_2. Global warming potentials for the following greenhouse gases are reported by the Intergovernmental Panel on Climate Change (IPCC): sulfur hexafluoride (23,900 GWP), hydrofluorocarbons (140-11,700 GWP), nitrous oxide (310 GWP), methane (21 GWP) and carbon dioxide (1 GWP). These potentials are based on a 100-year time span.

Figure 5 shows the GWP for both parts. Three bars are shown: one for primary aluminum, and two for both primary magnesium production processes. The arrows indicate high or low points in the range of data available. For aluminum, the downward arrow shows the GWP if secondary aluminum were used. Significant savings from energy and associated fossil fuel combustion emissions are apparent.

With the two magnesium production processes, high and low points correspond to the level of SF_6 emissions. Because SF_6 widely varies in use and has a large GWP per unit mass, the raw material acquisition phase GWP will also vary on a large scale. The low point corresponds to zero SF_6 use whereas the high point corresponds to 0.0014 kg SF_6/kg Mg as cited by Maiss (1998). Current trends reflect significant reductions of sulfur hexafluoride in the future. Some magnesium producers, such as Dow Chemical, have completely replaced the gas with a SO_2 substitute. Norsk Hydro, another large producer, cites 0.0005 kg SF_6/kg Mg emissions (which is represented by both magnesium histogram bars).

Global warming potential in the product fabrication phase is higher for the Thixomolded® part. As stated in the air emissions and energy consumption sections, the greater use of electricity contributes to increased primary energy consumption and air emissions. These air emissions, mostly the result of burning fossil fuels, are the main contributors to the GWP of the product fabrication phase.

ACIDIFICATION POTENTIAL – Acidification potential (AP) is a measure of the contribution of a chemical compound to acid rain. It is measured in kg equivalents of SO_2. Major contributors to acidification potential include SO_2 (1 AP), ammonia (1.88 AP), hydrochloric acid (0.88 AP) and NO_x (0.7 AP) (Heijungs, R., 1992).

As shown on Figure 6, acidification is highest in the raw material acquisition phase with primary aluminum. However, when secondary aluminum is considered instead AP drops significantly. In the product fabrication phase, the results indicate that magnesium part may contribute to a higher acidification potential. Much of the electricity used in Thixomolding® comes from coal that emits sulfur and nitrogen oxides whereas natural gas, which is used to melt aluminum in the die casting facility, is a cleaner burning fossil fuel.

CONCLUSION

Results of this study show significant sensitivity on the primary or secondary nature of the metal part and its mass. Use of secondary metals can achieve high savings in energy and reduce air pollution. According to Alcoa, recycled aluminum reduces energy consumption by approximately 95%, carbon dioxide emissions by 92%, and solid waste by 80% (ALCOA, 1994). Similar patterns can be expected with secondary magnesium use. However, the secondary magnesium industry is as of yet still emerging.

Variation in the reported use of sulfur hexafluoride use also highly affects the GWP results. As an optimistic estimate, future SF_6 emissions will be close if not equal to zero (Norsk Hydro, Magnesium in Automotive, 1997). In this case, differences in GWP between the magnesium and aluminum part will be dominated even more significantly by primary and secondary aluminum content.

From the results of this study additional questions are raised that require further investigation. Among these include the need to refine the energy requirements, environmental impacts, including emissions produced from Thixotech, Inc. The Thixotech, Inc. data for this study corresponds to a period when the company was not a production facility. As a result, energy and material use efficiency may not be fully represented. In addition, the potential additional lightweighting effects from Thixomolding® and the difference in machining requirements between a Thixomolded® part and a diecast part should be investigated.

It must be emphasized that the results of this study are dependent on the assumptions stated in the methodology and results section. The results are an estimation of the environmental burdens associated with both semi-solid injection molded magnesium and diecast aluminum, but are not reflective of either industry as a whole. However, these results do provide a directional indication of where in the life-cycle of both parts the greatest environmental burdens exist. This study can be used by part designers and customers as an additional consideration in evaluating the differences between the two processes and materials and also assist in finding opportunities for improvement.

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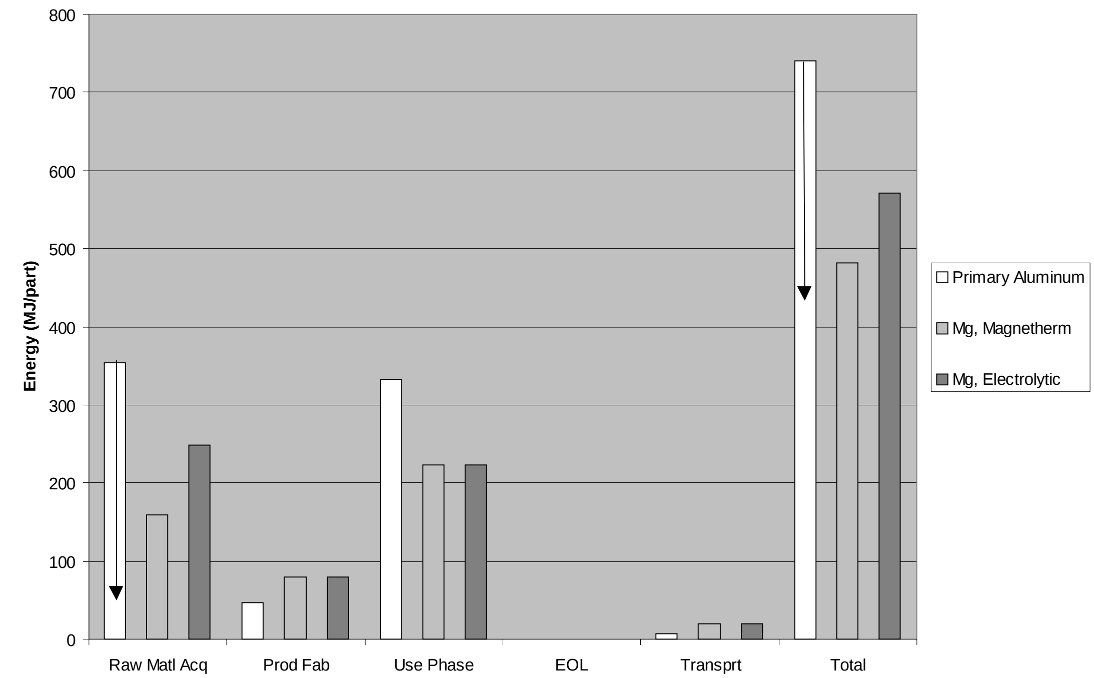

Figure 3. Primary Energy Consumption

Note: The arrows in Figure 3 represent the expected decrease in energy consumption by substituting secondary aluminum for primary aluminum.

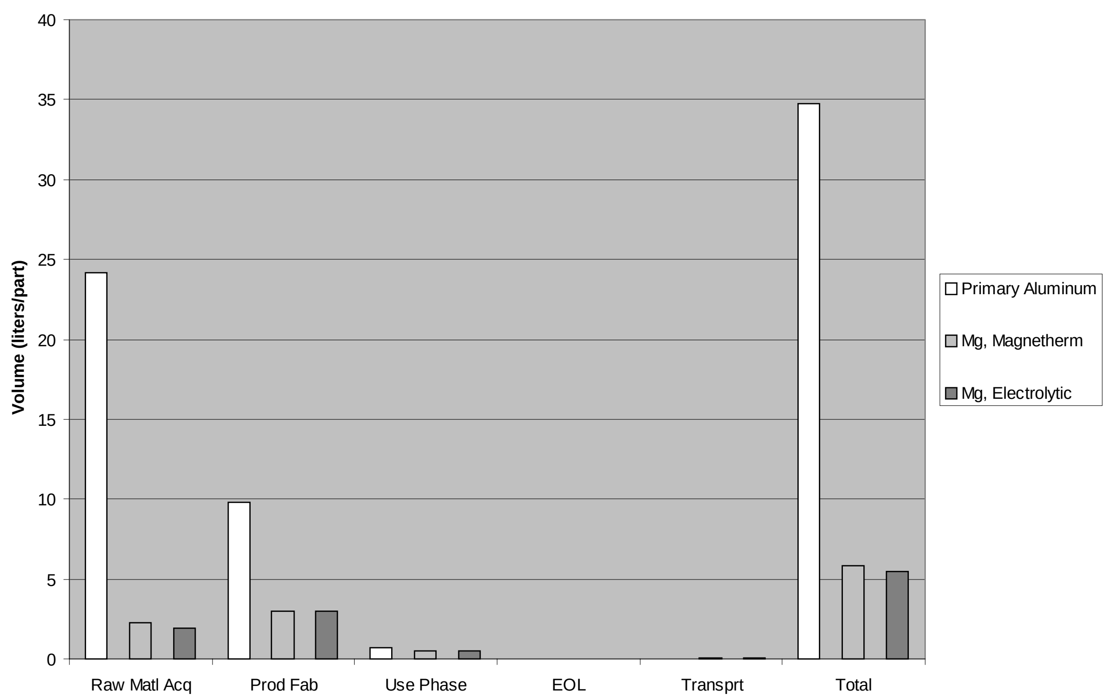

Figure 4. Water Use

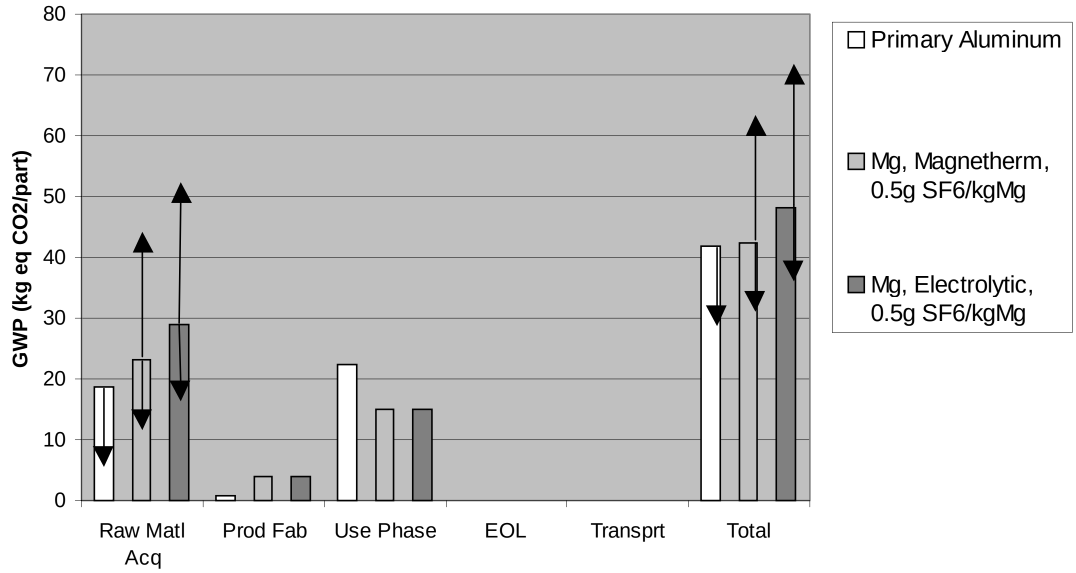

Figure 5. Global Warming Potential

Note: The single arrow in Figure 5 represents the expected decrease in greenhouse gas emissions by substituting secondary aluminum for primary aluminum. The double arrows represent the range of values related to SF_6 emissions from magnesium production.

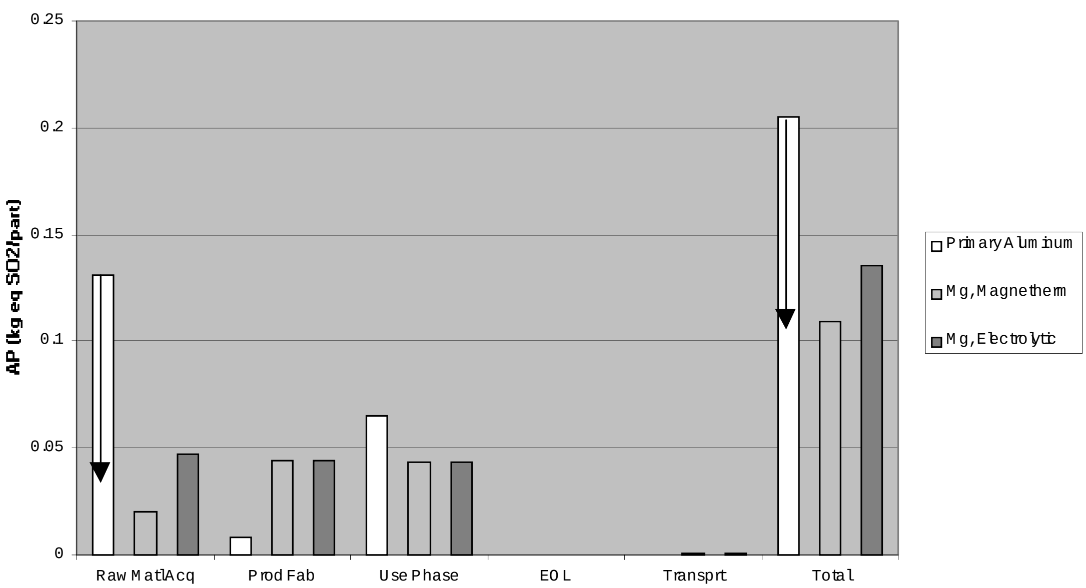

Figure 6. Acidification Potential (AP)

Note: The arrows in Figure 6 represent the expected decrease in acidification potential by substituting secondary aluminum for primary aluminum.